

Lecture Notes in Mechanical Engineering

Justyna Trojanowska
Agnieszka Kujawińska
Ivan Pavlenko
Jozef Husar *Editors*

Advances in Manufacturing IV


Volume 2 - Production Engineering:
Digitalization, Sustainability and
Industry Applications

 Springer

Lecture Notes in Mechanical Engineering

Series Editors


Fakher Chaari, *National School of Engineers, University of Sfax, Sfax, Tunisia*

Francesco Gherardini , *Dipartimento di Ingegneria “Enzo Ferrari”, Università di Modena e Reggio Emilia, Modena, Italy*

Vitalii Ivanov, *Department of Manufacturing Engineering, Machines and Tools, Sumy State University, Sumy, Ukraine*

Mohamed Haddar, *National School of Engineers of Sfax (ENIS), Sfax, Tunisia*

Editorial Board Members

Francisco Cavas-Martínez , *Departamento de Estructuras, Construcción y Expresión Gráfica Universidad Politécnica de Cartagena, Cartagena, Murcia, Spain*

Francesca di Mare, *Institute of Energy Technology, Ruhr-Universität Bochum, Bochum, Nordrhein-Westfalen, Germany*

Young W. Kwon, *Department of Manufacturing Engineering and Aerospace Engineering, Graduate School of Engineering and Applied Science, Monterey, CA, USA*

Tullio A. M. Tolio, *Department of Mechanical Engineering, Politecnico di Milano, Milano, Italy*

Justyna Trojanowska, *Poznan University of Technology, Poznan, Poland*

Robert Schmitt, *RWTH Aachen University, Aachen, Germany*

Jinyang Xu, *School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China*

Lecture Notes in Mechanical Engineering (LNME) publishes the latest developments in Mechanical Engineering—quickly, informally and with high quality. Original research or contributions reported in proceedings and post-proceedings represents the core of LNME. Volumes published in LNME embrace all aspects, subfields and new challenges of mechanical engineering.

To submit a proposal or request further information, please contact the Springer Editor of your location:

Europe, USA, Africa: Leontina Di Cecco at Leontina.dicecco@springer.com

China: Ella Zhang at ella.zhang@springer.com

India: Priya Vyas at priya.vyas@springer.com

Rest of Asia, Australia, New Zealand: Swati Meherishi at swati.meherishi@springer.com

Topics in the series include:

- Engineering Design
- Machinery and Machine Elements
- Mechanical Structures and Stress Analysis
- Automotive Engineering
- Engine Technology
- Aerospace Technology and Astronautics
- Nanotechnology and Microengineering
- Control, Robotics, Mechatronics
- MEMS
- Theoretical and Applied Mechanics
- Dynamical Systems, Control
- Fluid Mechanics
- Engineering Thermodynamics, Heat and Mass Transfer
- Manufacturing Engineering and Smart Manufacturing
- Precision Engineering, Instrumentation, Measurement
- Materials Engineering
- Tribology and Surface Technology

Indexed by SCOPUS, EI Compendex, and INSPEC.

All books published in the series are evaluated by Web of Science for the Conference Proceedings Citation Index (CPCI).


To submit a proposal for a monograph, please check our Springer Tracts in Mechanical Engineering at <https://link.springer.com/bookseries/11693>.


Justyna Trojanowska · Agnieszka Kujawińska ·
Ivan Pavlenko · Jozef Husar
Editors

Advances in Manufacturing IV

Volume 2 - Production Engineering:
Digitalization, Sustainability and Industry
Applications

Editors

Justyna Trojanowska 
Faculty of Mechanical Engineering
Poznań University of Technology
Poznan, Poland

Agnieszka Kujawińska 
Faculty of Mechanical Engineering
Poznan University of Technology
Poznan, Poland

Ivan Pavlenko
Sumy State University
Sumy, Ukraine

Jozef Husar 
Faculty of Manufacturing Technologies
Technical University of Košice
Presov, Slovakia

ISSN 2195-4356

ISSN 2195-4364 (electronic)

Lecture Notes in Mechanical Engineering

ISBN 978-3-031-56446-8

ISBN 978-3-031-56444-4 (eBook)

<https://doi.org/10.1007/978-3-031-56444-4>

© The Editor(s) (if applicable) and The Author(s), under exclusive license
to Springer Nature Switzerland AG 2024

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Paper in this product is recyclable.

Preface

This volume of Lecture Notes in Mechanical Engineering gathers selected papers presented at the 8th International Scientific-Technical Conference MANUFACTURING 2024, held in Poznan, Poland, on May 14–16, 2024. The conference was organized by the Faculty of Mechanical Engineering, Poznan University of Technology, Poland.

The aim of the conference was to present the latest achievements in the wide field of mechanical engineering and to provide an opportunity to discuss and exchange views and opinions in the area of automation strategies, digitalization, and improvement of process efficiency, with particular emphasis on sustainable practices. The conference covered the following topics:

- mechanical engineering,
- production engineering,
- quality engineering,
- measurement and control systems,
- biomedical engineering.

The organizers received 197 contributions from 34 countries around the world. After a thorough peer-review process (double-blind review), the committee accepted 107 papers for conference proceedings prepared by 310 authors from 29 countries (acceptance rate 54%). At least three independent reviewers reviewed each paper. Reviewers needed to evaluate each paper by answering, among others, the questions about the originality of the paper, the significance of presented results, comprehensibility, and presentation of chapters and relevance for this conference. The reviewers came from 19 countries in Europe, North America, South Asia, and North Africa. Each article was checked using iThenticate and achieved a similarity index of less than 12%.

The book **Advances in Manufacturing IV** is organized into five volumes that correspond to the main conference disciplines mentioned above.

Advances in Manufacturing IV – Volume 2 – Production Engineering: Digitalization, Sustainability and Industry Applications gathers papers on cutting-edge research and technologies aimed at increasing the efficiency of production processes and supporting the implementation of Industry 4.0 and Industry 5.0 solutions in production. It reports on research on and applications of artificial intelligence and digital technologies to improve the production process and highlights cutting-edge solutions for green and sustainable production. Chapters are devoted to digital transformation and innovation and to the optimization of production processes. Written by scientists and practitioners around the world, this book is intended to promote the exchange of views and experiences and contribute to the dissemination and effective application. It includes 30 chapters, prepared by 94 authors from 12 countries.

We would like to thank the members of the International Program Committee for their hard work during the review process. We acknowledge all people who contributed to the staging of MANUFACTURING 2024: authors, committees, and sponsors. Their

involvement and hard work were crucial to the success of the MANUFACTURING 2024 conference.

May 2024

Justyna Trojanowska
Agnieszka Kujawińska
Ivan Pavlenko
Jozef Husár

Adam Gąska	Cracow University of Technology, Poland
Arkadiusz Gola	Lublin University of Technology, Poland
Filip Górski	Poznan University of Technology, Poland
Marta Grabowska	Poznan University of Technology, Poland
Adam Hamrol	Poznan University of Technology, Poland
Mukund Harugade	Padmabhooshan Vasantraodada Patil Institute of Technology, India
Magdalena Hryb	Poznan University of Technology, Poland
Jozef Husar	Technical University of Košice, Slovakia
Aminul Islam	Technical University of Denmark, Denmark
Vitalii Ivanov	Sumy State University, Ukraine
Andrzej Jardzioch	West Pomeranian University of Technology in Szczecin, Poland
Sabahudin Jasarevic	University of Zenica, Bosnia & Herzegovina
Małgorzata Jasiulewicz-Kaczmarek	Poznan University of Technology, Poland
Jakub Kaščák	Technical University of Košice, Slovakia
Sławomir Kłos	Poznan University of Technology, Poland
Lucia Knapcikova	Technical University of Košice, Slovakia
Józef Kuczmaszewski	Lublin University of Technology, Poland
Agnieszka Kujawińska	Poznan University of Technology, Poland
Vijaya Kumar Manupati	National Institute of Industrial Engineering, India
Stanisław Legutko	Poznan University of Technology, Poland
Sławomir Luściński	Kielce University of Technology, Poland
José Machado	University of Minho, Portugal
Marek Macko	Kazimierz Wielki University in Bydgoszcz, Poland
Damjan Maletic	University of Maribor, Slovenia
Józef Matuszek	University of Bielsko-Biala, Poland
Dragomir Mihai	Technical University of Cluj-Napoca, Romania
Andrzej Milecki	Poznan University of Technology, Poland
Piotr Moncarz	Stanford University, USA
Leticia Neira	Autonomous University of Nuevo León, Mexico
Magdalena Niemczewska-Wójcik	Cracow University of Technology, Poland
Przemysław Niewiadomski	University of Zielona Góra, Poland
Joanna Oleśków Szłapka	Poznan University of Technology, Poland
Joaquin Ordieres-Miere	Universidad Politécnica de Madrid, Spain
Zaida Ortega	University of Las Palmas de Gran Canaria, Spain
Razvan Ioan Pacurar	Technical University of Cluj-Napoca, Romania
Sandra Paszkiewicz	West Pomeranian University of Technology, Poland
Justyna Patalas-Maliszewska	University of Zielona Góra, Poland

Ivan Pavlenko	Sumy State University, Ukraine
Cesar Pinzon Acosta	Technological University of Panama, Panama
Marian Grigore Pop	Technical University of Cluj-Napoca, Romania
Florin Popișter	Technical University of Cluj-Napoca, Romania
Paulina Rewers	Poznan University of Technology, Poland
Joaquín Francisco Roca González	Polytechnic University of Cartagena, Spain
Izabela Rojek	Kazimierz Wielki University, Poland
Michał Rychlik	Poznan University of Technology, Poland
Krzysztof Santarek	Warsaw University of Technology, Poland
Alzbeta Sapietova	University of Žilina, Slovakia
Miguel Afonso Sellitto	University of Vale do Rio dos Sinos, Brazil
Natalya Shramenko	Lviv Polytechnic National University, Ukraine
Sebastian Skoczypiec	Cracow University of Technology, Poland
Bożena Skołod	Silesian University of Technology, Poland
Beata Starzyńska	Poznan University of Technology, Poland
Manuel Suárez-Barraza	Universidad de las Américas Puebla, Mexico
Marek Szostak	Poznan University of Technology, Poland
Jozef Török	Technical University of Košice, Slovakia
Justyna Trojanowska	Poznan University of Technology, Poland
Wiesław Urban	Bialystok University of Technology, Poland
Leonilde Varela	University of Minho, Portugal
Alexandre Voisin	University of Lorraine, France
Edmund Weiss	Calisia University, Poland
Michał Wieczorowski	Poznan University of Technology, Poland
Szymon Wojciechowski	Poznan University of Technology, Poland
Ralf Woll	BTU Cottbus-Senftenberg, Germany
Nermina Zaimovic-Uzunovic	University of Zenica, Bosnia & Herzegovina
Jozef Zajac	Technical University of Košice, Slovakia
Danuta Zawadzka	Koszalin University of Technology, Poland

Program Committee

Adam Górny	Poznan University of Technology, Poland
Adnan Corum	Bahçeşehir University, Turkey
Adam Hamrol	Poznan University of Technology, Poland
Agnieszka Kujawińska	Poznan University of Technology, Poland
Agnieszka Stachowiak	Poznan University of Technology, Poland
Aleksandar Miltenovic	University of Nis, Serbia
Aleksander Hejna	Poznan University of Technology, Poland
Alena Vagaská	Technical University of Košice, Slovak Republic
Alexandre Voisin	Université de Lorraine, France

Aminul Islam	Technical University of Denmark, Denmark
Ana González Marcos	Rioja University, Spain
Andrea Lucchese	Politecnico di Bari, Italy
Andrii Rogovyi	National Technical University, Ukraine
Andrzej Gessner	Poznan University of Technology, Poland
Andrzej Jardzioch	West Pomeranian University of Technology in Szczecin, Poland
Andrzej Loska	Silesian University of Technology, Poland
Andrzej Świdorski	Motor Transport Institute, Poland
Angel Mena-Nieto	Huelva University, Spain
Anna Borucka	Military University of Technology Warsaw, Poland
Anna Burduk	Wroclaw University of Science and Technology, Poland
Anna Karwasz	Poznan University of Technology, Poland
Anouar Hallioui	Sidi Mohamed Ben Abdellah University, Morocco
Antonio Sanchez Herguedas	Seville University, Spain
Arkadiusz Gola	Lublin University of Technology, Poland
Bartosz Gapiński	Poznan University of Technology, Poland
Beata Starzyńska	Poznan University of Technology, Poland
Beata Stasiak-Cieślak	Motor Transport Institute, Poland
Bożena Skołod	Silesian University of Technology, Poland
Cesar Pinzon Acosta	Technological University of Panama, Panama
Chiara Franciosi	Université de Lorraine, France
Christopher Brown	Worcester Polytechnic Institute, USA
Claudiu Ioan Abrudan	Technical University of Cluj-Napoca, Romania
Dagmara Łapczyńska	Wroclaw University of Science and Technology, Poland
Damjan Maletič	University of Maribor, Slovenia
Daniel Černý	Czech Technical University in Prague, Czech Republic
Dariusz Mikołajewski	Kazimierz Wielki University, Poland
Dmytro Lesyk	National Technical University of Ukraine “Kyiv Polytechnic Institute”, Ukraine
Dorota Stadnicka	Rzeszow University of Technology, Poland
Elżbieta Piesowicz	West Pomeranian University of Technology in Szczecin, Poland
Erika Ottaviano	University of Cassino and Southern Italy, Italy
Erwin Rauch	Free University of Bolzano, Italy
Fernando González Aleu Gonzalez	Universidad de Monterrey, Mexico
Grzegorz Wojnar	Silesian University of Technology, Poland
Ivan Dehtiarov	Sumy State University, Ukraine

Ivan Pavlenko	Sumy State University, Ukraine
Izabela Irska	West Pomeranian University of Technology in Szczecin, Poland
Izabela Rojek	Kazimierz Wielki University, Poland
Jacek Andrzejewski	Poznan University of Technology, Poland
Jacek Diakun	Poznan University of Technology, Poland
Jakub Pizoń	Lublin University of Technology, Poland
Ján Ivan	Technical University of Kosice, Slovak Republic
Ján Majerník	University of Technology and Economics in České Budějovice, Czech Republic
Jarosław Selech	Poznan University of Technology, Poland
Jesus Vazquez	Universidad de Monterrey, Mexico
Jiří Tengler	University of Žilina, Czech Republic
Joanna Kočańska	Wroclaw University of Science and Technology, Poland
Joanna Ryszkowska	Warsaw University of Technology, Poland
Joaquin Ordieres	Universidad Politécnica de Madrid, Spain
José Machado	University of Minho, Portugal
Jozef Husár	Technical University of Košice, Slovak Republic
Jozef Török	Technical University of Kosice, Slovak Republic
Józef Kuczmaszewski	Lublin University of Technology, Poland
Justyna Patalas-Maliszewska	University of Zielona Góra, Poland
Justyna Trojanowska	Poznan University of Technology, Poland
Kamil Krot	Wroclaw University of Science and Technology, Poland
Kamil Musiał	Wroclaw University of Science and Technology, Poland
Katarzyna Piotrowska	Lublin University of Technology, Poland
Khrystyna Berladir	Sumy State University, Ukraine
Krzysztof Santarek	Warsaw University of Technology, Poland
Krzysztof Talaśka	Poznan University of Technology, Poland
Krzysztof Żywicki	Poznan University of Technology, Poland
Ladislav Morovic	Slovak University of Technology in Bratislava, Slovak Republic
Lennart Grüger	Brandenburg University of Technology Cottbus-Senftenberg, Germany
Leonilde Varela	University of Minho, Portugal
Leticia Neira	Universidad Autonoma de Nuevo Leon, Mexico
Lucia Knapčíková	Technical University of Košice, Slovak Republic
Maciej Matuszewski	Bydgoszcz University of Science and Technology, Poland
Magdalena Niemczewska-Wójcik	Cracow University of Technology, Polska
Małgorzata Sławińska	Poznan University of Technology, Poland

Manuel Castejón-Limas	Leon University, Spain
Manuel F. Suarez Barraza	University of the Americas, Mexico
Marcin Butlewski	Poznan University of Technology, Poland
Marcin Hinz	Munich University of Applied Sciences, Germany
Marek Szostak	Poznan University of Technology, Poland
Marian Bartoszuk	Opole University of Technology, Poland
Mariusz Piechowski	WSB MERITO Universities, Poland
Martin Korol'	Technical University of Kosice, Slovak Republic
Maryna S. Ivanova	National Technical University "Kharkov Polytechnic Institute", Ukraine
Michał Wieczorowski	Poznan University of Technology, Poland
Monika Kulisz	Lublin University of Technology, Poland
Mosè Gallo	University of Napoli Federico II, Italy
Mukund Harugade	Padmabhooshan Vasantraodada Patil Institute of Technology, India
Nikola Korunovic	University of Nis, Serbia
Nikola Vitković	University of Nis, Serbia
Oksana Dynnyk	Sumy State University, Ukraine
Olexandr Prykhodko	Sumy State University, Ukraine
Pablo Rubén Bordón Pérez	University of Las Palmas de Gran Canaria, Spain
Pacurar Ancuta	Technical University of Cluj-Napoca, Romania
Patrik Grznár	University of Žilina, Slovak Republic
Paweł Buń	Poznan University of Technology, Poland
Peter Košťál	Slovak University of Technology, Slovak Republic
Piotr Cyplik	Poznan University of Technology, Poland
Piotr Trojanowski	West Pomeranian University of Technology in Szczecin, Poland
Pop Grigore Marian	Technical University of Cluj-Napoca, Romania
Przemysław Niewiadomski	University of Zielona Góra, Poland
Quirino Estrada	Universidad Autónoma de Ciudad Juárez, Mexico
Radu Comes	Technical University of Cluj-Napoca, Romania
Radu Cotetiu	Technical University of Cluj-Napoca, Romania
Rafał Burdzik	Silesian University of Technology, Poland
Ratnesh Raj	Indian Institute of Technology, India
Robert Waszkowski	Military University of Technology Warsaw, Poland
Rubén Paz Hernández	University of Las Palmas de Gran Canaria, Spain
Rusan Claudiu	Technical University of Cluj-Napoca, Romania
Ryszard Wyczółkowski	Silesian University of Technology, Poland
Samir Maity	Aalborg University, Denmark
Sandra Paszkiewicz	West Pomeranian University of Technology in Szczecin, Poland

Sara Ester Díaz Guzmán	University of Las Palmas de Gran Canaria, Spain
Sebastian Skoczypiec	Cracow University of Technology, Poland
Stanisław Legutko	Poznan University of Technology, Poland
Stanisław Młynarski	Cracow University of Technology, Poland
Stefan Bodi	Technical University of Cluj-Napoca, Romania
Stefan Bracke	University of Wuppertal, Germany
Stella Hrehova	Technical University of Košice, Slovak Republic
Sven Maricic	Juraj Dobrila University of Pula, Croatia
Szymon Wojciechowski	Poznan University of Technology, Poland
Vitalii Ivanov	Sumy State University, Ukraine
Wiesław Kuczko	Poznan University of Technology, Poland
Yuliia Denysenko	Sumy State University, Ukraine
Zaida Cristina Ortega Medina	University of Las Palmas de Gran Canaria, Spain
Zbigniew Banaszak	Koszalin University of Technology, Poland

Special Sessions and Special Session Organizing Committee

Manufacturing and Management Tools Increasing Production Efficiency in Era of Digitalization

Leonilde Varela	University of Minho, Portugal
Justyna Trojanowska	Poznan University of Technology, Poland
Vijaya Kumar Manupati	NITIE Mumbai, India
Khrystyna Berladir	Sumy State University, Ukraine

Operational Excellence and Continuous Improvement/Innovation. Lean Thinking, Kaizen Philosophy, and Toyota Production System

Manuel F. Suárez-Barraza	University of the Americas, Mexico
Fernando González Aleu Gonzalez	Universidad de Monterrey, Mexico

Quality and Metrology in Production Systems

Pop Marian Grigore	Technical University of Cluj-Napoca, Romania
Popișter Florin	Technical University of Cluj-Napoca, Romania
Câmpean Emilia Maria	Technical University of Cluj-Napoca, Romania
Dragomir Mihai	Technical University of Cluj-Napoca, Romania

Quality Assurance for Sustainability of Manufacturing Processes and Systems

Yuliia Denysenko	Sumy State University, Ukraine
Vitalii Ivanov	Sumy State University, Ukraine
Cesar Pinzon Acosta	Technological University of Panama, Panama
Sławomir Luściński	Kielce University of Technology, Poland

Industry 5.0 – from Theory to Practice

Joanna Oleśków Szłapka	Poznan University of Technology, Poland
Joaquin Ordieres-Miere	Universidad Politécnica de Madrid, Spain
Adnan Corum	Bahçeşehir University, Turkey
Miguel Afonso Sellitto	University of Vale do Rio dos Sinos, Brazil

New Perspectives in the Development of Material Solutions and Technologies for Sustainable Polymers and Composites

Zaida Ortega	University of Las Palmas de Gran Canaria, Spain
Sandra Paszkiewicz	West Pomeranian University of Technology, Poland
Mateusz Barczewski	Poznan University of Technology, Poland

Advanced Methods for Additive Manufacturing

Jakub Kaščák	Technical University of Košice, Slovakia
Jozef Török	Technical University of Košice, Slovakia

Intelligent Technologies in Production and Maintenance - Industry 4.0

Katarzyna Antosz	Rzeszow University of Technology, Poland
Anna Burduk	Wroclaw University of Science and Technology, Poland
Arkadiusz Gola	Lublin University of Technology, Poland
José Machado	University of Minho, Portugal

Innovations in Design and Manufacturing of Customized Medical Products in the Wake of Digital Healthcare Revolution

Filip Górski	Poznan University of Technology, Poland
Răzvan Păcurar	Technical University of Cluj-Napoca, Romania
Joaquín Francisco Roca González	Polytechnic University of Cartagena, Spain
Michał Rychlik	Poznan University of Technology, Poland

Intelligent Solutions for Industry 4.0 and 5.0

Izabela Rojek

Kazimierz Wielki University in Bydgoszcz,
Poland

Ewa Dostatni

Poznan University of Technology, Poland

Alzbeta Sapietova

University of Žilina, Slovakia

Sustainable Manufacturing and Maintenance in the Industry 4.0 Context

Małgorzata

Jasiulewicz-Kaczmarek

Poznan University of Technology, Poland

Chiara Franciosi

University of Lorraine, France

Alexandre Voisin

University of Lorraine, France

Robert Čep

VSB - Technical University of Ostrava,
Czech Republic

Contents

Digital Transformation and Innovation

Exploring the Potential of Digital Twins for New Product Design and Development: A Review of Research Gaps	3
<i>Adeniyi Sobowale, Helena Lopes, Justyna Trojanowska, Ana Lima, Pedro Marujo, and Jose Machado</i>	
Innovation of the Manufacturing Company by Using of Digitization Tools	21
<i>Lucia Knapčíková, Annamária Behúnová, Rebeka Tauberová, Matúš Martiček, and Jozef Husár</i>	
Recent Trends in Artificial Intelligence and Machine Learning Methods Applied to Water Jet Machining	34
<i>Rehan Khan, Michał Wieczorowski, Ariba Qureshi, Muhammad Ammar, Tauseef Ahmed, and Umair Khan</i>	
Virtual and Augmented Reality: Past, Present, and Future	46
<i>Hugo Silva, André S. Santos, Leonilde R. Varela, Justyna Trojanowska, and Vitalii Ivanov</i>	
Mixed Reality as a Perspective Education Tool in Industry 5.0	60
<i>Jozef Husár, Stella Hrehová, Lucia Knapčíková, and Piotr Trojanowski</i>	
Lean Manufacturing in Digital Transformation of Manufacture	74
<i>Agnieszka Terelak-Tymczyna and Beata Niesterowicz</i>	
The Scenario Approach to the Concept of Maintenance of Technical Systems of Urban Engineering	84
<i>Andrzej Loska, Waldemar Paszkowski, and Robert Waszkowski</i>	
Manufacturing Line-Level Root Cause Analysis and Bottleneck Detection Using the Digital Shadow Concept and Cloud Computing	98
<i>Jan Dąbrowski, Tomasz Bartkowiak, Piotr Wierzchowski, and Dariusz Dąbrowski</i>	
3D Printing in Non-planar Layers as a New Tool for Increasing the Quality of FDM Production	112
<i>Jakub Kašćak, Marek Kočíško, Jozef Török, and Adrián Vodilka</i>	

Potential of Graph Database Visualization of the Supplier Network to Increase Resilience in Multi-tier Supply Chains	125
<i>Erwin Rauch, Ali Asghar Bataleblu, Michaela Golser, Asja Emer, and Dominik T. Matt</i>	
A Racing Approach: The Evolution of Racing Techniques, A Systematic Literature Review	140
<i>Hugo Silva, André S. Santos, Leonilde R. Varela, Magdalena Diering, and Khrystyna Berladir</i>	
The Impact of PLM Systems on the Digital Transformation of Manufacturing Companies	151
<i>Jan Duda, Sylwester Oleszek, and Krzysztof Santarek</i>	
Using Visions Systems and Manipulators in Industry 4.0	165
<i>Anna Karwasz and Igor Wawrzynowicz</i>	
Geometric Complexity Evaluation Method for Adoption of Additive Manufacturing	178
<i>Ankur Krishna and Rajesh Duraisamy</i>	
Using AI Tools to Enhance the Risk Management Process in the Automotive Industry	189
<i>Diana Dragomir, Florin Popișter, and Kamil Erkan Kabak</i>	
Optimization of Production Processes	
Innovations - Changes in the Environment of the Production Planning Process in Enterprises	201
<i>Marek Fertsch, Agnieszka Stachowiak, and Joanna Oleśków-Sztańska</i>	
Heuristic-Based Algorithm for Suboptimal Scheduling Realized in Hybrid Production Environment	213
<i>Wojciech Danilczuk, Arkadiusz Gola, and Jakub Pizoń</i>	
Minimum Job Completion Time in Petri Nets	227
<i>Reggie Davidrajuh, Damian Krenczyk, and Bożena Skolud</i>	
Optimization and Evaluation of Storage Processes Based on a Selected Example	239
<i>Anna Borucka, Krzysztof Patrejko, Łukasz Patrejko, and Konrad Polakowski</i>	

Comparison of Different Production Systems Approaches of a Manufacturing Line in the Aeronautical Sector	251
<i>Carmen de Vilanova Diego, Miguel Ortega-Mier, Tamara Borreguero, Álvaro García-Sánchez, and Carlos García-Castellano Gerbolés</i>	
Cooperation Between Companies in Technology Management Really Matters - Explored Through PLS-SEM Modelling	265
<i>Elżbieta Krawczyk-Dembicka and Wiesław Urban</i>	
Proactive Resource Maintenance in Product-as-a-Service Business Models: A Constraints Programming Based Approach for MFP Offerings Prototyping	276
<i>Eryk Szwarz, Paulina Golińska-Dawson, Grzegorz Bocewicz, and Zbigniew Banaszak</i>	
Throughput Evaluation of Serial-Parallel Manufacturing Systems for Different Production Flow Strategies	290
<i>Sławomir Kłos and Justyna Patalas-Maliszewska</i>	
Ensuring the Stability of Production Processes Using Statistical Models	300
<i>Lukasz Łampika, Dagmara Łapczyńska, Joanna Kochańska, Anna Burduk, and Kamil Musiał</i>	
Modern Technologies Supporting the Development of the Automotive Industry	313
<i>Krzysztof Santarek</i>	
Failure Analytics of Defects in Mechanical Engineering Parts Using Root Cause Analysis: Case Study	328
<i>Khrystyna Berladir, Tetiana Hovorun, Justyna Trojanowska, Vitalii Ivanov, and Angelina Iakovets</i>	
Consumer Awareness and Customization of Footwear in the Context of the Idea of Industry 4.0: Analysis of Survey Results	342
<i>Karolina Wrześniowska and Cezary Grabowik</i>	
The Impact of KAIZEN on the Operational Performance of Multinational Manufacturing Companies Through the Degree of Maturity. A Mixed Study in Mexico	359
<i>Manuel F. Suárez-Barraza, Jesús A. Chávez-Pineda, Dailin A. Ramirez Altamirano, and María Isabel Huerta-Carvajal</i>	

Applying Kaizen (Incremental Innovation) in a Mexican Handcrafted
Talavera Company: A Case Study Approach 381
*Manuel F. Suárez-Barraza, José Ángel Miguel-Davila,
and María Isabel Huerta-Carvajal*





Success Factor Driven Adaptive Approach to Pro-ergonomic Project
Management 395
Wiktoria Czernecka and Marcin Butlewski

Author Index 409

Digital Transformation and Innovation



Exploring the Potential of Digital Twins for New Product Design and Development: A Review of Research Gaps

Adeniyi Sobowale¹ , Helena Lopes¹ , Justyna Trojanowska² , Ana Lima³ , Pedro Marujo⁴ , and Jose Machado¹ 

¹ University of Minho, Guimarães, Portugal
jmachado@dem.uminho.pt

² Poznan University of Technology, Poznan, Poland

³ CCG/ZGDV – ICT Innovation Institute, Guimarães, Portugal

⁴ Sonae Arauco Portugal, S.A., Oliveira do Hospital, Portugal

Abstract. A rapidly developing technology, digital twins have the potential to completely change how products are designed and developed. Digital twins enable the simulation of the performance of various design concepts, the identification of potential issues with a design, and the optimization of the design for certain performance needs. However, in terms of digital twins and their utilization in product development, there are some gaps in the existing literature. There is also a lack of a standardized digital twin framework. There is currently no structure for creating and utilizing digital twins that is universally approved. Because of this, it is challenging for many organizations to share and work together on digital twin initiatives. Another aspect to consider is the huge investment of putting digital twin technology into practice. Implementing digital twin technology can be costly, particularly for large and complicated products. This may prevent small and medium-sized firms from adopting the technology. Real-time data integration is also lacking. For digital twins to be accurate, the physical product must provide real-time data. Getting real-time data from sensors and other devices might, however, be challenging to include into the digital twin. This paper examines the bibliographic research gaps concerning the use of digital twins specifically for new product design and development. The report also addresses some solutions and how the limitations might affect the development of digital twin technologies in the future.

Keywords: Digital Twin · Product lifecycle management PLM · Research gaps · Real-time monitoring

1 Introduction

The emergence of digital twin technology has revolutionized product development and system optimization processes. As an effective way to realize information fusion and intelligent interaction between the physical world and the information world in production line, digital twin has recently attracted high attention from scholars in related fields at

home and abroad [1]. The concept, first proposed in 2002 by Professor Michael Grieves of the University of Michigan. He described it as a model that represents information in a virtual and digital form, which is equal to physical products. He characterized this model as consisting of three essential components: the physical environment, virtual space and an interference that connects the two spaces. Over the years, however, digital twin (DT) technology has seen immense growth. They are generally digital simulations of physical products or systems that can be utilized to simulate their functionality. By enabling engineers to conduct testing and make modifications to designs in a virtual environment prior to producing physical prototypes, virtual environments have the potential to fundamentally transform the process of product creation. While digital twins have proven effective in assisting re-design and product improvement [2], their application for generating new design ideas remains underexplored. While digital twin may not be the primary tool for generating new design ideas, they can be highly valuable during the ideation process by providing insights into the performance and behavior of existing products or systems thus providing with more options than the traditional design methods [3]. While this reduces the difficulty in exploring a wide range of design possibilities, there exist a few questions that should be answered. First, the accuracy and reliability of a digital twin is limited due to its reliance on a single data source i.e., sensor data; and secondly, there may be instances where its implementations may not meet all user expectations or fail to deliver desired insights due to variables such as limited data availability, data quality issues or challenges in integrating and analyzing complex real-time data [4]. The data-driven analysis and simulation capabilities of digital twin can inform the design process by identifying potential areas for improvement, optimizing designs, and ensuring that new ideas align with desired performance objectives. The use of digital twins to gather data from many sources and leverage it to optimize outcomes over the whole product life cycle (spanning from the design to production, maintenance, and support) is significantly impacting organizations. Several researchers such as [5] discussed a product DT approach that uses a skin-model structure to bridge the gap between the design and manufacturing stages while [3] outlined the technological advancements that may actualize this notion in the commercial domain including all stages of a product's lifecycle. Böttjer [4] subsequently verified that the collaboration between DT and PLM has the capacity to integrate products and production procedures, providing us with ongoing feedback on the product's performance. It is evident therefore that research efforts are focused on enhancing DT structures, creating novel applications, and investigating the significance of DT in many industrial sectors.

This paper thus reviews the bibliographic research gaps in the area of using digital twin for designing and developing a product. The remaining portion of the article is organized as follow: Sect. 1 introduces the research domain, while Sect. 2 discusses the research problem and approach of the study followed by discussions on digital twins and its role in product design and development, while Sect. 3 discussed the research gaps identification results, Sect. 4 addresses the gaps with a view of providing solutions to each of the identified gaps while Sect. 5 finalized the paper.

2 Research Problem

The objective of this study is to identify and explore the research gaps in the utilization of digital twins for new product design and development.

- Identify the key research gaps related to the integration of diverse data sources into the digital twin model for new product design and development.
- Examine the challenges and opportunities associated with ensuring model accuracy and validation in the context of digital twins.
- Investigate the research gaps pertaining to optimization and decision support techniques that can leverage the capabilities of digital twins in improving product design parameters and decision-making processes.
- Discuss the research gaps related to collaborative design and development facilitated by digital twin technology and explore potential solutions for enhancing collaboration among cross-functional teams.

By addressing these objectives, this study aims to contribute to the existing body of knowledge on digital twins in the context of new product design and development. The conclusions and insights from this study can help direct future research projects, educate practitioners, and offer insightful advice for effectively utilizing digital twin technology to accelerate the design and development of new products. The ultimate goal of the review is to provide academics and industry experts with the tools needed in the quest to fully realize the promise of digital twins and have a stronger impact on the product development process.

2.1 Methodology

The methodology intends to provide a rigorous and organized approach to ensuring the validity and reliability of the research findings by analyzing and synthesizing existing literature to identify and investigate research gaps related to the use of digital twins in new product design and development. The novel aspect of this research is the identification and comprehensive analysis of the gaps in literature in the domain of using digital twin for new product design and development. The review focuses on Scopus-referenced research publications based on the level of application of product design and development using DT technology and did not consider the application areas such as industrial applications. Below, there are presented the adopted steps for this research work;

Literature Review: A thorough review of existing literature on the utilization of digital twins in new product design and development will be conducted. This will involve searching academic databases, research repositories, and relevant industry publications to identify relevant articles, papers, and reports that address the research topic.

Gap Identification: The identified literature will be analyzed to identify the research gaps in the utilization of digital twins for new product design and development. This will involve an organized review of the literature to identify recurring themes, problems, and areas that require further research.

Gap Analysis: The identified research gaps will be further analyzed to understand their significance and impact on the field. This analysis will involve comparing and contrasting different viewpoints, identifying key challenges and opportunities, and assessing the potential implications of these research gaps on the design and development process of new products.

Discussion: The findings from the literature review and gap analysis will be synthesized and organized into coherent themes and subtopics. In-depth discussions of these topics will be held in order to shed light on the particular difficulties and chances mentioned in the earlier steps. Theoretical stances, practical implications, and viable remedies for filling in the research gaps will all be discussed.

Future Directions and Recommendations: Based on the analysis and discussion, future research directions and recommendations will be provided. These recommendations will guide researchers and practitioners in further exploration of the identified research gaps and outline strategies for effectively leveraging digital twins in designing and developing a new product.

2.2 Digital Twins in Product Design and Development

Digital twin concept has gained significant attention in recent years due to its potential applications in various domains. The definition of the term “Digital Twin” differs between the academia and the industry. Dr. Michael Grieves of the University of Michigan initially introduced the notion of digital twin (DT) in the first executive product lifecycle management (PLM) courses in early 2002 as shown in Fig. 1 and called it Mirroring Spaces Model (MSM) in 2005 [6], and Information Mirroring Model in 2006 [7] calling it “Conceptual Ideal for Product Lifecycle Management (PLM)” [8] and illustrating the relationship between real space and virtual space as shown in Fig. 1.

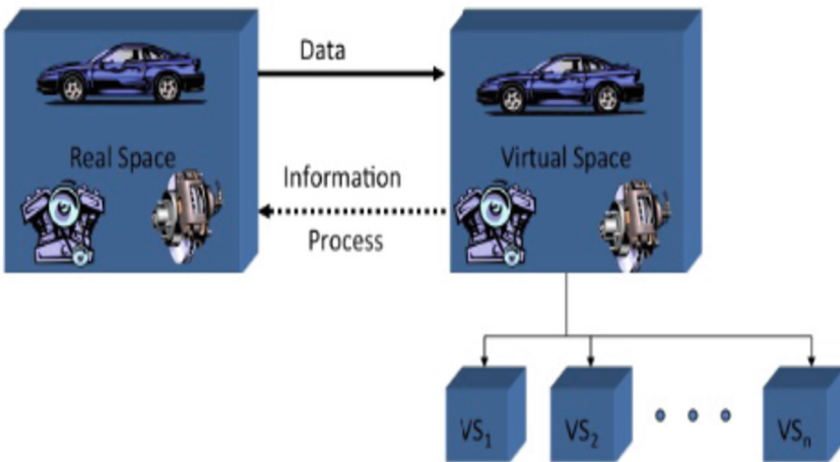


Fig. 1. Conceptual product lifecycle management (PLM) schematic in 2001. Adapted from [8]

There have been several other attempts to explain the concept of digital twins. For instance, the works presented in [9] and [10] called it digital avatars with the objective of providing an information management framework that facilitates a two-way flow of information, with a focus on the product-centric viewpoint. The works developed at [11, 12] and [13] also referred to the term digital avatar in their papers, [14] referred to it as digital masters, digital shadows [15], and digital double [16] are some of the concepts and names used to describe digital twin (DT) in the past. The term was widely recognized and used to refer to the technology that replicates and connects actual objects and digital models before NASA officially approved the term “Digital Twin” in 2010. Glaessgen and Stargel in 2012 defined the concept as a comprehensive simulation of a complicated product or system, including several physical factors, scales, and probabilities. This simulation utilizes the most accurate physical models, sensor data updates and historical performance information to accurately replicate the lifespan of its corresponding physical counterpart. [17, 18] described digital twin as a virtual representation of a physical asset that is almost identical to its physical counterpart, including the asset’s design, technical details, dimensions, materials, components and behavior or performance. However, clearer descriptions termed digital twin as a virtual representation or model that interacts with its physical counterpart in real-time, providing a synchronized and dynamic view of the physical system [19]. It serves as an intermediary between the physical and digital worlds, enabling instantaneous monitoring, analysis, and enhancement of the physical system [20]. In other research papers, for instance, [21] conducted a literature review to identify the application contexts, life cycle phases, functionalities, architectures, and components of existing digital twins. They highlighted the different application domains and technologies associated with digital twins, emphasizing their role in the Factory of the Future, cyber-physical systems, and Industry 4.0 technologies. Emphasis was also on the importance of data and models in the digital twin concept. The data layer of the digital twin includes different types of data, such as sensor data, historical data, and contextual data, which are processed and analyzed to generate insights and support decision-making. [2] described digital twins as virtual representations of physical assets, systems, or processes, stating that digital twins combine and portray the attributes of a physical thing or system virtually. Regardless of all definitions, there has clearly been a huge interest in the subject. Digital twin technology has become a key technology in mechanical engineering, offering a virtual depiction of a physical system.

Throughout the years, digital twin technology has significantly advanced in terms of capabilities and functionality. Initially, digital twins were static models that were primarily used for simulation and analysis during the design phase of a product [11]. However, with the advent of Internet of Things (IoT) and advanced data analytics, digital twins have become dynamic and real-time models that continuously capture and integrate data from sensors embedded in physical products. [22] developed a generic procedure for the conception and execution of a Digital Twin in an industrial case study. Product-based enterprises and customers may get several advantages from DTs, they may assist in optimizing design, minimizing costs and time to market, and expediting the organization’s reaction to changing client demands. Additionally, they may play a crucial role in facilitating new sources of income such as remote maintenance and support services,

as well as business models based on providing services. The DT is a significant application of digitalization, intelligence, and service. It overcomes limitations such as time, space, cost, and security on physical entities. It expands and improves the functions of physical entities, thereby increasing their value in practical applications. This phenomenon has received much scrutiny in both academic and industrial settings [23]. The concept of digital twin was first developed as a tool for the purposes of manufacturing and product lifecycle management (PLM), consequently, the first study subjects mostly concentrated on themes related to manufacturing. Nevertheless, the concept of DT has rapidly expanded its reach to several sectors such as manufacturing, information & communication technology (ICT), building and smart city, aerospace, automotive, energy, medical and healthcare, education, and others [20]. The field of research is broadening its scope to include several phases of the product lifecycle, with a specific focus on production planning and monitoring, resource management, machine or tools prognosis, predictive maintenance and product design and development [2]. In [24] it is stated that the digital twin concept involves the creation of virtual models that simulate the behavior and state of the physical entities. These models include not only geometric representations but also material properties, mechanical analysis, and health monitoring [25]. Authors of [26] described it as a real mapping of all components in the product life cycle using physical data, virtual data and interacting data between them. Extensively applied for fault diagnosis, predictive maintenance, and performance analysis, however, there has been limited exploration of their applicability in product design. Specifically, little attention has been given to understanding how the communication, synergy, and coevolution between a physical product and its digital twin can contribute to a more informed, expedited, and innovative design process [27]. The study conducted by [28] emphasized the significance of DT in expediting product development, discerning customers' requirements, enhancing performance, and facilitating remote commissioning and diagnostics. They emphasized the potential of digital twins in improving the efficiency and effectiveness of various stages of the product life cycle. With advancements in technologies such as artificial intelligence (AI), machine learning, and augmented reality (AR), digital twins are poised to become even more powerful tools for product design and development. AI algorithms can leverage the data captured by digital twins to identify patterns and optimize various aspects of product design, production, and performance. AR can provide designers and engineers with immersive experiences, allowing them to interact and collaborate with digital twins in a more intuitive and efficient manner. As shown in Fig. 2, the research presented at [3] examined the many digital twin applications throughout several stages of the lifecycle and identified three applications in design phase, seven applications in manufacturing phase and five applications in service phase.

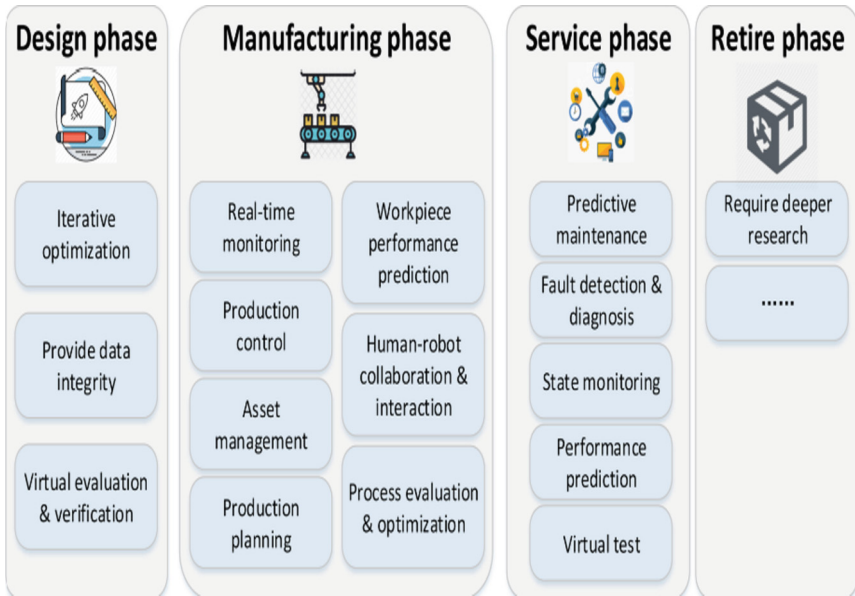


Fig. 2. Industrial implementation of digital twins throughout many stages of the product lifecycle. Adapted from [3]

2.3 Role of Digital Twins in Product Design and Development

The role of DT in manufacturing has been associated with various applications, mainly production, maintenance and quality management [29]. For production scheme, services are mainly related to dynamic scheduling and monitoring [30, 31], while the maintenance are closely related to fault prediction [32] and predictive maintenance [33]. Quality management services are related to monitoring process quality through the use of production process models [34, 35]. Clearly DT technology has evolved and found widespread applications across various industries, including product design and development. In the context of product design and development, digital twins have emerged as powerful tools that enable designers, engineers, and manufacturers to create virtual representations of physical products, providing insights and opportunities for innovation and optimization.

Product design is the primary phase of the lifecycle of a product that has an immediate impact on the following phases, such as production, distribution, usage, and the end of life [36, 37]. Consequently, the utilization of digital twins during the conceptualization phase yields advantages for both the process of design (such as aiding in design decision-making, enhancing design effectiveness, forecasting product characteristics, etc.) and future occurrences (such as manufacturing planning, product health monitoring, recycling management, etc.). As seen in Fig. 3, some works, such as [2] and [38] also noted that insufficient focus was given to the utilization of digital twin in the product design phase. If a product's digital twin model could be established from the design stage, it would allow for the integration of various design data, marketing, user experience data, and more into the product's digital model. This integration would ultimately lead to improved service during the production and post-product stages. However, due to

the high development cost of it, more research cases have been focused on the optimization of high-value products with the view to improving the productivity, performance, and cost, while digital-twin for low-cost products are not popular. In [39] it is presented a novel methodology for implementing DT in the apparel industry, highlighting its effectiveness in addressing a unique industry challenge.

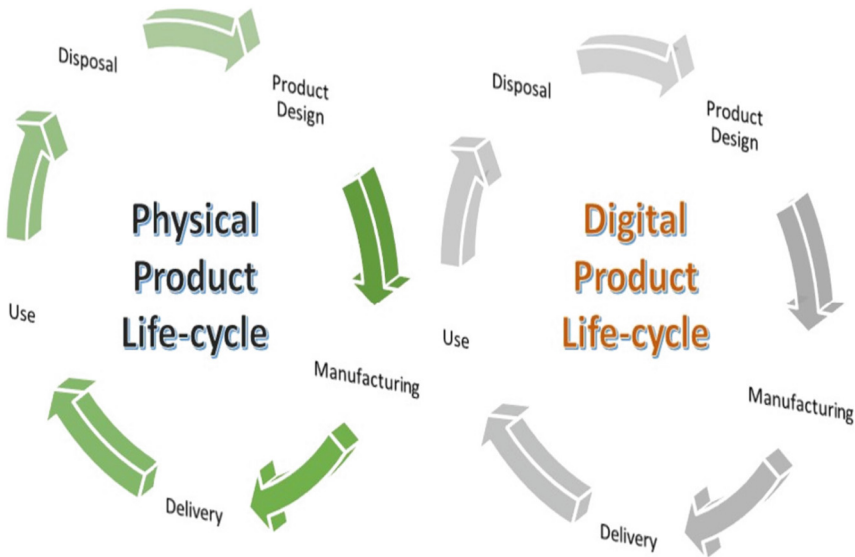


Fig. 3. Product Lifecycle DT model. Adapted from [2]

The role of digital twins in product design and development is multi-faceted and encompasses various key aspects. A brief overview of the significant roles digital twins plays throughout the process of designing and developing a product are hereby presented:

Conceptualization and Design: Digital twins enable designers to create virtual representations of products early in the design phase [40]. These virtual prototypes allow designers to visualize and explore different design iterations, test product functionalities, and evaluate performance characteristics. By interacting with the digital twins, designers gain crucial insights that facilitate informed decision-making throughout the conception and design phases.

Simulation and Evaluation: Digital twins provide a platform for simulation and analysis, enabling designers and engineers to evaluate the effectiveness and behavior of the product under different conditions [41]. By simulating various scenarios and conducting virtual tests, digital twins help identify potential design flaws, optimize performance, and mitigate risks before physical prototypes are produced. This capability significantly reduces development cycles and costs associated with physical testing [27].

Iterative Design Optimization: Through real-time monitoring and evaluation, digital twins enable iterative design optimization. They continuously capture and integrate data

from embedded sensors, providing valuable insights into product performance and usage patterns [42].

Collaboration and Communication: Digital twins provide a collaborative platform for cross-functional teams involved in the design and development process. In a virtual setting, designers, engineers, producers, and other stakeholders can communicate and share information, promoting effective teamwork [32]. This prevents misunderstandings and enhances overall project coordination by ensuring that everyone has access to the most recent product information.

Real-time Monitoring and Predictive Maintenance: Once a product is deployed, digital twins continue to play a pivotal role in continuously evaluating product performance and doing predictive maintenance. By analyzing real-time data from sensors, digital twins can detect anomalies, predict potential failures, and recommend preventive actions. This proactive approach to maintenance reduces downtime, improves product reliability, and enhances customer satisfaction.

Lifecycle Management: Digital twins also assist in product lifecycle management by providing a centralized repository of product data, documentation, and historical records. [26, 38] studied the role of DT in efficient tracking and management of product changes, updates, and versions, ensuring seamless integration and collaboration across various stages of the product lifecycle.

3 Research Gap Identification Results

Identifying research gaps in the application of digital twins for product design is critical for stimulating creativity, optimizing design processes, and improving product development outcomes. We acquire a better grasp of the issues and constraints associated with integrating digital twins in product design by identifying the gaps. This helps in efforts on developing new approaches, algorithms, and tools to overcome these obstacles and bridge the current gaps, hence, propelling digital twin-based product design forward and ensures its effectiveness in real-world applications. Furthermore, it enables continuous improvement and encourages collaborations among practitioners, researchers and industry professionals thereby accelerating advances in the use of DT for product design while also creating a thriving ecosystem of information sharing and innovation.

3.1 Gap 1: Integration of Diverse Data Sources

A notable study deficiency in the use of digital twins for new product design and development is the integration of various data sources. In today's digital era, organizations have access to vast amounts of data from various sources, including sensors, social media, customer feedback, and supply chain systems [43]. Integrating and harmonizing this diverse data within the digital twin model is crucial to ensure an accurate representation of the physical product and enable effective decision-making. One of the obstacles in the process of combining diverse data sources is the absence of standardized methods for exchanging data and the presence of compatibility problems. Each data source may

have different data formats, structures, and semantics, making it complex to seamlessly integrate the data into the digital twin model [3]. This can lead to incomplete or inconsistent representation, hindering the usefulness and reliability of the digital twin. Moreover, data sources may have varying levels of data quality and reliability. Ensuring the accuracy, consistency, and integrity of the data when integrating diverse sources is critical to prevent erroneous conclusions or misleading insights from the digital twin model. Dealing with the volume, variety and speed of incoming data is another difficulty [4]. The handling and processing of huge volumes of data in a timely manner is crucial in the context of new product design and development, where real-time or near-real-time insights are frequently required. Efficient data management techniques are needed to handle the data influx and ensure the digital twin remains up to date and provides real-time insights [44]. Researchers such as [45] relied on the HDF5 file format while [46] utilized the XML description for data management.

3.2 Gap 2: Model Accuracy and Validation

Generally, models should reflect the physical entity such as manufacturing processes or machine tool accurately however, DT model are hitherto simplified models of the actual physical entity hence the extent to which separate components and processes are captured may be restricted. This limitation in turn leads to a less accurate and comprehensive DT model. [4] reinstated the importance of carefully considering the scope of developing a DT and it is crucial to comprehend the constraints and uncertainties of it. This model accuracy and validation of DT models thus poses another research gap in the utilization of digital twins for new product design and development. The reliability of the digital twin heavily depends on the fidelity of the model and its ability to accurately represent the complex dynamics of the physical product [47]. One of the challenges in ensuring model accuracy is the complexity and heterogeneity of physical systems. Products in various industries can involve intricate interactions between multiple components, subsystems, and processes [48]. Capturing and modeling this complexity accurately within the digital twin is a complex task that requires advanced modeling techniques and domain expertise. Another challenge is the validation of digital twin models. Validating the precision and dependability of the digital twin in comparison to its physical counterpart is essential in establishing trust and confidence in the digital twin technology. However, the process of validating the digital twin might pose difficulties as a result of the absence of direct physical system access or constraints in accurately replicating real-world circumstances in the virtual environment [27].

3.3 Gap 3: Optimization and Decision Support

Another significant research gap in the utilization of digital twins for new product design and development is the optimization of design parameters and decision-making processes within the digital twin framework. While digital twins provide significant and informative perspectives on the performance and behavior of the product, [49] stated that there is a need to develop effective techniques and algorithms that can leverage insights to optimize design parameters and support decision-making. Optimization involves finding the

best set of design variables or parameters that maximize desired objectives, such as product performance, cost, or efficiency, while meeting constraints. Currently, there is limited research on the integration of optimization techniques and decision support tools within the digital twin framework for new product design and development [3]. Most existing research focuses on data acquisition, modeling, and analysis, rather than utilizing the insights gained from the digital twin to enhance the design and decision-making process. Some research studies have started examining the integration of optimization and decision support within the digital twin framework. For instance, a study by [50] proposed an optimization-based framework that integrates the digital twin with multi-objective optimization algorithms to optimize manufacturing processes. The study showcased the potential of utilizing digital twins for optimization and decision support in manufacturing systems. Furthermore, research by [51] explored the use of reinforcement learning algorithms to optimize design parameters in the digital twin framework for autonomous guided vehicles.

4 Discussion

Addressing research gaps is critical because it contributes to knowledge expansion, intellectual curiosity, practical applications, and laying a solid foundation for future research endeavors. It is in the hope of the researchers that providing these significant and relevant contributions will help drive advancement in the use of DT for designing and developing a product. Solutions to the identified research gaps are presented in this section of the work.

4.1 Integration of Diverse Data Sources: Architecture and Integration Techniques

The integration of diverse data sources is a significant research gap in the utilization of digital twins for designing and developing new products. In order to enable the efficient and smooth integration of data from diverse sources, it is required to build strong architecture and integration methodologies. The creation of adaptable data models and frameworks that can handle many data types, formats, and standards is one strategy for filling this research gap. For example, the use of ontology-based data models can provide a common semantic framework for integrating diverse data sources as described by [52]. Ontologies enable the representation and integration of diverse information by defining standardized concepts, relationships, and rules. Research by [53] emphasizes the importance of data integration in digital twins for complex systems, particularly in the context of Cyber-Physical Systems (CPS). Given that databases are often filled with unprocessed data obtained from the physical entity, it is crucial to encourage the use of database management software to facilitate the storing and retrieval of data components inside the physical database [4]. Figure 4 shows a proposed database system involving the ingestion of raw data into the physical data storage where it is stored using symbols to represent real-world assets, events and other information. Semantic data models (also referred to as ontology models) therefore relate these symbols and the real world.

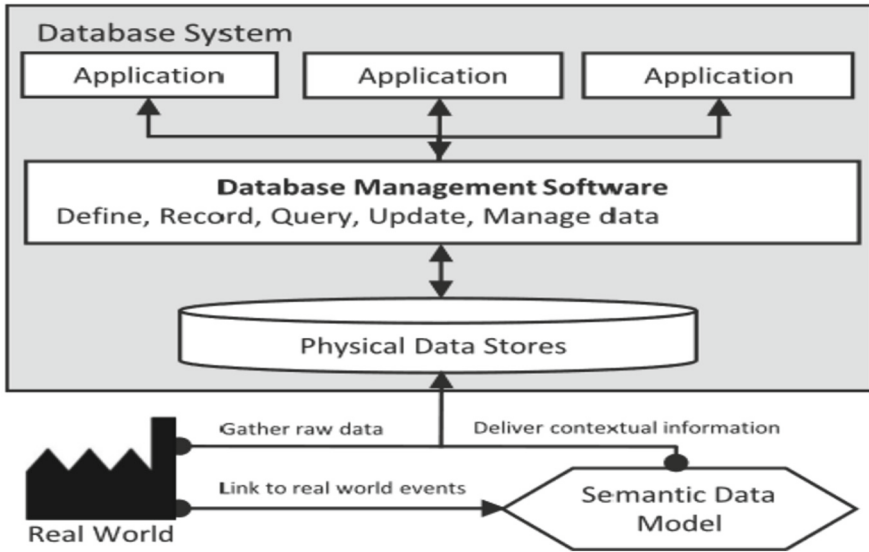


Fig. 4. The database system displays database management tools, application interfaces and database storage. Adapted from [4]

4.2 Model Accuracy and Validation: Data Fusion and Machine Learning Techniques

In the utilization of digital twins for new product design and development, ensuring model accuracy and validation is a crucial step. To address this, the application of data fusion and machine learning techniques holds great promise in enhancing the accuracy and validation of digital twin models [33, 54]. Machine learning techniques play a vital role in integrating information from diverse sources and improving the accuracy of the digital twin model. Machine learning algorithms can learn from historical data and patterns, enabling the prediction of product behavior and performance. Supervised learning techniques, such as regression and classification algorithms, can be utilized to train the digital twin model using labeled data, while unsupervised learning techniques, like clustering and anomaly detection, can uncover hidden patterns and identify deviations in the product's behavior [50]. By combining data from various sensors, databases, and simulation tools, the digital twin can provide a more comprehensive and accurate representation of the physical product. The study by [50] focused on the use of machine learning algorithms for damage detection in structures, the research incorporates integrated physics-based DT with machine learning and stochastic method to handle uncertainties.

These studies illustrate the potential of data fusion and machine learning techniques in improving model accuracy and validation within the digital twin framework. By integrating data from diverse sources and leveraging machine learning algorithms, researchers and practitioners can develop more accurate and reliable digital twin models for new product design and development.

4.3 Optimization and Decision Support: AI and Analytics Integration

Optimization of design parameters and decision-making processes within the digital twin framework is a significant research gap in the utilization of digital twins for new product design and development. The main goal of optimization is to improve overall performance and efficiency with the explicit intent of accomplishing predetermined targets. It strives to maximize efficiency, minimize waste, and align operations with the desired objectives by carefully analyzing processes and implementing improvements. Several focus areas were identified by [4] for DT optimization including virtual commissioning where potential issues and optimization of layouts and design workstations occur in the virtual representation of the manufacturing system, parameter optimization which would involve simulating numerous simulations and testing different parameters in order to determine the ideal process settings. The integration of artificial intelligence (AI) and analytics techniques holds immense potential for enhancing optimization and decision support capabilities within the digital twin ecosystem. [55] presented a digital twin refers to a virtual replica or representation of a physical object, system, or process. The study utilized a what-if simulation model and proposed a recommendation system model that incorporates reinforcement learning and trust models. The findings demonstrated that the recommendation system generated recommendations based on user feedback over time, resulting in a substantial decrease in decision-making time and an increase in trustworthiness. The authors in [56] introduced a machine learning-based recommendation system for agriculture. This system suggests fertilizers that may improve crop growth. The incorporation of AI techniques, such as machine learning, deep learning, and reinforcement learning, can enable data-driven optimization and decision-making in the digital twin. These techniques can analyze large volumes of data generated by the digital twin, identify patterns and correlations, and derive valuable insights to optimize design parameters or support decision-making processes. Machine learning algorithms can be employed to develop predictive models based on historical data from the digital twin [33]. Other statistical analysis techniques, such as regression analysis and sensitivity analysis, can provide insights into the relationships between design variables and performance metrics, aiding in decision-making and optimization processes. Research by [50] focuses on the integration of AI techniques such as heuristics and reinforcement learning and optimization in the context of digital twins for production planning. The paper suggests a way to systemically optimize and analyze industrial design using data and models, as opposed to traditional approaches that heavily depend on the engineer's expertise and address problems during operation.

5 Conclusion

In conclusion, digital twins have emerged as a transformative technology with immense potential in various domains, particularly in new product design and development. This paper examined the bibliographic research gaps concerning the use of digital twins specifically for new product design and development and also addressed some solutions and how the limitations might affect the development of digital twin technologies in the future. The research paper identified and addressed critical gaps in three key

areas: data integration, model accuracy and validation, optimization, and decision support. Advanced data integration methods are essential for incorporating diverse data sources and ensuring the accuracy and completeness of digital twin models. Future research should focus on leveraging advanced data fusion techniques, exploring real-time data integration, and addressing scalability challenges. Enhancing model accuracy and validation techniques is crucial for ensuring the reliability and validity of digital twin models. Efforts should be made to incorporate advanced machine learning algorithms, explore validation techniques using real-world data, and quantify uncertainties for robust model assessment. Developing efficient optimization and decision support tools is vital for leveraging the full potential of digital twins. Future directions include investigating advanced optimization algorithms, integrating artificial intelligence techniques, and developing real-time adaptive decision support tools. By addressing these research gaps, the potential for the use of digital twins in new product design and development can be unlocked and organizations can streamline innovation processes, improve decision-making, and achieve significant development in the design and development of products. The future of digital twins holds immense promise, and continued research and innovation in these areas will play a crucial role in realizing their transformative capabilities in diverse industries. By embracing these advancements, organizations can gain a competitive edge, foster innovation, and drive sustainable growth in the era of digital transformation.

Acknowledgements. This work has received support from the European Union under the Next Generation EU, through a grant of the Portuguese Republic's Recovery and Resilience Plan (PRR) Partnership Agreement, as part of the PRODUTECH R3 project – “Agenda Mobilizadora da Fileira das Tecnologias de Produção para a Reindustrialização”, aimed at the mobilization of the production technologies industry to promote the reindustrialization of the manufacturing sector (Project ref. nr. 60 - C645808870-00000067; Total project investment: 166.988.013,71 Euros; Total Grant: 97.111.730,27 Euros).

References

1. Ke, G., et al.: Intelligent machine plus production line digital twin model construction technology. In: *Journal of Physics: Conference Series*, vol. 2478, no. 10, p. 102011 (2023). <https://doi.org/10.1088/1742-6596/2478/10/102011>
2. Lo, C.K., Chen, C.H., Zhong, R.Y.: A review of digital twin in product design and development. *Adv. Eng. Inf.* **48**, 101297 (2021). <https://doi.org/10.1016/j.aei.2021.101297>
3. Liu, M., Fang, S., Dong, H., Xu, C.: Review of digital twin about concepts, technologies, and industrial applications. *J. Manuf. Syst.* **58**, 346–361 (2021). <https://doi.org/10.1016/j.jmsy.2020.06.017>
4. Böttjer, T., et al.: A review of unit level digital twin applications in the manufacturing industry. *CIRP J. Manuf. Sci. Technol.* **45**, 162–189 (2023). <https://doi.org/10.1016/j.cirpj.2023.06.011>
5. Schleich, B., Anwer, N., Mathieu, L., Wartzack, S.: Shaping the digital twin for design and production engineering. *CIRP Ann.* **66**(1), 141–144 (2017). <https://doi.org/10.1016/j.cirp.2017.04.040>
6. Grieves, M.W.: Product lifecycle management: the new paradigm for enterprises. *Int. J. Prod. Dev.* **2**(1–2), 71–84 (2005). <https://doi.org/10.1504/IJPD.2005.006669>

7. Grieves, M.: Product lifecycle management: driving the next generation of lean thinking | CiNii Research (2006). Accessed 17 July 2023. <https://cir.nii.ac.jp/crid/1130000796648190464>
8. Grieves, M.: Origins of the Digital Twin Concept (2016). <https://doi.org/10.13140/RG.2.2.26367.61609>
9. Hribernik, K.A., Rabe, L., Thoben, K.D., Schumacher, J.: The product avatar as a product-instance-centric information management concept. *Int. J. Prod. Lifecycle Manag.* **1**(4), 367–379 (2006). <https://doi.org/10.1504/IJPLM.2006.011055>
10. Garner, T., Powell, W., Carr, V.: Virtual carers for the elderly: a case study review of ethical responsibilities (2016). Accessed 10 July 2023. <https://doi.org/10.1177/2055207616681173>
11. Hribernik, K., Wuest, T., Thorben, K.-D.: Towards product avatars representing middle-of-life information for improving design, development and manufacturing processes (2013). Accessed 07 July 2023. https://doi.org/10.1007/978-3-642-41329-2_10
12. Rios, J., Hernandez, J.C., Oliva, M., Mas, F.: Product avatar as digital counterpart of a physical individual product: literature review and implications in an aircraft. In: *Transdisciplinary Lifecycle Analysis of Systems*, pp. 657–666. IOS Press (2015). <https://doi.org/10.3233/978-1-61499-544-9-657>
13. Wuest, T., Hribernik, K., Thoben, K.D.: Assessing servitisation potential of PLM data by applying the product avatar concept. *Prod. Plan. Control* **26**(14–15), 1198–1218 (2015). <https://doi.org/10.1080/09537287.2015.1033494>
14. Fuller, A., Fan, Z., Day, C., Barlow, C.: Digital twin: enabling technologies, challenges and open research. *IEEE Access* **8**, 108952–108971 (2020). <https://doi.org/10.1109/ACCESS.2020.2998358>
15. Schuh, G., Rebentisch, E., Riesener, M., Ipers, T., Tönnies, C., Jank, M.H.: Data quality program management for digital shadows of products. *Procedia CIRP* **86**, 43–48 (2019). <https://doi.org/10.1016/j.procir.2020.01.027>
16. Ploeger, D.: Digital Parts/Modular Doubles: fragmenting the ‘digital double’. *Body Space Technol.* **10**(1) (2011). <https://doi.org/10.16995/bst.92>
17. Glaessgen, E., Stargel, D.: The digital twin paradigm for future NASA and U.S. air force vehicles. In: *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, American Institute of Aeronautics and Astronautics (2012). <https://doi.org/10.2514/6.2012-1818>
18. Loaiza, J.H., Cloutier, R.J.: Analyzing the implementation of a digital twin manufacturing system: using a systems thinking approach. *Systems* **10**(2), 22 (2022). <https://doi.org/10.3390/systems10020022>
19. Luo, W., Tianliang, H., Wendan, Z., Fei, T.: Digital twin modeling method for CNC machine tool. *IEEE Conference Publication | IEEE Xplore* (2018). Accessed 06 July 2023. https://ieeexplore.ieee.org/abstract/document/8361285?casa_token=Laaxv5POraQAAAAA:6MWesh-wTmhY_5R482yC-4sFr5edcUFtJ_KCDe7-0hPIU9eQJAB_6RqufbFFaouzWYbilYiTA
20. Semeraro, C., Lezoche, M., Panetto, H., Dassisti, M.: Digital twin paradigm: a systematic literature review. *Comput. Ind.* **130**, 103469 (2021). <https://doi.org/10.1016/j.compind.2021.103469>
21. Söderberg, R., Wärmefjord, K., Carlson, J.S., Lindkvist, L.: Toward a Digital Twin for real-time geometry assurance in individualized production. *CIRP annals* **66**(1), 137–140 (2017). <https://doi.org/10.1016/j.cirp.2017.04.038>
22. Schweigert-Recksiek, S., Trauer, J., Engel, C., Spreitzer, K., Zimmermann, M.: Conception of a digital twin in mechanical engineering—a case study in technical product development. In: *Proceedings of the Design Society: DESIGN Conference*, vol. 1, pp. 383–392 (2020). <https://doi.org/10.1017/dsd.2020.23>





23. Yao, J.F., Yang, Y., Wang, X.C., Zhang, X.P.: Systematic review of digital twin technology and applications. *Visual Comput. Ind. Biomed. Art* **6**(1), 10 (2023). <https://doi.org/10.1186/s42492-023-00137-4>
24. Abramovici, M., Göbel, J.C., Savarino, P.: Reconfiguration of smart products during their use phase based on virtual product twins. *CIRP Annals* **66**(1), 165–168 (2017). <https://doi.org/10.1016/j.cirp.2017.04.042>
25. Alcácer, V., Cruz-Machado, V.: Scanning the industry 4.0: a literature review on technologies for manufacturing systems. *Eng. Sci. Technol. Int. J.* **22**(3), 899–919 (2019). <https://doi.org/10.1016/j.jestch.2019.01.006>
26. Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., Sui, F.: Digital twin-driven product design, manufacturing and service with big data. *Int. J. Adv. Manuf. Technol.* **94**, 3563–3576 (2018). <https://doi.org/10.1007/s00170-017-0233-1>
27. Tao, F., et al.: Digital twin-driven product design framework. *Int. J. Prod. Res.* **57**(12), 3935–3953 (2019). <https://doi.org/10.1080/00207543.2018.1443229>
28. Durão, L.F.C.S., Haag, S., Anderl, R., Schützer, K., Zancul, E.: Digital twin requirements in the context of Industry 4.0. In: Chiabert, P., Bouras, A., Noël, F., Ríos, J. (eds.) *PLM 2018. IAICT*, vol. 540, pp. 204–214. Springer, Cham (2018). https://doi.org/10.1007/978-3-030-01614-2_19
29. Neto, A. A., da Silva, E.R., Deschamps, F., do Nascimento Junior, L.A., de Lima, E.P.: Modeling production disorder: procedures for digital twins of flexibility-driven manufacturing systems. *Int. J. Prod. Econ.* **260**, 108846 (2023). <https://doi.org/10.1016/j.ijpe.2023.108846>
30. Longo, F., Nicoletti, L., Padovano, A.: Ubiquitous knowledge empowers the smart factory: the impacts of a service-oriented digital twin on enterprises' performance. *Ann. Rev. Control* **47**, 221–236 (2019). <https://doi.org/10.1016/j.arcontrol.2019.01.001>
31. Stark, R., Fresemann, C., Lindow, K.: Development and operation of Digital Twins for technical systems and services. *CIRP Ann.* **68**(1), 129–132 (2019). <https://doi.org/10.1016/j.cirp.2019.04.024>
32. Luo, W., Hu, T., Zhang, C., Wei, Y.: Digital twin for CNC machine tool: modeling and using strategy. *J. Ambient Intell. Humanized Comput.* **10**, 1129–1140 (2019). <https://doi.org/10.1007/s12652-018-0946-5>
33. Aivaliotis, P., Georgoulas, K., Arkouli, Z., Makris, S.: Methodology for enabling Digital Twin using advanced physics-based modelling in predictive maintenance. *Procedia Cirp* **81**, 417–422 (2019). <https://doi.org/10.1016/j.procir.2019.03.072>
34. Bao, J., Guo, D., Li, J., Zhang, J.: The modelling and operations for the digital twin in the context of manufacturing. *Enterp. Inf. Syst.* **13**(4), 534–556 (2019). <https://doi.org/10.1080/17517575.2018.1526324>
35. Ghosh, A.K., Ullah, A.S., Teti, R., Kubo, A.: Developing sensor signal-based digital twins for intelligent machine tools. *J. Ind. Inf. Integrat.* **24**, 100242 (2021). <https://doi.org/10.1016/j.jii.2021.100242>
36. Sudarsan, R., Fenves, S.J., Sriram, R.D., Wang, F.: A product information modeling framework for product lifecycle management. *Comput.-Aided Des.* **37**(13), 1399–1411 (2005). <https://doi.org/10.1016/j.cad.2005.02.010>
37. Ming, X.G., et al.: Collaborative process planning and manufacturing in product lifecycle management (2008). Accessed 10 July 2023. <https://www.sciencedirect.com/science/article/pii/S0166361507001005>
38. Alam, M.D., Kabir, G., Mirmohammadsadeghi, S.: A digital twin framework development for apparel manufacturing industry. *Decis. Anal. J.* **7**, 100252 (2023). <https://doi.org/10.1016/j.dajour.2023.100252>

39. Campi, F., Favi, C., Germani, M., Mandolini, M.: CAD-integrated design for manufacturing and assembly in mechanical design. *Int. J. Comput. Integr. Manuf.* **35**(3), 282–325 (2022). <https://doi.org/10.1080/0951192X.2021.1992659>
40. Zhang, S., et al.: Digital Twin of a Generic Jack-Up Platform (2023). <https://doi.org/10.4043/32221-MS>
41. Classens, K., Heemels, W.M., Oomen, T.: Digital twins in mechatronics: from model-based control to predictive maintenance. In: 2021 IEEE 1st International Conference on Digital Twins and Parallel Intelligence (DTPI), pp. 336–339 (2021). <https://doi.org/10.1109/DTPI52967.2021.9540144>
42. Monsone, C., Mercier-Laurent, E., János, J.: The overview of digital twins in Industry 4.0: managing the whole ecosystem. In Proceedings of the 11th International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management, pp. 271–276 (2019). SCITEPRESS - Science and Technology Publications, Vienna. doi: <https://doi.org/10.5220/0008348202710276>
43. Lim, K.Y.H., Zheng, P., Chen, C.H.: A state-of-the-art survey of Digital Twin: techniques, engineering product lifecycle management and business innovation perspectives. *J. Intell. Manuf.* **31**, 1313–1337 (2020). <https://doi.org/10.1007/s10845-019-01512-w>
44. Caesar, B., Hanel, A., Wenkler, E., Corinth, C., Ihlenfeldt, S., Fay, A.: Information model of a digital process twin for machining processes. In: 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA) pp. 1765–1772. IEEE, Vienna (2020). <https://doi.org/10.1109/ETFA46521.2020.9212085>
45. Liu, J., Du, X., Zhou, H., Liu, X., Ei Li, L., Feng, F.: A digital twin-based approach for dynamic clamping and positioning of the flexible tooling system. *Procedia CIRP* **80**, 746–749 (2019). <https://doi.org/10.1016/j.procir.2019.01.063>
46. Mabkhot, M.M., Al-Ahmari, A.M., Salah, B., Alkhalefah, H.: Requirements of the smart factory system: a survey and perspective. *Machines* **6**(2), 23 (2018). <https://doi.org/10.3390/machines6020023>
47. Bianconi, C., Bonci, A., Monteriù, A., Pirani, M., Prist, M., Taccari, L.: System thinking approach for digital twin analysis. In: 2020 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC), pp. 1–7 (2020). <https://doi.org/10.1109/ICE/ITMC49519.2020.9198392>
48. Howard, D.: The digital twin: virtual validation in electronics development and design. In: 2019 Pan Pacific Microelectronics Symposium (Pan Pacific), pp. 1–9 (2019). <https://doi.org/10.23919/PanPacific.2019.8696712>
49. Lee, D., et al.: Digital twin-based analysis and optimization for design and planning of production lines. *Machines* **10**(12), 1147 (2022). <https://doi.org/10.3390/machines10121147>
50. Pires, F., Ahmad, B., Moreira, A.P., Leitão, P.: Recommendation system using reinforcement learning for what-if simulation in digital twin. In: 2021 IEEE 19th International Conference on Industrial Informatics (INDIN), pp. 1–6 (2021). <https://doi.org/10.1109/INDIN45523.2021.9557372>
51. Bao, Q., Zhao, G., Yu, Y., Dai, S., Wang, W.: Ontology-based modeling of part digital twin oriented to assembly. *Proc. Inst. Mech. Engineers Part B: J. Eng. Manuf.* **236**(1–2), 16–28 (2022). <https://doi.org/10.1177/0954405420941160>
52. Somers, R.J., Douthwaite, J.A., Wagg, D.J., Walkinshaw, N., Hierons, R.M.: Digital-twin-based testing for cyber–physical systems: a systematic literature review. *Inf. Softw. Technol.* **156**, 107145 (2023). <https://doi.org/10.1016/j.infsof.2022.107145>
53. Qi, Q., et al.: Enabling technologies and tools for digital twin. *J. Manuf. Syst.* **58**, 3–21 (2021). <https://doi.org/10.1016/j.jmsy.2019.10.001>

54. Ritto, T.G., Rochinha, F.A.: Digital twin, physics-based model, and machine learning applied to damage detection in structures. *Mech. Syst. Signal Process.* **155**, 107614 (2021). <https://doi.org/10.1016/j.ymssp.2021.107614>
55. Archana, K., Saranya, K.G.: Crop yield prediction, forecasting and fertilizer recommendation using voting based ensemble classifier. *SSRG Int. J. Comput. Sci. Eng.* **7**(5), 1–4 (2020). <https://doi.org/10.14445/23488387/IJCSE-V7I5P101>
56. Kapteyn, M.G., Knezevic, D.J., Huynh, D.B.P., Tran, M., Willcox, K.E.: Data-driven physics-based digital twins via a library of component-based reduced-order models. *Int. J. Numer. Methods Eng.* **123**(13), 2986–3003 (2022). <https://doi.org/10.1002/nme.6423>



Innovation of the Manufacturing Company by Using of Digitization Tools

Lucia Knapčíková¹ (✉) , Annamária Behúnová² , Rebeka Tauberová¹ ,
Matúš Martiček¹, and Jozef Husár¹ 

¹ Technical University of Košice, Prešov, Slovak Republic
lucia.knappcikova@tuke.sk

² Technical University of Kosice, Kosice, Slovak Republic

Abstract. The quality of production, the performance of deliveries and the success of the business depend to a large extent on the people who work in production. It is why, despite the growing robotisation and digitisation in the manufacturing industry, human capital remains one of the strengths of today's organisations. In this context, education and the professional training of workers in the activities performed are crucial for any company to prosper and maintain its position in an increasingly competitive and changing environment. In some industries, such management of operator skills training is even more important due to the complexity of production processes and work changes caused by different volumes of activities or demand variability. If employees have to rely on low-quality work instructions, they are less efficient, make more mistakes and are less satisfied with their work. Therefore, it is in the interest of companies to avoid this quality deficiency. The manuscript is dedicated to digitalisation, specifically e-workstations in a manufacturing company, where it is important to minimise worker errors and time wasting.

Keywords: workflow · e-workstation · employee training

1 Introduction

In the literature, we can come across the claim that the low quality of data/information in companies can have a significant negative economic and social impact on the organisation [1]. But, poor quality data/information has more negative impacts, such as less customer satisfaction, increased operating costs, inefficient decision-making processes, lower performance and reduced job satisfaction [2]. The framework is structured within an industrial management perspective, which means focusing on instructions for design procedures, machine operation, component manufacturing, component assembly, supply handling, service inspections after sales, technology use, etc. frameworks need not be limited to this context [2]. Poor quality data/information is common, and even small data inaccuracies can have a big impact. However, this literature focuses almost exclusively on the types of “factual information” that can be compared to “instructional information”. Studies show that the quality of on-the-job training is a significant problem

in many industrial contexts [1, 3]. It includes studies of work instructions about aircraft maintenance, process control plant maintenance, chemical plant operation, process re-engineering at a tele-operator and truck manufacturer, railway operation and maintenance, transport safety, assembly line operation in cars and the process of designing hearing aids [3, 4]. In the worst case, poor work instructions can lead to fatal injuries. This claim was proven by a study investigating industrial maintenance accidents in the Finnish industry. In studies, up to 63% of accidents were fatal, and 38% of non-fatal accidents involved faulty work instructions [2]. One such problem that affected the quality of the instructions was the process of approving (verifying) the instructions. We all know that the document verification process is extremely long and problematic [4]. We often encounter problems such as [5]:

- absence of a supervisor at the workplace,
- pages from documents are often lost or returned from too-dirty production,
- if it is necessary to correct something in a document, many documents must be printed again and again, while the approval of superiors is essential, which includes their signing,
- the document verification process is carried out at an often inconvenient time for the superior.

The term digitization includes several actions - from removing papers to changing the functioning of the entire company and employees. The result is faster processes, saved costs for running the company, and attractiveness for customers [4].

Therefore, with the help of Work Station (WS), it was possible to contain all these problems. The process of documentation and validation has become much clearer and simpler.

1.1 Problem Definition

A master list is a set of work instructions at a station. When a work order changes, the index of the master list is incremented, requiring the relevant operators to consider the changes [2]. The goal is to be notified early during development and always to be trained on the latest version of the documents. Consultation of this master list is available at the operator's station in PDF format.

The approval process and documentation responsibilities are shown in Fig. 1. How it worked so far [2]:

- The document author (document owner) prepares a new document or a new version of an old document according to a valid template and forwards it to the quality system engineer to assign a number or a new version in the PDM system.
- The system quality engineer assigns the document number or creates a new version, checks the template, writes the number, records it in the document matrix and sends it back to the document's author.
- The document's author, by e-mail or in print, presents the new document or changes in the old document to the control (quality department).
- Suppose the document template (last page in the footer) requires a review of the document's content by a quality technician, team leader or operator (4 skill level). In that case, a performance test is performed, and then the document continues for approval ($N + 1$).
- Suppose the document passes the approval process without comments. In that case, the document's author submits the final signed version to the system quality engineer for release, who, after releasing the document in the PDM system, will inform the author of the document's validity.

If comments appear, the document's author incorporates them into the document and resends it for checking, testing, and approval (in this case, it is no longer sent to the records - the document already has an assigned number or a new version!) The document's author trains the users of the document (those to which the document relates) and makes a record of the training. (e.g. the process engineer instructs the team leader, and the team leader trains the operators - all are recorded in the training record for the new document or version) [5].

The training record remains at the workplace or is kept by the supervisor/team leader at a predetermined location). When a new document is created, the supervisor will receive an email notification. Each superior person validates the document using an electronic signature in their free time, and it is moved to other superiors [6]. As soon as all relevant persons verify the document is updated on the eWS panel, and the operator is automatically forced to confirm it when he starts working with the eWS [4].

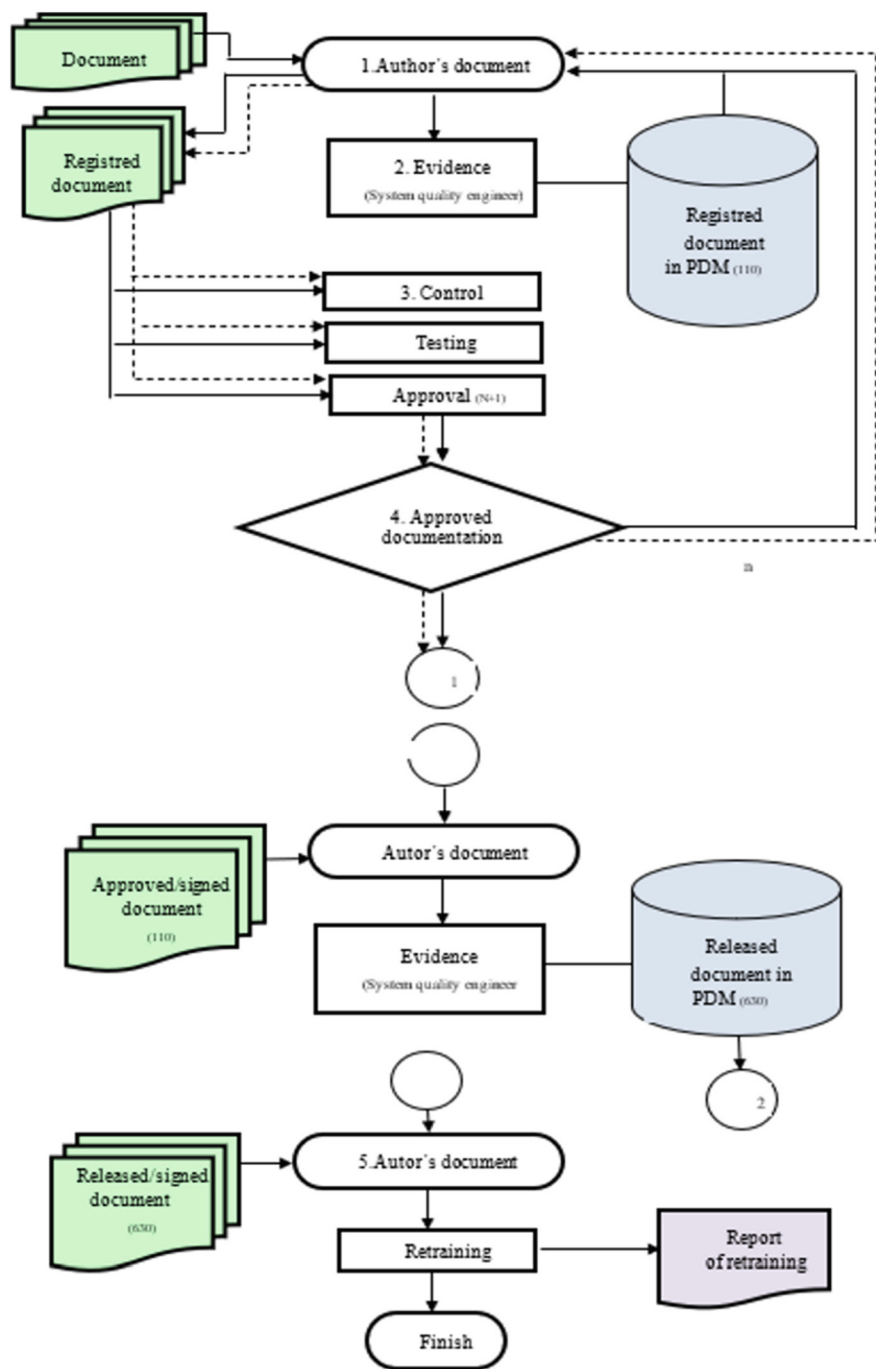


Fig. 1. Description of approval process in the manufacturing company [Authors own processing, 2]

2 Work Methodology

With the e-workstation (eWS) tool, managers now have an opportunity to improve the the qualifications of employees for that station and to react quickly if someone lacks training (Fig. 2). The registration of each worker (team leader, supervisor) is linked in the database with individual levels of polyvalence or levels of the magic square [5]. Here, we can also often encounter the term polyvalency, which represents the ability of an employee (operator) to perform work in several positions in production while ensuring quality and productivity (efficiency) requirements according to work instructions [3, 6]. Within the framework of polyvalence, it is possible to ensure the substitutability of employees (operators) in different job positions within one line or several lines. Polyvalence levels are set for each workstation and linked to the corresponding master list index [7].



Fig. 2. Digital competitiveness in the manufacturing company using e-workstation [Authors own processing]

Goals and benefits of the work methodology [2, 8]:

Companies that choose to implement this model of acquisition and measurement of operator skill levels in their manufacturing plants pursue various goals, for example:

- Monitor the development of the organisation's employees and quantify the effectiveness of training actions.
- Guarantee operational continuity of the factory and the ability to respond to market demands, ensuring a person is always available to carry out the most critical and complex processes.
- Ability to rotate personnel in the most demanding, difficult or repetitive jobs.
- Achieve maximum productivity by investing the necessary resources to bring most operators to level 3 or 4 training.
- Constantly improve and raise the level of quality because a trained operator produces faster and with fewer errors and incidents.

The implementation of the magic square system also brings several benefits that have a very positive impact on [6]:

- Production quality;
- Minimisation of waste;
- Reduction of breaks due to absences, turnover or lack of knowledge and experience;
- Prevention of accidents at the workplace;
- Level of customer satisfaction;
- Motivation of operators.

Despite these facts, Slovakia still needs to catch up with the digitization of companies. In the European Center for Digital Competitiveness ranking, Slovakia achieved a negative score of -102 , putting us in third place from the bottom. On the contrary, Bulgaria is in first place in the ranking with a score of $+130$, thanks to the "Digital Bulgaria 2025" initiative [8].

3 Results and Discussion

The eWS project comprises of eWS applications and AODocs (Smart Docs). AoDocs is a new document management tool [8]. The service is based on the Google Apps engine and a cloud-based document management solution that relies on Google Drive technology to store documents. Priority was to reduce paper consumption and to increase intercommunication processes. Using a magic square allows each operator to identify their certification level at the workstation. The magic square has four steps [9]:

Step 1: The operator understands all relevant instructions in the workstation master list and confirms that he meets all workstation safety requirements.

Step 2: The operator ensures compliance with all work standards.

Step 3: The operator produces in the standard time specified in the workflows.

Step 4: Operator Trains another operator to all work standards of that workstation to reach level 2.

There is a customised questionnaire for each step. The degree of polyvalence means the achieved level of qualification of an employee (operator) in a specific job position. We distinguish 4 degrees of polyvalency [2, 10]:

1. Employee (operator) knows and understands all work standards (first level);
2. Employee (operator) applies work standards in practice with quality assurance (second degree);
3. Employee (operator) can perform work independently at a standard work pace (third level);
4. Employee (operator) can train another worker (fourth level).

At each training, there must be a person who ensures familiarisation of the employee (operator) with the instructions (work, control, maintenance instruction, general, etc.), with all work standards related to the given work position and who must show the employee the procedure for connecting to the station [11]. The trainer can be an employee (operator) or a team leader with a polyvalence level of 3 or 4 in the position where the employee (operator) is being trained. The trainer can also be a process engineer, quality engineer or maintenance worker in the case of a revision of one of the basic instructions (work, control, maintenance instruction, general, etc.). In such a case, the review's author will provide training for the workers of all shifts. At the same time, the supervisors/team leaders for the given lines must also participate in the training to ensure adequate transfer of information to other shifts as well [12].

The team leader and supervisor will prepare the training plan for the following month. It means they agree on which work position and the given employee (operator) will be trained on which line. Subsequently, the supervisor will ensure the update of the qualification improvement plan [12, 13]. No, later than the end of the first week of the new month. The current qualification improvement plan must be available on each line. Using eWS, the trainer enters the training into the system, indicates the date and time, and selects the skill he wants to train the employee. The notification appears to the operator automatically on the eWS station (Fig. 3).

The screenshot displays a 'Training Session' form with the following details:

- Skill: Polyvalence
- Master List: Podklady na pracovisku
- Code: PTS/PSD/PRE1/OE/Audi B8/AUDI B8/Audi B8 Station 1/M/1
- Version: 6*
- To Level: 3
- Trainer: Serhii Mlynyskyi
- Scheduled On: 1/25/2023 12:00:00 AM
- Location: Prešov

A purple circular logo with the text 'STFE' is located in the bottom left corner of the interface.

Fig. 3. Planning of training using e-workstation [2]

The qualification improvement plan shows the current level of polyvalence in specific job positions and the qualification improvement plan for the following month [13]. If a new employee (operator) starts working on the line during the month, the supervisor must enter training on the current version of the documents on the day of the start and outline the plan for the current month [14]. The polyvalency (magic square) of the operator in the workstation system can change depending on the stage of training the employee (operator) is in. If there is no level 3 or 4 employee (operator) in the team, the supervisor is responsible for the training in cooperation with the process engineer and the quality engineer. In the case of the project line, the project team is accountable for increasing polyvalence [5, 9]. The following rules apply to the qualification improvement plan: when joining the line, the employee (operator) must have at least the 2nd degree of polyvalency, at most two positions [2, 15]. Work positions must not follow one another. After awarding the 2nd degree of polyvalence, it is possible to develop polyvalence to a higher level, or it is necessary to continue the development of polyvalence in other positions lines. The rules for polyvalency are always linked to a specific job (job position) and must be applied in the following cases [2, 17]:

- an employee (operator) working in a new post/job position,
- the employee (operator) has not worked at the given post for 1 to 3 months (in case of recertification and long-term absence, the system will not allow the operator to work at the workplace and will not have access to the station.

In that case, it is necessary to repeat the training on the current master list and the first and second levels of polyvalence in the trainer's presence.

3.1 The 1st Degree of Polyvalence

The first degree of polyvalence means that the employee (operator) knows and understands all work standards [6, 11]. The system is automatically set so that for the first level of polyvalence and training on the current version of documents at the workplace, the operator (employee) must read and check all documents listed at the workplace [13]. Training will not be complete until all instructions have been reviewed (Fig. 4).

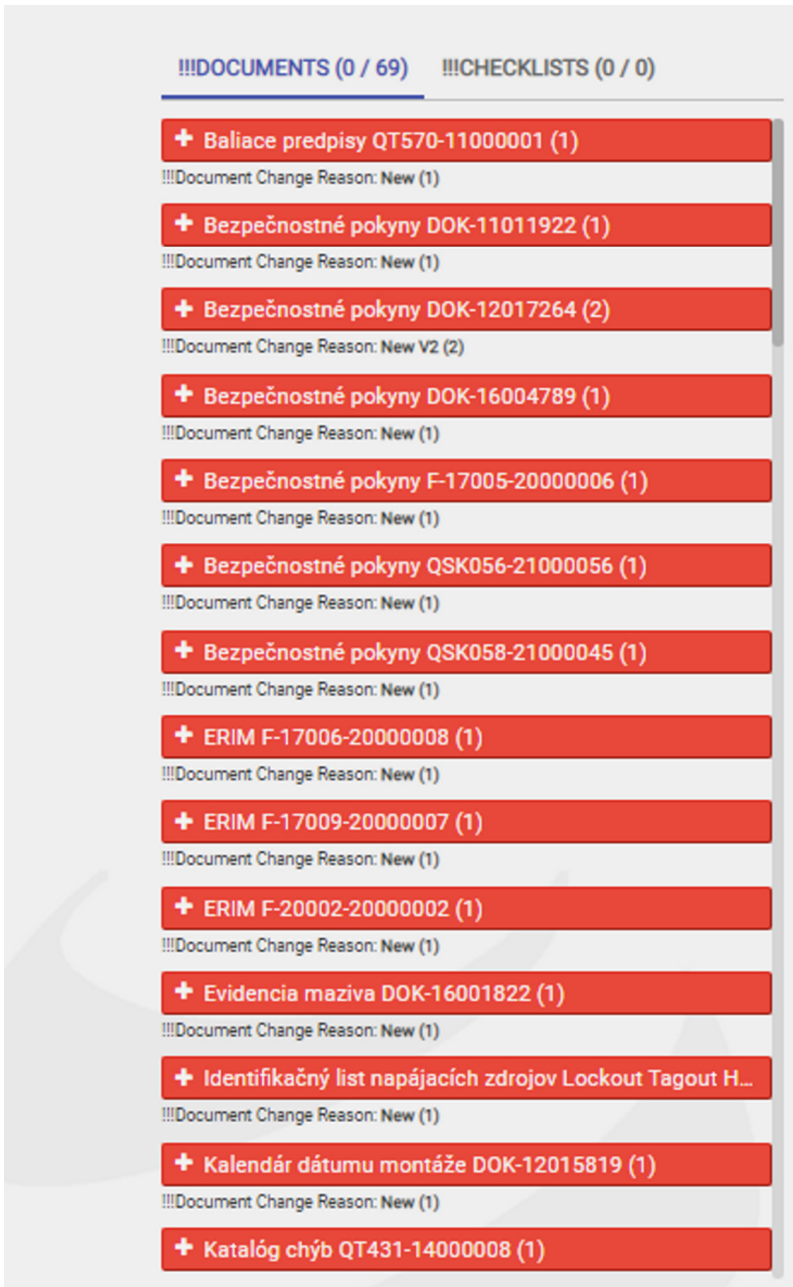


Fig.4. Training on 1st degree of polyvalence [2]

*Legend to the Fig. 4 (From the Slovak language – to the English language):
Baliace pokyny- Packing instructions*

Evidencia maziva- Lubricants monitoring

Bezpečnostné predpisy- Safety regulations

Identifikačný list napájacích zdrojov- Identification sheet of power sources

Kalendár dátumu montáže- Assembly date calendar

Kalendár chýb-Failure calendar

The trainer will provide the employee (operator) with information on the following points: - on the day of starting the work [2, 17]:

- Immediate training regarding instructions: work, control and others, which are related to the given post before carrying out any activity on this post (in specific cases also for valid temporary instructions).
- Immediate recording of training on instructions: working, control and others at the workplace (in specific cases also for valid temporary instructions).

Familiarisation with the workplace (workspace, workload, tasks of line members). Acquaintance with the task at the workstation about the final product, including all components with an emphasis on product quality [14] (OK pieces are input for the next post), basic information about the product (product presentation according to APU), special characteristics of the post - if applicable (S /R, CC, etc.) familiarisation with error messages and malfunctions occurring at a given station immediate reaction in case of a problem (according to the escalation process of the line - production stop rule) reference change process records from the production or control (traceability record, etc.) 5S and product respect, explanation of line indicators (QCDM board) [18, 19]. Until the polyvalence employee reaches level 2 in the given position, he must be visibly marked with a blue vest “IN PRACTICE,” and 100% control of this production must be ensured or inspected according to the quality guidelines of the respective APU. The employee must complete this level on the first day of the job.

3.2 The 2nd Degree of Polyvalence

The second degree of polyvalence means that the employee (operator) applies work standards in practice along with quality assurance. The employee (operator) must know/be able to [2, 12]:

- Perform self-check (can identify errors)
- React adequately in case of problems (apply the escalation process of the line correctly – Rules for stopping the line)
- Carry out the correct inspection or measurement in the production process (by the inspection/sorting plan and also the inspection specified in the production order)
- Maintain your workplace by the 5S methodology
- Must successfully pass sample testing or a knowledge verification test

Validation: Trainer + quality manager (Quality Technician or Quality Engineer).

Validation has two parts:

A – Oral verification of the application of the knowledge acquired at level 1 (assessed by the trainer).

During the oral verification of the operator, the trainer must fill out a checklist for the second level of polyvalence in the system so that the operator is authorised to work at the workplace and the workstation.

B – Verification of the identification of defects on the products (assessed by the quality inspector) – at least one of the forms according to the production operation:

- Knowledge verification test
- Testing knowledge verification with samples [2, 9].

The employee must complete the second level between the 2nd and 10th day after taking up the post.

3.3 The 3rd Degree of Polyvalent

The third degree of polyvalence means that the employee (operator) can perform work independently at a standard pace. The employee (operator) must be able to [2, 19]:

- Keep the pace of the post/line/machine
VALIDATION: Trainer + supervisor or VPS Engineer/technician + quality manager (in the case of a critical post)

The skills and abilities of the employee (operator) in the given position depend on the type and complexity of the work. It is validated whether the employee (operator) achieved or did not achieve the output at the post (i.e. the shift output determined based on the cycle time of the given post) [13].

The daily production report is used to verify the results of the line output. The employee (operator) is identified (the name of the trained operator is indicated in the daily production report during the shift performance) on four shifts in a row for the entire shift, i.e. he completes four measurements to achieve the pace. At the same time, if 1 test result is NOK, the testing begins all over again, i.e. four new measurements, but in a week at the earliest [16, 18].

The third-level validation can occur when the employee (operator) reaches the required pace. The record is made in the workstation system, and the trainer must fill out a checklist for the third level of polyvalency [19]. The employee (operator) should reach this level from the 11th to the 30th day after starting the work [20].

3.4 The 4th Degree of Polyvalent

The fourth degree of polyvalence means an employee (operator) can train another worker. General requirements for an employee (operator) [2, 21]:

- must know the process of polyvalency following this instruction and respect the stages of the given document,
- must work for at least two months at the given post,
- must train at least one employee (operator) per job from level 1 to level 3.

Validation: Trainer + supervisor

At least a trainer must be present during the training to assess the skills of the employee (operator) for level 4 [14]. The record is made in the workstation system, and

the trainer fills out the checklist for the fourth level of operator polyvalence. For the operator to reach the fourth level of polyvalence in this eWS system, the training of an employee (operator) must be entered for one job from level 1 to level 3, and the given operator must pass correctly [21].

4 Conclusions

Digitization is a key tool that allows businesses to adapt to rapid market changes and use modern technologies. Regardless of the size and industry of your business, digitization offers the opportunity to increase efficiency, reduce costs, improve service and maintain a competitive advantage.

Considering the facts of the conducted research, it is known:

1. The employee (operator) did not work at the job for more than one month and less than three months:
 - in that case, it is necessary to do a partial validation, which consists of verifying the recognition of errors on the products - testing with samples or a knowledge verification test and verification of the worker's pace.
2. Entries from this verification are made directly into the plan for increasing the polyvalence of the given department - it is necessary to complete other tests in order and add a note about additional validation in the "Remarks" column.
3. The employee (operator) has not worked at the job for more than three months: in this case, it is necessary to do the entire training and the entire validation from the beginning = make a new entry in the plan for increasing polyvalence.
4. Return of the employee (operator) to the workplace after incapacity for work: the team leader is obliged to check the validity of the employee's training at individual positions after the return of the employee (operator) after the illness.

Suppose documents and instructions were updated during the employee's absence. In that case, the team leader will provide the necessary training in the eWS system immediately - on the 1st day after the employee's return from the sickness.

Intelligent and digitally connected network systems enable direct communication between people, machines, equipment, logistics and products. By improving the digital skills of workers in their personal and working lives, we save them time, but we also prepare them for better future digital functioning in the company.

Acknowledgements. This manuscript is supported by the project VEGA 1/0268/22 and KEGA 038TUKE-4/2022-granted by the Ministry of Education, Science, Research and Sport of the Slovak Republic.



References

1. Mandičák, T., Mesároš, P., Tkáč, M.: Impact of management decisions based on managerial competencies and skills developed through BIM technology on performance of construction enterprises. *Pollack Periodica* **13**(3), 131–140 (2018)

2. Mlynynskiy, S.: Use of Digitalization in the real manufacturing conditions. *TUKE* **67** (2023)
3. Periša, M., Kuljanić, T.M., Cvitić, I., Kolarovszki, P.: Conceptual model for informing user with innovative smart wearable device in industry 4.0. *Wirel. Netw.* **27**, 1615–1626 (2019). <https://doi.org/10.1007/s11276-019-02057-9>
4. Kaufmann, S.A.: *The Origins of Order: Self-Organization and Selection in Evolution*. Oxford University Press, New York (1993)
5. Fiebig, S., Sellschopp, J., Manz, H., Vietor, T., Axmann, K., Schumacher, A.: Future challenges for topology optimisation for the usage in automotive lightweight design technologies. In: *Proceedings of the 11th World Congress on Structural and Multidisciplinary Optimisation*, Sydney, Australia, 7–12 June 2015, vol. 142, pp. 1–8 (2015)
6. Rosová, A., et al.: Case study: the simulation modeling to improve the efficiency and performance of production process. *Wirel. Netw. J. Mob. Commun. Comput. Inf.* **28**, 863–872 (2020)
7. Liu, J., et al.: Current and future trends in topology optimisation for additive manufacturing. *Struct. Multidiscip. Optim.* **57**, 2457–2483 (2018)
8. Kanáliková, A., Behúnová, A., Mandičák, T., Mesároš, P.: New technologies for sustainable development in infrastructure, logistics and construction industry. In: *Acta Logistica* **6**(4), 171–177 (2019)
9. Al-Salamah, M.: Economic production quantity in batch manufacturing with imperfect quality, imperfect inspection and non-destructive acceptance sampling in a two-tier market. *Comput. Ind. Eng.* 275–285 (2016)
10. Irwan, I., et al.: Problem-based Collaborative Learning Strategy in Computer Programming. *SAR J.* **5**(1), 40–45 (2022). ISSN 2619–9955. <https://doi.org/10.18421/SAR51-05>
11. Turisová, R., Pačaiova, H., et al.: Evaluation of eMaintenance application based on the new version of the EFQM model. *Sustainability* **13**(7) (2021). <https://doi.org/10.3390/su13073682>
12. Tymofiiiv, V., Al-Rabeei, S., et al.: Hydrogen production for improved transportation system as a part of smart cities. In: *Future Access Enablers for Ubiquitous and Intelligent Infrastructures*. 6th EAI International Conference. Springer, Heidelberg (2022). https://doi.org/10.1007/978-3-031-15101-9_16
13. Lin, C.C., Wang, T.H.: Build-to-order supply chain network design under supply and demand uncertainties. *Transport. Res. Part B* **45**, 1162–1176 (2011)
14. Smeringaiova, A., Wittner, M.: Parametric modeling as efficient way of designing. *MM Sci. J.* 2701–2705 (2018)
15. Olakanmi, O.O., Dada, A.: An efficient privacy-preserving approach for secure verifiable outsourced computing on untrusted platforms. *Int. J. Cloud Appl. Comput. (IJCAC)* **9**(2), 79–98 (2019)
16. Greci, R.T., Watts, C.A.: Maximising customer value via mass customised e-customer services. In: *Business Horizons*, pp. 123–132 (2007)
17. Guenov, M.D.: Complexity and cost effectiveness measures for systems design. In: *Manufacturing Complexity Network Conference 2002 – proceedings*, Cambridge, pp. 455–466 (2022)
18. Kaplan, A.M., Haenlein, M.: Toward a parsimonious definition of traditional and electronic mass customisation. *J. Product Innov. Manag.* **23**, 168–182 (2006)
19. Herrmann, F.: The smart factory and its risks. *Systems.* **6**, 38 (2018). <https://doi.org/10.3390/systems6040038>
20. Islam, M.A., Vrbsky, S.V.: Transaction management with tree-based consistency in cloud databases. *Int. J. Cloud Comput.* **6**(1), 58–78 (2017)
21. Pollák, M., Kočíško, M.: Development of a knowledge system for data management of the pre-production stages. *TEM J.* **11**(4), 1774–1779 (2022)



Recent Trends in Artificial Intelligence and Machine Learning Methods Applied to Water Jet Machining

Rehan Khan¹ , Michał Wieczorowski² , Ariba Qureshi¹, Muhammad Ammar¹, Tauseef Ahmed³, and Umair Khan³

¹ National University of Sciences and Technology, Islamabad, Pakistan
mrehan.khan@ceme.nust.edu.pk

² Poznan University of Technology, Poznan, Poland

³ Universiti Teknologi PETRONAS, Seri Iskandar, Darul Ridzuan Perak, Malaysia

Abstract. Abrasive Water Jet Machining is a revolutionary unconventional cutting technology that has a wide range of applications in the machining of difficult-to-machine materials. Process parameters are critical in determining the efficiency and economics of a high-quality machining process. As a consequence of advancements in sensor technology, machining operations may now be automated, and the massive amounts of data generated can be used to model and monitor the processes using Artificial Intelligence (AI) and Machine Learning (ML) approaches. This paper presents an overview of the current research trends linking the application of AI and ML methods to AWJM processes for enhanced performance metrics, process monitoring and control, and improved variable optimization. Overcoming challenges related to data quality, model interpretability, and system integration will be essential for the successful implementation of AI and ML in the field of water jet machining. The potential future directions in the ever-expanding field of AI and machining processes, particularly AWJM, are also discussed.

Keywords: Abrasive Waterjet · modelling · artificial neural network · process parameters

1 Introduction

The manufacturing industry has witnessed several paradigm shifts over the last century in an effort to become more time-conscious, catering to the need for rapid prototyping and the versatility of advanced material usage. These ever-evolving trends have placed a premium on numerous advanced machining processes, persistently competing for enhanced efficiency and economic sustainability [1]. The use of advanced materials, such as ceramics, composites, and thermo-sensitive materials, at an industrial scale can only be made possible if their machining is carried out economically. In the context of industry, 4.0 for smart manufacturing, Abrasive water jet (AWJM) cutting has forged a positive reputation as an increasingly effective non-traditional manufacturing process, owing to its speed, low machining force, and adaptability while processing a wide array

of materials with ranging properties [2]. The technique employs a fine nozzle which produces a supersonic and coherent waterjet, followed by the introduction of abrasives into the stream; the most common abrasive material used in AWJM is silica sand due to its hardness properties [3–8]. The water along with the entrained abrasive particles leave the nozzle at a pressure in the range of 400–600 MPa and a velocity up to 1000 m/s. The material surface is degraded and finally eroded through four sub-mechanisms which all act simultaneously, in combination: cutting, fatigue, melting, and brittle fracture. The distinct advantages of AWJM become particularly evident during the fabrication of engineering materials with extensive applications that are difficult to machine due to complex geometry or composition. The efficiency of AWJM cutting is determined by operating parameters as well as material qualities [9]. Moreover, numerous process elements, such as water pressure, abrasives, target work material, and cutting parameters, influence AWJM cutting a schematic layout of an abrasive water injection jet as shown in Fig. 1. Prediction of the ideal parameters for a depth of cut and roughness in any material while using AWJM cutting is a complex engineering challenge that requires thorough monitoring and modeling [10]. Therefore, a remarkable enhancement in the overall performance of AWJM can be achieved if the industry implements intelligent machining techniques in order to enable self-optimization and decision-making in unanticipated circumstances. Leveraging Artificial Intelligence (AI) and Machine Learning (ML) has enhanced productivity and improved the quality of the products by employing advanced data analytics at various stages in the production line. This paper explores the recent trends in applying AI and ML methods to enhance the efficiency, precision, and quality of water jet machining processes. Our main objectives in this research project were to clarify the ways in which Abrasive Water Jet Machining (AWJM) processes and Artificial Intelligence (AI) and Machine Learning (ML) techniques complement each other, while also utilizing these technologies to accomplish enhanced efficiency and to improve AWJM performance metrics by exploring aspects related to accuracy, reliability, and efficiency. Furthermore, we aimed to investigate the viability of integrating AI/ML for real-time monitoring and control, which would enable adaptive decision-making based on continually updated inputs. The methodology employs a twofold approach: computational modeling with machine learning algorithms and experimental studies for data collection in AWJM processes under various conditions.

1.1 AI and ML in Manufacturing

Artificial intelligence (AI) is a field that concerns itself with the development of software agents and physical systems able to execute functions that generally require human intelligence [12]. The corresponding ‘intelligence’ is data-driven and finds traces of its origin in the assumption that all logic-based learning and decision-making share a set of common traits that can be simulated by a machine. Historically, the initiation of the notion of AI dates back to the 1940s alongside the origin of Artificial Neural Networks, a subfield of AI modeled after the workings of neurons inside the human brain, via the introduction of the MP model and Hebb rule. This infancy period was followed by various upsurges through the development of new models, each aimed at enhancing product quality and reducing required human interception for model construction and monitoring.

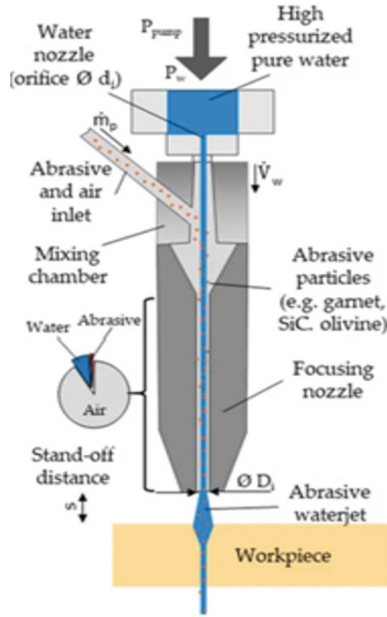


Fig. 1. Schematic of a typical AWJM machine [11]

AI systems typically aim to generate agents that recognize an objective function, that is the required outcome, and in turn, work to maximize the rational approach that would provide the optimum solution for any problem at hand [13]. This phenomenon of choosing the best option out of several other possibilities is referred to as optimization. For instance, optimization of a self-cleaning robot can be achieved by assigning the objective function as quality surface finish minus the cleaning cost so that the robot can devise an economic approach to keeping the surface clean.

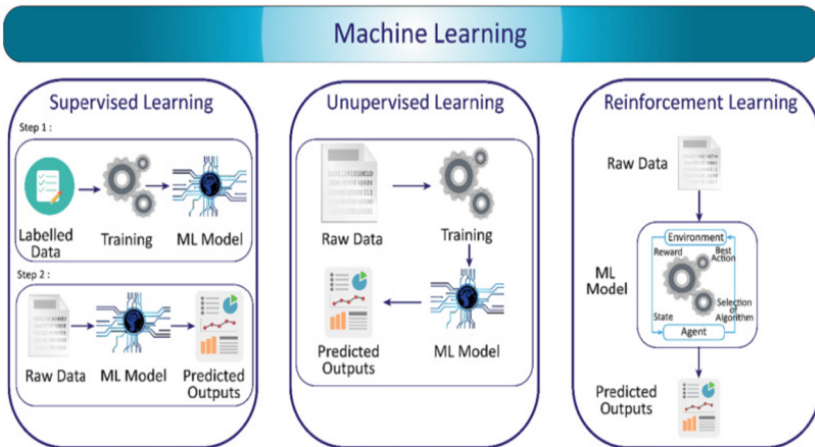


Fig. 2. Categorization of machine learning [14].

Similar to ‘intelligence’, learning encompasses a wide range of processes and propositions and is inconvenient to define precisely. In a broader context, Machine Learning is a branch of AI that generates algorithms in response to external stimuli, such as data or examples, to constantly alter the system’s structure in order to improve future outcomes. For example, the performance of image classification algorithms learns and improves through training consisting of feeding in new images. It is important, however, to maintain a distinction between learning and memorization. The goal of machine learning is to learn a function that maps well onto the given data but also remains reliable through reasonably generalizing in case of unseen examples or data, in turn minimizing the approximation error. This function of data-informed classification and predictions for future outcomes can be achieved under three major settings: supervised, unsupervised, and reinforcement learning as shown in Fig. 2. The evolution of AI and ML coupled with the availability of larger datasets and enhanced computational capacities further led to the development of a significant subfield, known as Deep Learning (DL). Deep learning is a branch of machine learning that evolved from artificial neural networks and is distinguished by several nonlinear processing layers.

The systems resulting from these techniques have revolutionized our approach to problem-solving in various domains.

Smart manufacturing requires careful monitoring and modeling of machining processes in order to maintain tight tolerances and enhance the quality of the system and products [15, 16]. The capacity to timely control the input and output parameters enables the system to prevent or mitigate potential process faults, minimizing uncertainty concerning output quality and system productivity. Enhanced productivity and quality output are two of the most significant motivations for the integration of artificial intelligence and machine learning into modern manufacturing [17]. Such implementation of machine intelligence for modeling and monitoring necessitates the use of numerous sensors and process variables as inputs, as well as an AI approach trained on these data for a specific goal. With the advancement in new technologies such as the Internet of Things (IoT) and Big Data, the modern manufacturing industry has witnessed an unprecedented surge of sensory data available in a variety of forms and structures [18]. Naturally, handling this high-volume data while simultaneously supporting its real-time processing necessitates the indulgence of data modeling and analysis techniques. These techniques combined with the optimal ML and DL algorithms are used for processing the information obtained from the sensors in order to equip the system with self-monitoring and decision-making abilities.

The big data environment in modern manufacturing has inspired varied uses for machine learning and AI at different stages of a product’s lifecycle. Data analytics can be categorized into different levels based on the complexity and depth of analysis. Some key levels of data analytics include descriptive analytics, diagnostic analytics, predictive analytics, and prescriptive analytics (Fig. 3).

Meanwhile, diagnostic analysis employs root test analysis to dissect equipment failure or reduced performance of the product to reveal the reasons behind it. Predictive analytics feeds on historical data and utilizes statistical models to forecast future risks or opportunities for the system. Prescriptive analysis goes a step ahead by enabling

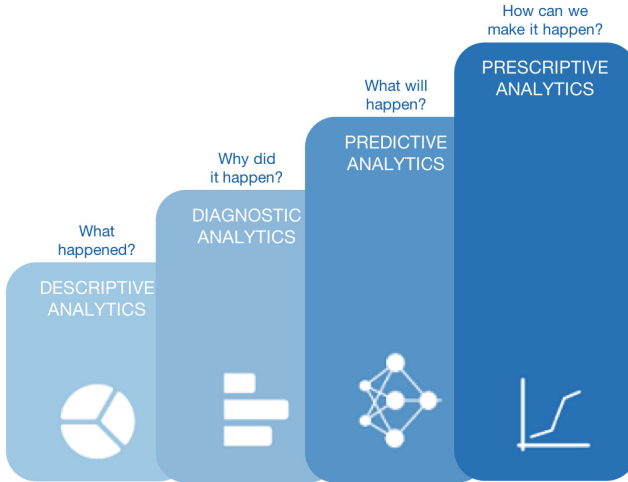


Fig. 3. Key Levels of Data Analytics [30].

recommendations on how to obtain the desired outcome through the use of optimization algorithms and decision support systems. The interference of AI and ML has truly transformed the manufacturing industries into autonomous, reliable, and increasingly optimized facilities. Manufacturing intelligence from sensory data has resulted in lower operational expenses, enhanced adaptability to varying customer demands, reduced downtime, and overall extraction of greater value within a globalized economy.

Smart manufacturing employs a wide range of AI approaches to monitor the machining state, prevent progressive tool wear, and offer predictive maintenance. This is done through decoding of highly complex patterns presented by the sensor data yielding key knowledge about a particular system or machine. The selection of ML approaches is essentially determined by prior knowledge of the process; sensor signal data attributes, empirical objective, and the level of precision necessary for industrial application. Computational time is another significant constraint to consider while assigning specific soft computing approaches and AI tools for automating decision-making and process monitoring. For instance, ML algorithms such as Artificial Neural Networks (ANN) and Fuzzy Inference Systems (FIS), often the hybridization of the two, are often utilized in the modeling and monitoring of manufacturing processes and systems [19]. Similarly, Convolutional Neural Networks (CNNs) have been proven to be effective for image analysis and real-time quality assessment of tools and machinery, and future predictions concerning their status can be made through architectures of the likes of Naïve Bayes, Hidden Markov Models (HMM's) or Genetic Algorithms (GA). Having a good understanding of the system model and successful integration of the right AI and ML approaches can effectively improve system productivity, profitability, and safety. Gupta et al. [20] employed ANN to predict the geometrical characteristics of a micro-channel fabricated through AWJM. They used optimum values of the process parameters to predict the response parameters and found that the ANN-predicted values are in good agreement with the experimental results. Madic et al. [21] developed the ANN model in

terms of workpiece material thickness, traverse rate, and abrasive flow rate. They found that ANNs are a good alternative in analyzing the quality of cutting and the abrasive water jet cutting parameters relationship. Reddy et al. [22] use full factorial design and multiobjective teaching learning-based optimization to improve the water jet-cutting process to optimize variables such as water pressure, feed, stand-off distance, and jet speed.

2 Application of AI and ML in Water Jet Machining

2.1 Process Optimization

Many investigations in the field of abrasive machining processes have concentrated on determining the impact of the most significant characteristics on responses such as material removal rate (MRR), surface roughness, kerf, and microstructural features. Material cutting of hard-to-cut materials such as titanium, kevlar, and composites necessitates great precision and a thorough understanding of the machine's controllable parameters due to the high cutting costs incurred during the process. Numerous process elements, such as water pressure, abrasives, material of the workpiece, and cutting parameters, influence AWJM cutting. Some of these parameters, such as the water pressure, abrasive flow rate, number of passes, standoff distance, and jet traverse speed, are controllable with reasonable precision. However, other variables such as the nozzle and orifice diameters alter progressively due to potential wear and erosion and, therefore, are challenging to control. These nonlinear changes in dimensions of the nozzles and orifice sway the flow rate as well as the mixing of abrasives in the mixing chamber, in turn influencing the depth of cut (DoC). DoC in waterjet machining refers to the maximum possible depth to which a high-pressure waterjet stream may penetrate or cut through a workpiece material. While many empirical and analytical models have been proposed in the past to model, monitor, and predict the DoC, limitations of the cutting environment and material assumptions have rendered them largely unreliable [23]. Various materials are processed at a range of periods in the workshop setting, utilizing unique process parameters. Such rapid and unsystematic data generation is referred to as Sparse Data. An architecture that can be designed to model sparse data will be extremely useful for AWJM processing since it can be used to determine process parameters. In this context, AI and ML algorithms have introduced promising modeling techniques aimed at deciphering patterns out of unplanned data that capture complex knowledge of machining systems and processes and could help with the optimization of the discussed parameters.

Several approaches have been presented to cater to these limitations using ML tools. One of these modeling techniques is derived from Artificial Neural Networks (ANNs) due to the framework's reputation for immense parallel processing capacity and noise suppression abilities. ANN is an advanced modeling method ideally suited for modeling complicated nonlinear systems. Inspired by the cerebral cortex of the brain and the workings of the neurons, ANN consists of interconnected processing units, termed artificial neurons or nodes. The number of neural cells required depends on the complexity of the task and the level of tolerance requested.

The greatest advantage of working with ANNs is that the number of input and output variables is theoretically endless and the precision of the model can cater to

very tight tolerances [2]. ANN models tend to deliver good approximation on data they have not been trained on previously and this is the reason why they are well-suited for continuously collected sparse data from AWJM machining. Further, this modeling technique, combined with GA has depicted the capability for suggesting the optimal number of inputs for a reliable approximation of the output (eg. depth of cut or cutting speed) [24].

In addition to the DoC, process variables can influence other important parameters such as surface roughness and MRR. Simultaneous reduction in surface roughness and an increment in MRR can be achieved by multi-attribute optimization where data obtained from experiments is processed using ANN and Response Surface Methodology (RSM). RSM is one of the operational strategies for augmenting, refining, and optimizing the AWJM machining process by integrating numerous process factors and determining the influence of diverse input parameters on the output [25]. Hence, these ML tools can be modified for various process optimization purposes in AWJM machining processes and can assist in the enhancement of desired quality cutting and reliable parameter selection.

2.2 Defect Detection and Quality Control

As discussed earlier, the efficiency of AWJM machining is determined by process parameters such as depth of cut, kerf structure, traverse cutting speed, surface topography, and MRR. The water, impinged with abrasives, used for the machining is forced out through a narrow orifice. Hence, the size of the orifice and nozzle impacts the kinetic energy and coherence of the jet as well as the distribution of the abrasives and suction capacity [26]. Therefore, it is essential to monitor variations in the orifice and nozzle size to maintain consistent cutting quality by optimizing process parameters accordingly. Such small and quick changes require reliable and efficient modeling techniques with an ability to respond swiftly, in real-time. In the context of AWJM machining, the task of developing analytical, semi-empirical, or empirical models is tedious and limited in scope. To achieve the required cutting performance while taking orifice and focusing tube bore variation into account, a hybrid technique combining the empirical model's response equations with a fuzzy model has been proven to be useful [24]. The interactions between different parameters, such as the abrasive flow rate and orifice size, are monitored and assigned weights according to their respective influence while employing soft computing techniques. The performance of the proposed AI and ML tools is then validated using data obtained from full factorial experiments.

Compared to conventional technologies, AWJM machining offers expanded tool life and reduced wear on supporting elements. However, the process is still associated with certain defects that need to be monitored and evaluated for quality assurance. To begin with, AWJM machining produces areas with varying surface quality due to the non-uniform thickness of the material and corresponding. Similarly, the uneven dispersion of kinetic energy of the water jet causes varied kerf widths at either end of the material, showcased as a taper angle. These deviations from the standard geometry result in micro and macro-geometric variations in the final product and can contradict the design specifications. Moreover, at high traverse speeds or relatively thicker workpieces, wavy striations are formed on the cut surface of the material due to jet instability or inaccurate machine calibration.

The ML modeling techniques discussed earlier for process optimization are valid here as well, however, for automated visual evaluation of surface filth, scratches, burrs, and wears, ML-based image analysis methods have been widely popular in industries. In this context, CNN algorithms combined with vision systems have been recognized as superior to conventional inspection techniques, either through the naked human eye or onerous statistical classification-based models. CNN adapts a deep layer architecture and accomplishes feature extraction and recognition on a single network at the same time, enhancing the overall performance of the inspection system for AWJM machined products.

2.3 Predictive Maintenance

Machines are susceptible to wear and tear in any industry and anticipating failure through data-driven approaches is essential to perform maintenance just in time to minimize costly breakdowns and optimize operational efficiency. Predictive maintenance (PdM) is a proactive maintenance strategy that leverages data, sensors, and analytics to forecast equipment failures. It is an important aspect of Industry 4.0, in which automation and interaction of data play a key role in optimizing industrial operations [15].

In the context of AWJM machining, several machining factors, such as set values for hydraulic processes, abrasive material, workpiece material, and cutting parameters, influence quality and efficiency. One of the primary signifiers of product quality in AWJM machining is surface roughness. Therefore, any modeling method that seeks to validate a relationship between product surface roughness and machining parameters brings great value to this industry. Several soft computing techniques involving AI and ML have been explored in order to introduce an estimation model for the prediction of surface roughness of materials processed through AWJM machining. Modeling techniques like neuro-fuzzy inference systems, GA, regression, and ANNs have been investigated for feature extraction and predicting roughness of the surface with minimal training time for the algorithm. In order to forecast the precise process parameters for a desired cutting quality, ANN has been used to propose a more practical and straightforward parametric AWJ model among these, owing to its ability to complex patterns and non-linear relationships to a desired degree of accuracy [27].

Predictive maintenance comprises several core components including proactive data acquisition and integration followed by curation of advanced analytical models using ML and DL algorithms. Due to the convenience of deploying low-cost sensors brought by the expansion of IoT, data-driven machine health monitoring is gaining popularity in modern production systems. In this context, deep learning offers valuable techniques for processing and analyzing large amounts of equipment data. The popularity of DL algorithms in the field of maintenance of machining processes can be attributed to enhanced computing power with the introduction of Graphics Processing Unit (GPU) and the advent of Big Data. Given deep learning's capacity to handle vast amounts of data and acquire high-level representations, it can be a strong and effective solution for machine health monitoring systems (MHMS).

MHMS typically share certain key components including feature design and extraction, followed by model training using various ML techniques. In comparison to traditionally deployed manual inspections to ensure health monitoring of AWJM machining

systems, DL-based MHMS requires less human labor and expertise for feature creation. All model parameters, including the feature and pattern classification/regression modules, may be trained simultaneously. Furthermore, MHMS. However, it is still useful to appreciate the incorporation of domain knowledge as it can aid in enhancing the efficiency of DL models. For instance, extraction of discriminative features, such as hydraulic and cutting parameters, can lower the size of the subsequent DL models, and a suitable task-specific regularization term can improve overall performance. It is important to realize that there are imbalanced class distribution is a typical difficulty in machine learning, especially in applications such as defect detection in machinery, when one class (e.g., “faulty” equipment) is considerably less prevalent than the other class (e.g., “healthy” equipment). This imbalance can result in problems such as biased model training and poor model performance. Various methods have been suggested to tackle such imbalanced class problems involving Support Vector Machines (SVM), Extreme Learning Machines (ELM), and CNN models. The prospective future for AI, ML, and DL is immensely promising in the health monitoring of AWJM machining systems as machinery becomes more sophisticated and generates vast amounts of data. The ability to effectively monitor and maintain equipment health becomes increasingly critical and soft computing entailing AI and ML is well-positioned to aid the predictive management processes due to its adaptability and evolving efficiency [28].

3 Challenges and Future Directions

3.1 Physics Informed AI

Despite the numerous advantages of AI-enabled technologies, three major drawbacks prevent their broad use in manufacturing, expanding the scope for future research in the domain: (1) lack of high-quality dataset in the field of AWJM machining for training of AI models, (2) restricted generalization to unseen samples, and (3) a lack of interpretability. AI systems frequently overfit the data presented to them during the training phase which leads to the algorithm overlooking imbalances and biases to replicate the training samples too closely. Consequently, the new data may differ from that of the training database due to the naive use of AI and ML approaches and reduce the accuracy of the modeling architecture. Moreover, AI systems, particularly unsupervised DL models, are frequently realized as black boxes, with few tools available to decipher the logic behind their decision-making behaviors.

These challenges can be effectively addressed by integrating engineering insights into the AI models and focusing future research on multiscale and multiphysics modeling that generates mechanism-informed data. The current manufacturing literature lacks a unifying framework for the selection of mechanical characteristics; instead, the selection process relies extensively on the experience of specialists in the area. For instance, feature extraction plays an integral role in analyzing the manufacturing performance of AWJM machining. To optimize the machining process, it is essential to impose engineering knowledge concerning essential features such as jet kinematics, abrasive mass flow rate, erosion mechanism, diameter of focusing nozzle, stand of distance, number of passes, and type of abrasive material. This optimization currently relies heavily on a purely data-driven end-to-end paradigm where flexible learning often neglects the underlying

physics-based problem-solving approaches. Instead of relying solely on experimental data from in-situ measurements and monitoring to build models, hybrid physics-based and data-driven modeling approaches can provide further insights that experiments cannot easily capture. A good example of such a customized modeling architecture has been presented in recent studies where an additional loss function, informed by fundamental rules of conservation of energy, has been introduced into traditional neural networks. This effort to guide the training of the ML algorithms about governing laws of engineering is a promising research direction that could immensely enhance the productivity of AWJM machining processes [28].

3.2 Optimization

Many advancements are being made to make the AWJM process more cost-effective and standardized. This objective would be substantially aided by extensive experimental research combined with process modeling for a wide range of materials. The manufacturing industry requires an optimal balance between quality and production, meaning that neither of them should obstruct the execution of the other. It signifies that quality aspects such as good surface finish, dimensional accuracy, and efficient time management should not work towards reducing the production rate. Therefore, optimization of machining processes is a continuously evolving research field with a wide scope for AWJM machining. A substantial amount of research conducted in this field indicates that to improve AWJM, researchers have concentrated on a single quality factor. However, the optimal value of a process parameter for a particular feature may reduce the quality of other aspects of the process and the overall result. For this purpose, multiobjective optimization that focuses on maintaining quality without foregoing efficient production rate is a potential future research direction [29].

4 Conclusion

The AWJM technique has continued to gain favor in machining, particularly for hard-to-cut materials. The machining industry benefits immensely from its adoption due to its benefits over traditional and nonconventional processes. AI and ML methods provide advanced analytics and enable great potential for smart AWJM manufacturing processes in the age of big data. Recent advances in ML and DL have served to provide new insights into machining operations, as well as real-time performance metrics and expenses, by converting an unprecedented quantity of data into usable and meaningful information. From expanding the arena for AWJM applications to process optimization, predictive maintenance defect detection, and quality control, studies carried out in the field of AI and ML concerning smart manufacturing of unconventional techniques have greatly contributed to the overall enhanced efficiency of machining processes. Despite the encouraging outcomes obtained in the field, the prospective directions for future research remain substantial and open to optimization as well as cross-validation.

Acknowledgments. The authors acknowledge the support given by the National University of Sciences and Technology for this work.





References

1. Rajesh, A.S., Prabhuswamy, M.S., Krishnasamy, S.: Smart manufacturing through machine learning: a review, perspective, and future directions to the machining industry. *J. Eng.* **2022**, 9735862 (2022)
2. Azlan Mohd Zain, H.H., Sharif, S.: Estimation of the minimum machining performance in the abrasive waterjet machining using integrated ANN-SA. *Expert Syst. Appl.* (2011)
3. Khan, R., Petru, J., Seikh, A.H.: Erosion prediction due to micron-sized particles in the multiphase flow of T and Y pipes of oil and gas fields. *Int. J. Press. Vessels Pip.* **206**, 105041 (2023)
4. Khan, R., Mourad, A.I., Seikh, A.H., Petru, J., Hamdan, H.Y.: Erosion impact on mild steel elbow pipeline for different orientations under liquid-gas-sand annular flow. *Eng. Failure Anal.* **153**, 107565 (2023)
5. Rahman, S., et al.: Performance prediction of erosive wear of steel for two-phase flow in an inverse U-bend. *Materials* **15**, 5558 (2022)
6. Khan, R., Wiczorowski, M., Damjanović, D., Karim, M.R., Alnaser, I.A.: Erosion-corrosion failure analysis of a mild steel nozzle pipe in water-sand flow. *Materials* **16**, 7084 (2023)
7. Khan, R., Ya, H.H., Pao, W., Bin Abdullah, M.Z., Dzubir, F.A.: Influence of sand fines transport velocity on erosion-corrosion phenomena of carbon steel 90-degree elbow. *Metals* **10**(5), 626 (2020)
8. Khan, R., et al.: Effect of sand fines concentration on the erosion-corrosion mechanism of carbon steel 90° elbow pipe in slug flow. *Materials* **13**, 4601 (2020)
9. Selvan, C.P., Midhunchakkaravarthy, D., Pillai, S.R., Madara, S.R.: Investigation on abrasive waterjet machining conditions of mild steel using artificial neural network. *Mater. Today: Proc.* **19**, 233–239 (2019)
10. Sharma, R., Maurya, S., Saini, R.: A review paper on current research and development in abrasive waterjet machining. *Math. Statist. Eng. Appl.* **71**(4), 4160–4169 (2022)
11. Putz, M., Dix, M., Morczinek, F., Dittrich, M.: Suspension technology for abrasive waterjet (AWJ) cutting of ceramics. *Procedia CIRP* **77**, 367–370 (2018)
12. Soori, M., Arezoo, B., Dastres, R.: Artificial intelligence, machine learning and deep learning in advanced robotics, a review. *Cogn. Robot.* **3**, 54–70 (2023)
13. Jegaraj, J.J.R., Babu, N.R.: A soft computing approach for controlling the quality of cut with abrasive waterjet cutting system experiencing orifice and focusing tube wear. *J. Mater. Process. Technol.* **185**(1–3), 217–227 (2007)
14. Baduge, S.K., et al.: Artificial intelligence and smart vision for building and construction 4.0: Machine and deep learning methods and applications. *Autom. Constr.* **141**, 104440 (2022)
15. Wiczorowski, M., Trojanowska, J.: Towards metrology 4.0 in dimensional measurements. *J. Mach. Eng.* **23**, 100–113 (2023)
16. Wiczorowski, M., Kucharski, D., Sniatala, P., Pawlus, P., Krolczyk, G., Gapinski, B.: A novel approach to using artificial intelligence in coordinate metrology including nano scale. *Measurement* **217**, 113051 (2023)
17. Kim, D.H., et al.: Smart machining process using machine learning: a review and perspective on machining industry. *Int. J. Precision Eng. Manuf.-Green Technol.* **5**, 555–568 (2018)
18. Wang, J., Ma, Y., Zhang, L., Gao, R.X., Wu, D.: Deep learning for smart manufacturing: methods and applications. *J. Manuf. Syst.* **48**, 144–156 (2018)
19. Akman, G., Yorur, B., Boyaci, A.I., Chiu, M.-C.: Assessing innovation capabilities of manufacturing companies by combination of unsupervised and supervised machine learning approaches. *Appl. Soft Comput.* **147**, 110735 (2023)
20. Gupta, T.V.K., Ramkumar, J., Tandon, P., Vyas, N.S.: Application of artificial neural networks in abrasive water jet milling. *Procedia CIRP* **37**, 225–229 (2015)

21. Madić, M., Janković, P., Slătineanu, L., Radovanović, M.: Artificial intelligence model for the prediction of cut quality in abrasive water jet cutting. *Appl. Mech. Mater.* **657**, 206–210 (2014)
22. Meenakshi Reddy, R., et al.: Parametric optimization of abrasive water jet cutting on AA 5083 through multiobjective teaching-learning method. *Adv. Mater. Sci. Eng.* **2022**, 1123256 (2022)
23. Mesalamy, A.S.E., Youssef, A.: Enhancement of cutting quality of abrasive waterjet by using multipass cutting strategy. *J. Manuf. Process.* **60**, 530–543 (2020)
24. Srinivasu, D.S., Babu, N.R., Srinivasa, Y.G., Louis, H., Peter, D., Versemann, R.: Genetically evolved artificial neural networks built with sparse data for predicting depth of cut in abrasive waterjet cutting (2005)
25. Reddy N.S., Tirumala, D., Gajjelaa, R., Das, R.: ANN and RSM approach for modelling and multi objective optimization of abrasive water jet machining process (2018)
26. Jegaraj, J.J.R., Babu, N.R.: A strategy for efficient and quality cutting of materials with abrasive waterjets considering the variation in orifice and focusing nozzle diameter. *Int. J. Mach. Tools Manuf.* **45**(12–13), 1443–1450 (2005)
27. Yang, L., Song, J., Hu, B.: Neural network parametric modelling of abrasive waterjet cutting quality. *Int. J. Abrasive Technol.* **1**(2), 198–207 (2007)
28. Shukla, M., Tambe, P.B.: Predictive modelling of surface roughness and kerf widths in abrasive water jet cutting of Kevlar composites using neural network. *Int. J. Mach. Machinabil. Mater.* **8**(1–2), 226–246 (2010)
29. Ewees, A.A., Abd Elaziz, M., Oliva, D.: A new multi-objective optimization algorithm combined with opposition-based learning. *Expert Syst. Appl.* **165**, 113844 (2021)
30. Sarker, I.H.: Data science and analytics: an overview from data-driven smart computing, decision-making and applications perspective. *SN Comput. Sci.* **2**(5), 377 (2021). <https://doi.org/10.1007/s42979-021-00765-8>



Virtual and Augmented Reality: Past, Present, and Future

Hugo Silva¹, André S. Santos¹ , Leonilde R. Varela² , Justyna Trojanowska³ ,
and Vitalii Ivanov⁴ 

¹ Polytechnic Institute of Porto, Porto, Portugal

² University of Minho, Guimarães, Portugal

³ Poznan University of Technology, Poznan, Poland
justyna.trojanowska@put.poznan.pl

⁴ Sumy State University, Sumy, Ukraine

Abstract. Augmented and Virtual Reality are two intertwined concepts. These are distortions of the reality humans live in, either partially, for the first case, or creating a totally virtual environment. Both are related to the fourth industrial revolution. Although these are topics that were born during the past century, they have gained increasing relevance in the last decades. This paper performs a systematic literature review of the evolution of Augmented and Virtual reality. The past is explained through a brief overview of older developments, while the present is presented through a bibliometric research, coupled with case studies applied in various industries. Finally, future paths and conclusions are presented on the last section of the paper, which include a look at the tendencies of both technologies, that seems to lie in more mobility and convenience. The authors conclude that both Augmented and Virtual reality have a big potential to grow and become an important part of various industries.

Keywords: Augmented Reality · Virtual Reality · Environment

1 Introduction

The ongoing fourth industrial revolution is changing productions all around the globe. Although its beginning is commonly traced back to Germany in 2011, it is safe to say that it has never been more relevant [1]. This is an era marked by digitalization and innovation [2]. Never has been a time where humanity, and industries, have been so dependent on screens and the tendency is for this dependency to increase. As such, it is critical to properly implement new technologies into the production of any type of goods. It is clear that some industries are more traditional than others, but most of them have opportunities to improve with these implementations.

Along with Big Data, IoT (Internet of Things) and others, AR (Augmented Reality) is an integral part of the group of technologies leading the fourth industrial revolution [1]. VR (Virtual Reality) has been present in many applications related to leisure for many years [3], and, as explained in subsequent sections, AR is derived from VR. The

literature is not clear on how these are hierarchically distinct, but it is obvious that both lie in the manipulation of the perception of the user. Although research is not as vast as it would be desirable, this paper seeks to study what were their applications during the last decade, along with how they can be applied in different and improved ways in the present and in the upcoming years. Both AR and VR can enable companies to gain a competitive advantage, through operational effectiveness.

The structure of this paper is as follows: the Sect. 1 introduces the work; the Sect. 2 offers an overview of Virtual and Augmented Reality, along with a historical context of both technologies, serving as a literature review, which details the past of both concepts; the Sect. 3 introduces the research problem seeks to address; the Sect. 4 presents the results obtained, painting the picture of the present of both Virtual and Augmented Reality through a bibliometric research and case studies presentation; the Sect. 5 analyses the future paths and conclusions that can be taken from this work.

2 Literature Review

2.1 Virtual Reality

A keyword in defining virtual reality is “environment”. This relates to the creation of a space in a form of pictures, videos, or interactive videogames. It requires the processing of a software to immerse the user on mainly two dimensions: visually and through sound [4].

VR (Virtual Reality) it's one of the main drivers of industry 4.0, conquering a place of significance and complexity along its development [5]. Although its definition is not fixed, and may vary with the purpose and application of the technology [5], the usual way of portraying it, it the creation of an environment that immerses the user, transporting he or she to a different reality, supported by a virtual display [6]. VR can be portrayed as a good marketing tool and has been used in all sorts of applications, such as hospitals [7]. It normally recurs to hardware such as headsets, which allow the computer to fully immerse the user in the virtual world [8], **Błąd! Nie można odnaleźć źródła odwołania** (Fig. 1).



Fig. 1. User immersed in a virtual environment [5]

Creating an environment, virtual or not, is still extending the reality of the user. It can be done by fully immersing the user, VR, altering the user's reality while keeping some unaltered sensorial experience, AR (Augmented Reality), or a mixture of both, MR (Mixed Reality) [9], Fig. 2.

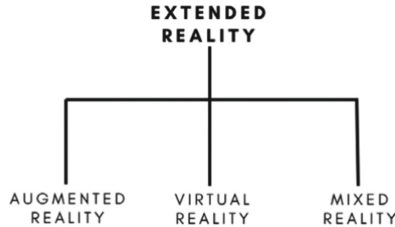


Fig. 2. The different paths of extended reality [9]

Although Fig. 2 may lead to conclude that VR and AR are two hierarchically equal developments of extended reality, most authors present AR as an extension of VR.

2.2 Augmented Reality

AR is derived from virtual reality. Although it doesn't fully immerse the user in an environment created by a software, it uses similar tools to modify the user's perception of reality. Generally, the most affected sense is the sight but all five senses can experience the enhancement reality provided by the software. Commonly, the perception of the use of AR is to add to reality, making it more complex. Although this is a famous application of AR, it can also be used to remove information from reality, with the goal of allowing the user to focus on the element they are looking for [10].

Through the combination of hardware and software, augmented reality can be displayed in four platforms, according to [10] (Table 1):

One of the terms used by [11] to describe the development of AR as a tool and its surrounding industry is the term "inevitable". As the author suggests, this technology enhances what are called the three C's: convenience, capability, and creativity. Diving deep into the three C's, some advantages to the use of AR are briefly presented [11]:

- It allows the user to see beyond the usual 2D world provided by digital tools like screens, reaching further to the realm of 3D.
- It is arguably accessible to the human interaction, due to the naturality of processing in our brains. Simply, it requires low effort for us to understand how to interact with AR.
- It is a tool that allows the user to express creativity in different ways, allowing them to go beyond the physical boundaries. The potential of expression is ever-growing with the development of AR and VR.

Augmented reality demands certain elements to properly work, most notably: a tracking agent; a software or tool that registers and displays the result to the user; a human-computer interface [12].

Table 1. AR Platforms and respective description

Platform	Description
Computers with webcams	An immobile device. A live feed is used, employing a marker, allowing the user to interact with the software capabilities
Kiosks and Digital signs	Both kiosks and digital signs are fixed. The difference between is that digital signs require other devices in order to access the AR features, such as a smartphone, while kiosks do not
Smartphones, Tablets and other mobile devices	Functions like filters, GPS and others make this type of platform the most common. It is differentiated by the mobility it allows the user, while using AR features
AR Glasses	A device normally attached to the head of the user, enhancing the sight with information given by the AR software

Currently, devices that are able to use are divided into three categories: head-worn (smart glasses and others); hand-worn (smartphones and others); spatial devices [13].

2.3 History of VR and AR

AR can be intertwined with a large number of concepts, from philosophical to historical ones. The human race has always sought to evolve, with the primary channel for evolution being the manipulation of its surrounding [14]. Through numerous revolutions, from political to industrial, information has never been so available and rapidly obtainable. As before, in order for people to get from point A to point B, a map would be needed if the direction was unknown. Nowadays, people can simply access their smartphone to know exactly where they are and where they should be headed. Although the world is faster than ever, there is still a lot of margin for growth, regarding AR and VR [3].

Considering that AR is derived from VR [6], it makes sense to look into the history of VR. A consideration to be made is that AR and VR are concepts that go together and have evolved at approximately the same pace, with the same phases and periods in its evolution.

VR has continuously gained interested in the last decades. As noted by [15], since 2002, this technology has been growing substantially, confirming to the authors predictions, and approving the Gartner Group curve used for new technologies, Fig. 3.

This graph shows the evolution of new technologies, being measured by their media presence over time [15].

Regarding the first stage, named “Technology Trigger” in figure X, four main contributors are suggested according to [16]:

1-Morton Heilig – Presented a product called *Sensorama* in New York, during 1962.



Fig. 3. Gartner Group curve [13]

2-Ivan Sutherland – Published “The Ultimate Display” in 1965, a work that intended to provide the user a virtual reality involving all five senses. The prototype device was named “The sword of Damocles”.

3-Tom Furness – A Medical Researcher working for the US Air Force, that evolved the VR concept within flight simulation. This was the kick-off for the contribution of flight simulation to the development of VR.

4-Mike McGreevy and Jim Humphries – Developed the modern VR setup, in NASA Ames’ facilities. They focused their work on head-mounted displays for astronauts, Fig. 4.



Fig. 4. The VIVED system, designed and built in 1984 by Dr Mike McGreevy and Jim [16]

Regarding the second phase of Fig. 3, the peak of expectations was reached between 1992 and 1995, according to [15]. It was seen as an innovative solution for both training multiple types of professionals and for promoting new products, with the end goal of shocking the viewer [3]. Around the referenced period, companies such as Sega planned to add features of VR to a gaming console, which never took off from the prototype phase. This period fits into the timeframe proposed by [15] for the third phase of Fig. 3: “Trough of Disillusionment”.

A product that was successful was the SAS cube, also named “The Cave” due to the parallelism with the Greek-history of Plato’s Cave, which took VR closer to the concepts described in Sutherland’s “The Ultimate Display” [3]. While it did not fulfil in its full potential due to graphic and other developmental constraints, it marked a significant stride forward, positioning itself as a noteworthy moment in the fourth phase depicted in Fig. 4: the “Slope of Enlightenment.” It is also understood that it is a fine line between the last two phases and is arguably acceptable to affirm that in 2023 VR is in the last phase, showing more maturity than ever [15].

3 Research Problem

This paper aims to investigate the evolutionary trajectory of Augmented and Virtual Reality through a systematic literature review. In preceding sections, an exploration of AR and VR, along with their historical developments, was presented to provide readers with contextual insights into past advancements. Transitioning to the present, a dual-pronged analysis is employed. Initially, a bibliometric research delves into both topics, illustrating their evolution and underscoring their relevance in academia. The research sample encompasses the 1000 most pertinent articles from Web of Science, covering journals and papers for both AR and VR. Biblioshiny, a tool from Bibliometrix, was utilized for data input and analysis, with the timespan limited to 1992 onwards due to software constraints. Subsequently, a series of case studies is expounded upon in two dimensions: a succinct overview of each study and the conclusions drawn by the authors from their respective works.

4 Results

Having reviewed the historical context, the current section delves into the present landscape of AR and VR. Initially, a bibliometric analysis was conducted on both subjects, showcasing their evolution from the past to the present and emphasizing their significance in academia. Subsequently, a set of case studies was studied, featuring a concise overview of each study followed by the authors’ conclusions drawn from their respective works.

4.1 Bibliometric Research

As presented in the Sect. 3 of this paper, the beginning of VR doesn’t have a defined date, but it can be concluded that its birth was around the 1960’s. To evaluate its growth since that decade, until the present, a bibliometric research was performed on AR and VR. Due to software’s restrictions, it was only possible to analyze the development of both concepts since 1992.

First, Fig. 5 presents the main information regarding the “Virtual Reality”. It can be concluded that it has been growing, as is reflected in its annual growth rate.

Then, Fig. 6 shows the main information for “Augmented Reality”. It can be concluded that AR and VR show similar growth and overall numbers, confirming the affirmation on the previous section that these topics go hand in hand. That makes sense due



Fig. 5. VR main information

to AR being derivative from VR [14]. As such, this analysis will be made in a complementary manner. That means that different analysis fields will be presented for AR and VR.



Fig. 6. AR main information

The annual scientific production of both AR and VR confirms the growing tendency presented in the main information before, Fig. 7.

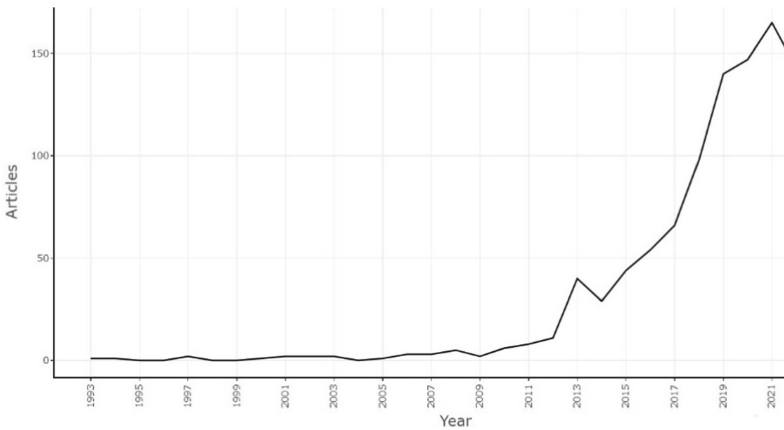


Fig. 7. AR annual scientific production

As for trends, the Fig. 8 represents the trending topics from this century, regarding VR in the utilized database. Curiously, terms such as “high efficiency” and “opportunities” show up during the last years, confirming the hypothesis that we are currently in the 4th industrial and scientific revolution [17], which focuses more on sustainability and efficiency than ever before.

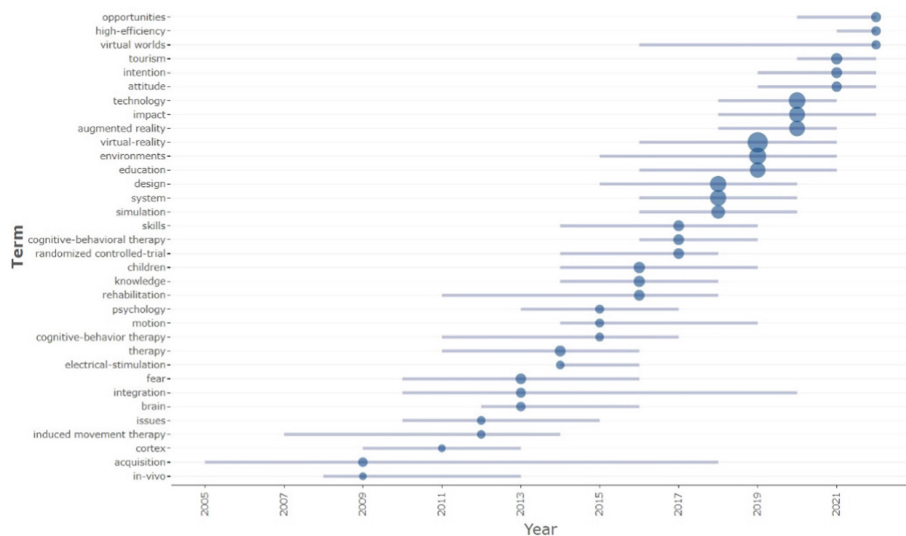


Fig. 8. VR trending topics

Geographically, the countries that contributed more to the development of AR and VR in the scientific community are the USA and China, Fig. 9.

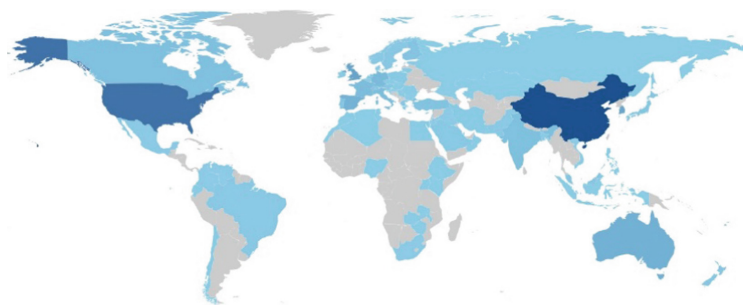


Fig. 9. Scientific production related to AR

Finally, the most frequent words that appeared in works about or containing VR are present in the Fig. 10.

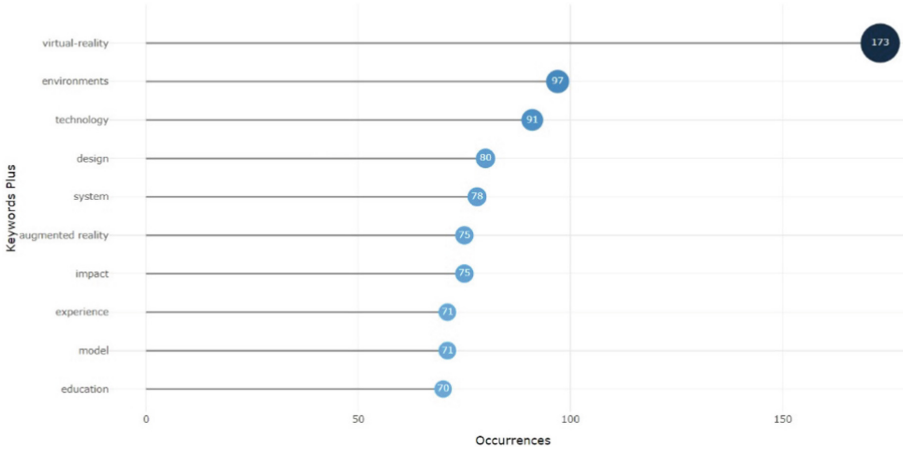


Fig. 10. Most frequent words in work related to VR

4.2 Case Studies

The manipulation of the environment has never had so much use, as explained in the previous section, given that this technologies, AR and VR, have entered a more mature phase a few years ago [15]. Its application is quite diverse, and more and more studies have supported the use of these devices, as seen in the bibliometric research.

This section presents some case studies in various industries and scenarios, published during the last 5 years. This period is purposefully selected to display modern applications of both AR and VR. Through a summary of the studies, explaining the methodology, results and conclusions, the information is presented to the reader with the goal of displaying the consequences these technologies, hopefully encouraging the reader to critically consider the use of AR and VR. Due to the content of the present study, only the conclusions regarding VR will be presented (Table 2).

Table 2. AR and VR case studies

Study	Description	Conclusions
Adding immersive virtual reality to a science lab simulation causes more presence but less learning [18]	This study seeks to understand the impact of implementing virtual reality on student learning, self-report ratings, and brain-based measures of overload. With a sample size of 52 students, a 2×2 matrix was employed in order to test two factors: the first was tested in two groups, where one had only text content in the simulation, and the other had text and narration; the second factor involved a simulation with a head-mounted display and a PC simulation, where two groups were created in parallel with the two running orders (PC first, HMD second, or otherwise). The independent variables of the test were the media usage and method, and the dependent variables were the gains (knowledge and transfer)	Although students gained more knowledge with the help of a PC than they did with VR immersion, the study concluded that those using VR first showed more presence in the self-report ratings. With the help of an EEG (electroencephalogram), it can be concluded that VR can be overstimulating.
Augmented reality for training formation flights: An analysis of human factors [19]	This study explores the impact of Augmented Reality (AR) on military pilot training for formation flights, focusing on performance, stress, and overload indicators. Unlike traditional training with two aircraft, the study proposes a wingman guided by a virtual leader using AR technology. The prototype includes four scenarios, ranging from no AR to increasing AR complexity. Key emphasis is placed on Scenarios 3 and 4, utilizing leader projection and AR glasses. Performance is measured by the average standard deviation of the distance between wingman and leader, considering training time. Training effectiveness is assessed through time interval metrics, and workload is gauged using a combination of questionnaires and physiological sensors. The experiment involves 10 users with varying flying skills, divided into two groups—one for each scenario	The limitations of this study lie on the differences between the AR version versus the real flight, due to factors such brightness and vibration not being present in the AR case Regarding performance, the test results indicate that the training scenario has significant impact. However, for training effectiveness this is not the case. For workload and stress, the results ultimately indicate that the stress levels do not vary significantly with the training scenario, although it is curious that workload is reported to increase with the AR glasses, according to the questionnaire. This was not enough to disturb physiological measures

(continued)

Table 2. (continued)

Study	Description	Conclusions
Augmented Reality in Logistics 4.0: implications for the human work [13]	<p>This study, situated in the context of Industry 4.0, examines the impact of Augmented Reality (AR) on logistics, specifically in warehouse operations, transportation, and training. With the aim of enhancing traditionally manual logistics processes, the research addresses two key questions: the applications of AR in logistics and the resulting impact of its implementation. Employing deductive research and drawing on the authors' experience along with secondary data from company reports, the study identifies several practical applications within the logistics subfields</p> <p>For warehousing, AR serves as a tool for verifying delivery notes, checking product locations using smart glasses, and optimizing picking orders. In transportation, AR provides real-time traffic data and optimal routes to delivery personnel via smart glasses or windshield projections, improving safety by allowing drivers to focus on the road. In terms of training, AR surpasses traditional instructional videos by offering interactive guides that adapt to individual learning needs, potentially enhancing worker motivation</p>	<p>This study concludes that AR shortens the gap between the worker and its surrounding environment. It can also offer other benefits, such as reduced failure rate and traceability. Finally, the disadvantages mentioned include the difficulty surrounding hardware and software, including lack of formation in machine learning and programming languages. AR can also cause discomfort on workers, such as headaches and eye damage. The last disadvantage to be highlighted revolves around data sharing and storage, as is the case with a lot of other technologies in the fourth industrial revolution and technology evolution</p>
Augmented reality in forensics and forensic medicine – Current status and future prospects [12]	<p>Due to a high-level of specialization required that forensic investigators, technological resources such as computers and displays are essential for these workers to deliver what they are requested. It is reported that forensic workers give little to no use to innovative technologies such as AR. In this sense, the study details the application of AR in such a specialized field and evaluates the impact it has on forensic investigation and forensic medicine. Four main applications for AR in forensic medicine and investigation were highlighted: supporting the forensic pathologist; data presentation; training; documentation</p> <p>Previous efforts have come in the form of a backpack computer that uses GPS (global positioning system) to track the path of a certain action, together with the use of a camera that allows the forensic worker to take notes along the way. This way, other investigators can pick exactly on the work done by the first user</p>	<p>This study suggests that AR holds potential benefits for the forensic field, particularly in forensic medicine for extracting improved case reports using tools like Head-Mounted Displays (HMD). However, further research is needed due to limited data on this application. Despite advantages, challenges include decreased visual quality and user fatigue with HMD use. The main hurdle for AR in forensic fields is the substantial investment required. Additionally, the study emphasizes the crucial need for tracking stability in AR technology, posing a significant obstacle to its immediate growth</p>

5 Future Paths and Conclusions

The future of AR and VR seems to lie in the convenience of usage [14]. This aligns with a world that's increasingly convenient for humanity. It can be scary, but the lines between the real and virtual world are getting more and more blurred, becoming almost indistinguishable [14]. The SM (Social Media) boom can be seen as a space where technologies such as AR could enter. SM is undeniably ingrained in most people's lives. In 2021 3,5 billion people used these platforms [20], mostly in developed countries,

and although it has contributed positively, it has also created many problems such as social relation problems and sleep disorders [21]. That begs the question: would it be beneficial to mankind if people were even more involved in a computer-manufactured environment? Of course, it is manipulated by, and a product of, humans. But has been proved by multiple studies that there is a positive association between social isolation and problematic social media use [20]. Humans tend to fall to excessive habits, a fact that has been amplified by online platforms, such as online casinos [22, 23]. Both AR and VR could easily increase the dopamine release in these types of scenarios, making it even more addictive. It is then recommended to adopt these technologies into our daily lives with some consideration. Although it is already present in tools like Instagram's filters, it's arguably still distant from being a necessity rather than a complement.

As presented in the case studies, the application of AR and VR in the various fields had different results. It can be beneficial, as seen in the Forensic medicine case study, or it can be prejudicial, as was seen in the overload results from the Flight training case study. Although there are various studies on both subjects, more work would make these technologies better understood and would clarify the boundaries of good and bad application of both.

Regarding the application of these technologies in engineering fields, the outlook is quite positive, as shown in the logistics case study. It can help operators and managers performing their tasks, optimizing time spent on repetitive activities. As such, it can increase operational effectiveness and, consequently, provide the company a competitiveness, due to its time or cost reduction.

As for future trends, the focus is clearly on mobility, accessibility, and improvement in tracking reliability. AR and VR are also expected to grow in the dimension of the undeveloped senses of the technologies, given that mostly they rely on sight distortion [14, 24]. Another global trend is the rise of short-form content [25, 26], which is impacting the development of peripheral technologies towards its disposition, demanding AR and VR to support readily swappable content [14, 27].

The increasing affordability and accessibility of VR and AR devices are catalyzing a surge in scholarly interest. As these technologies become more widespread, there is a noticeable uptick in the quantity of articles addressing VR and AR. The correlation is clear: increased accessibility leads to a broader user base, driving increased academic and professional discourse. Scholars are now delving into the multifaceted implications of these technologies, highlighting the dynamic relationship between accessibility and scholarly engagement.

Acknowledgment. The research was partially supported by the Polish National Agency for Academic Exchange within the project “Digitalization in mechanical engineering” (agreement no. BNI-UE-2023-2).

References

1. Xu, X., Lu, Y., Vogel-Heuser, B., Wang, L.: Industry 4.0 and Industry 5.0—inception, conception and perception. *J. Manuf. Syst.* **61**, 530–535 (2021)

2. Hizam-Hanafiah, M., Soomro, M.A.: The situation of technology companies in industry 4.0 and the open innovation. *J. Open Innov. Technol. Market Complexity* **7**(1), 34 (2021)
3. Bown, J., White, E., Boopalan, A.: Looking for the ultimate display: a brief history of virtual reality. In: *Boundaries of Self and Reality Online*, pp. 239–259. Elsevier (2017)
4. Joiner, I.A.: *Emerging Library Technologies: It's Not Just for Geeks*. Chandos Publishing, Witney (2018)
5. Guo, Z., et al.: Applications of virtual reality in maintenance during the industrial product lifecycle: a systematic review. *J. Manuf. Syst.* **56**, 525–538 (2020)
6. Theodoropoulos, A., Lepouras, G.: Augmented Reality and programming education: a systematic review. *Int. J. Child Comput. Interact.* **30**, 100335 (2021)
7. Lee, M., Lee, S.A., Jeong, M., Oh, H.: Quality of virtual reality and its impacts on behavioral intention. *Int. J. Hosp. Manag.* **90**, 102595 (2020)
8. Park, S., Lee, G.: Full-immersion virtual reality: adverse effects related to static balance. *Neurosci. Lett.* **733**, 134974 (2020)
9. Savir, S., et al.: Virtual reality: the future of invasive procedure training? *J. Cardiothorac. Vasc. Anesth.* **37**, 2090–2097 (2023)
10. Rampolla, J., Kipper, G.: *Augmented Reality: An Emerging Technologies Guide to AR*. Elsevier, Amsterdam (2012)
11. Wassom, B.: *Augmented reality law, privacy, and ethics: Law, society, and emerging AR technologies*. Syngress (2014)
12. Golomingi, R., Dobay, A., Franckenberg, S., Ebert, L., Sieberth, T.: Augmented reality in forensics and forensic medicine-current status and future prospects. *Sci. Just.* **63**, 451–455 (2023)
13. Lagorio, A., Di Pasquale, V., Cimini, C., Miranda, S., Pinto, R.: Augmented reality in logistics 4.0: implications for the human work. *IFAC-PapersOnLine* **55**(10), 329–334 (2022)
14. Craig, A.B.: *Understanding augmented reality: concepts and applications* (2013)
15. Sherman, W.R., Craig, A.B.: *Understanding Virtual Reality*. Morgan Kaufman, San Francisco (2003)
16. Gigante, M.A.: Virtual reality: definitions, history and applications. In: *Virtual Reality Systems*, pp. 3–14. Elsevier (1993)
17. Aoun, A., Ilinca, A., Ghandour, M., Ibrahim, H.: A review of Industry 4.0 characteristics and challenges, with potential improvements using blockchain technology. *Comput. Ind. Eng.* **162**, 107746 (2021)
18. Makransky, G., Terkildsen, T.S., Mayer, R.E.: Adding immersive virtual reality to a science lab simulation causes more presence but less learning. *Learn. Instr.* **60**, 225–236 (2019)
19. Arjoni, D.H., de Souza Rehder, I., Figueira, J.M.P., Villani, E.: Augmented reality for training formation flights: An analysis of human factors. *Heliyon* **9**(3), 1–18 (2023)
20. Meshi, D., Ellithorpe, M.E.: Problematic social media use and social support received in real-life versus on social media: associations with depression, anxiety and social isolation. *Addict. Behav.* **119**, 106949 (2021)
21. Bou-Hamad, I.: The impact of social media usage and lifestyle habits on academic achievement: Insights from a developing country context. *Child Youth Serv. Rev.* **118**, 105425 (2020)
22. Gainsbury, S.M., King, D.L., Russell, A.M.T., Delfabbro, P., Hing, N.: Virtual addictions: an examination of problematic social casino game use among at-risk gamblers. *Addict. Behav.* **64**, 334–339 (2017)
23. Husár, J., Hrehova, S., Trojanowski, P., Wojciechowski, S., Kolos, V.: Perspectives of lean management using the poka yoke method. In: Ivanov, V., Trojanowska, J., Pavlenko, I., Rauch, E., Piteř, J. (eds.) *Advances in Design, Simulation and Manufacturing VI. DSMIE 2023. Lecture Notes in Mechanical Engineering*, pp. 121–131 (2023). Springer, Cham. https://doi.org/10.1007/978-3-031-32767-4_12

24. Kujawińska, A., Diering, M.: The impact of the organization of the visual inspection process on its effectiveness. *Int. J. Adv. Manuf. Technol.* **112**, 1295–1306 (2021). <https://doi.org/10.1007/s00170-020-06543-9>
25. Gan, J., Shi, S., Filieri, R., Leung, W.K.S.: Short video marketing and travel intentions: the interplay between visual perspective, visual content, and narration appeal. *Tour. Manag.* **99**, 104795 (2023)
26. Kaščák, J., Husár, J., Knapčíková, L., Trojanowska, J., Ivanov, V.: Conceptual use of augmented reality in the maintenance of manufacturing facilities. In: Trojanowska, J., Kujawińska, A., Machado, J., Pavlenko, I. (eds.) *MANUFACTURING 2022. LNME*, pp. 241–252. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-99310-8_19
27. Wojciechowski, S., Przystacki, D., Chwalczuk, T.: The evaluation of surface integrity during machining of inconel 718 with various laser assistance strategies. *MATEC Web Conf.* **136**, 01006 (2017)



Mixed Reality as a Perspective Education Tool in Industry 5.0

Jozef Husár¹  , Stella Hrehová¹ , Lucia Knapčíková¹ ,
and Piotr Trojanowski² 

¹ Technical University of Košice, Prešov, Slovak Republic
jozef.husar@tuke.sk

² West Pomeranian University of Technology in Szczecin, Szczecin, Poland

Abstract. In this paper, we evaluate several aspects of mixed reality (MR) and its use in Industry 5.0. In the introduction, we define the term Industry 5.0 and its connection with mixed reality as a key educational tool. Next, we devoted ourselves to the scientific interpretation of the terms Industry 5.0 and mixed reality. We then moved on to software and hardware tools in the field of MR and summarized the methods and materials in dealing with the topic of mixed reality in Industry 5.0. We assess the importance of MR in Industry 5.0 education, emphasizing its ability to provide authentic and immersive learning experiences for university students. Finally, we discuss ways to evaluate the results of MR implementation in education, including quantitative and qualitative methods. With this article, we cover a wide range of topics related to mixed reality and its applications in Industry 5.0 and education. By implementing the proposed methodology, we will provide students with a competitive advantage in their application in the smart factories of the future.

Keywords: mixed reality · education · methodology · Industry 5.0

1 Introduction

In the context of dynamic industrial development, which is called Industry 5.0, we observe an evolution in which production and management traditional models are combined with modern information technologies [1]. This era sees a radical transformation in the way we interact with automated systems, with an emphasis on increasing collaboration and synergistic integration of human labor and technological innovation. Within this framework, mixed reality (MR) stands out as a promising tool that not only merges the physical and virtual worlds, but also represents a revolutionary possibility of transforming education in industries [2]. Industry 5.0 emphasizes the need to adapt intelligently and flexibly to rapidly changing technological trends. In this new industrial age, it is not only about automation, but also about complex interaction where humans and machines work together in symbiosis. In the context of education, this means that workers must acquire new skills and knowledge at a level that allows effective collaboration with advanced technologies [3]. Mixed reality, as a key tool, offers the tools to simulate real

work situations and enables hands-on training where employees can gain experience in a safe and controlled environment. In this light, the door opens to new educational models that integrate MR into training and educational programs. Simulations created in mixed reality can provide a realistic and interactive environment for training on new technologies, processes and procedures. In addition, augmented reality (AR) can play a significant role in repair and maintenance, where employees can use MR glasses to solve problems in real time, increasing the efficiency and speed of diagnosis and repair [4]. Another key aspect is the mixed reality ability to facilitate remote collaboration. Workers from different locations can collaborate on projects and share knowledge through MR, regardless of geographical limitations. This is essential in a globalized industrial operations environment where there is a frequent need to consult and collaborate with teams from different parts of the world. In the overall assessment, it is important to remember that the implementation of mixed reality as a key educational tool in Industry 5.0 requires not only technological investments, but also the transformation of the educational mind set and adaptation to new educational paradigms. In connection with the ever-increasing emphasis on the human factor in industrial processes, it seems that mixed reality represents a promising way to increase the workforce qualifications and supports the development of modern Industry 5.0 [5]. In this article, we want to provide an insight into the possibilities of using MR in the education of university students. Therefore, we must define the basic terms.

1.1 Industry 5.0

It represents the conceptualization of a new stage development in industrial sectors, which is characterized by a deep integration of advanced digital technologies and intelligent systems with traditional production processes. This approach follows previous industrial revolutions, from mechanization and electrification in the 18th and 19th centuries to automation and computerization in the 20th century [6]. In contrast to previous paradigms where the focus is on efficiency and automation, Industry 5.0 emphasizes human-machine collaboration, where smart technologies such as artificial intelligence, robotics, the Internet of Things (IoT) and more serve to support and enhance capabilities of human workforce. This integration aims to create flexible, intelligent and adaptable production systems that respond to market dynamics and meet individualized customer needs [7]. Industry 5.0 thus stands for a holistic approach to industrial innovation, creating a symbiosis between technological progress and human skills to achieve higher productivity, flexibility and sustainability in 21st century industries.

1.2 Mixed Reality

It is a significant scientific concept that merged the boundaries between the physical and virtual worlds, creating an innovative interactive environment. MR integrates virtual reality (VR) and augmented reality (AR) to create a synergistic and immersive experience where digital objects and information are transferred into a real environment [8, 9]. In this complex model, virtual elements are not limited to creating isolated digital worlds, but are dynamically linked back to the real world, allowing users to interact with these hybrid elements. MR requires advanced sensors, image processing algorithms and high

performance computing systems to create a smooth and authentic experience. The use of mixed reality is multi-level, ranging from education and training to industrial applications and medical procedures [10]. This technology moves the digital environment boundaries and opens doors for new forms of communication, education and collaboration. It provides interesting space for further research and innovation in the field of interactive technologies. MR was first defined by Milgram and Kishi-no in 1994 [11]. It can also be used as a tool in robotics, which reduces the gap between simulation and implementation and enables the prototyping of algorithms [12]. The Mixed Interaction model provides a unified understanding of MR systems, considering the interaction modalities and forms of multimodality involved [13]. The potential of mixed reality in industry is explored in a range of studies. Heimo [14] and Moser [15] both highlight the challenges and potential research areas in this field, including interaction and usability, immersion and storytelling, and international business processes. Holly takes a strategic approach, proposing a systematic method for integrating mixed reality into industry, with a focus on sustainability [16]. Hain presents a case study on the use of mixed reality in the presentation of industrial heritage, demonstrating its potential for creating immersive experiences. These studies collectively underscore the need for further research and development to fully realize the potential of mixed reality in industry [17]. The use of mixed reality in Industry 4.0 is a growing area of interest, with applications in production optimization, employee training, and scientific workflows [18, 19]. Guo highlights the potential of mixed reality systems in vocational training, emphasizing their motivational effects and pedagogical aspects [20]. Juraschek further explores the use of mixed reality in learning factories, discussing its potential for information visualization, remote collaboration, and human-machine interfaces. These studies collectively underscore the diverse and promising applications of mixed reality in the context of Industry 4.0 [21]. Mixed reality, a combination of virtual and artificial objects in the real environment, is increasingly being integrated into education [22]. This technology has the potential to significantly impact the future of education, with recent developments and future trends being explored [23]. In particular, mixed reality has been found to enhance engagement, critical thinking, and problem-solving skills in students, aligning with the expectations of a new generation of learners [24]. Furthermore, it has been shown to have benefits over traditional teaching methods, with positive user reactions [25]. However, there is a need for further research and refinement of mixed reality solutions for the classroom [24].

2 Materials and Methods

When solving the topic of our article, it is possible to use a combination of quantitative and qualitative research methods to get a comprehensive view of the mixed reality impact in the educational context within Industry 5.0. On the side of quantitative research, statistical analyzes could be used to evaluate the effectiveness of MR in the educational process, monitor the success of training and measure improvements in work performance [26]. The use of questionnaires or survey studies can help collect data on the attitudes, experiences and preferences of participants in the educational program [27]. At the same time, it would be useful to conduct qualitative studies, such as interviews and

observations, to gain a deeper understanding of individuals experiences and perspectives in using mixed reality [28]. Content analysis of documents, training, and employee feedback can provide valuable information about the specific outcomes of a training program. In addition, case studies could be used to support a broader understanding of successful MR implementations in an Industry 5.0 educational environment [29]. The integration of these quantitative and qualitative approaches would enable a systematic analysis of the mixed reality impact on education in industrial environments, offering valuable knowledge for the further improvement of educational programs in the context of Industry 5.0 [30]. Therefore, in this article we want to provide a comprehensive view of the software and hardware equipment necessary for the implementation of MR in the educational process.

2.1 Software Tools for MR

Mixed reality (MR) software tools can be divided according to their purpose, usage, and supported platforms [31] (Table 1).

This division is general and many tools can fall into multiple categories depending on their specialization and functionality [32]. Therefore, we selected the most important software and created a simple overview:

- **Unity 3D:** A development engine that supports the creation of games, simulations and applications in various platforms, including mixed reality. With support for ARKit, ARCore and other platforms, Unity is a popular tool for creating MR content.
- **Unreal Engine:** Epic Games' Unreal Engine is another development engine that enables the development of large-scale and visually impressive MR applications. It provides tools for creating both VR and AR environments.
- **Microsoft HoloLens Development Tools:** To create applications for Microsoft HoloLens, one of the leading MR devices, Microsoft offers its own development tools and SDK (Software Development Kit). This includes HoloLens Emulator and Windows Mixed Reality Toolkit.
- **Vuforia:** It is a platform from PTC that enables the development of AR applications. It provides image recognition, motion tracking, and other features that are useful for creating high-quality MR content.
- **ARKit (for iOS) and ARCore (for Android):** These are software tools from Apple (ARKit) and Google (ARCore) that provide an environment for developers to create mobile applications with AR features. They are excellent for implementing mixed reality on smartphones and tablets.
- **ZapWorks:** Platform for creating AR and MR content. It provides tools for creating interactive 3D scenes, image recognition and motion tracking for various applications.
- **MixedRealityToolkit (MRTK):** An open-source toolkit from Microsoft designed to simplify the development of MR applications for various platforms, including HoloLens and Windows Mixed Reality.
- **Lens Studio (Snap Inc.):** Enables the creation of AR and MR filters for Snapchat. It is a tool that enables the creation of creative and interactive content.

Table 1. Classification of MR software according to purpose

	Description	Examples
Development Environments	They are intended for developers and programmers to create MR applications. They contain development environments and frameworks that enable the creation and testing of MR content	Unity 3D, Unreal Engine, ARKit, ARCore, Vuforia
Design tools	They are aimed at content creators and designers who create visual and interactive elements for MR applications. They help in creating 3D models, animations and interfaces	Tilt Brush, Blender, Adobe Aero, ZapWorks
SDK a API (Software Development Kits and Application Programming Interfaces)	They provide a set of tools, libraries and interfaces that allow developers to integrate MR functionalities into their existing applications or create new applications	Microsoft Mixed Reality Toolkit (MRTK), HoloLens Development Tools, ARFoundation
Content creation platforms for filters and effects	These tools allow content creators to create MR effects, filters and interactive visual stories, especially for social media	Lens Studio (Snap Inc.), Spark AR Studio (Facebook)
Monitoring and calibration systems	They provide technologies for tracking motion and calibrating equipment in the MR environment, thereby increasing accuracy and stability	Steam VR Tracking, Microsoft Inside-Out Tracking
Educational and training platforms	Tools that enable the creation of educational content and training programs in the field of MR	zSpace, Lifeliqe
Analytical tools	They provide tools for monitoring and evaluating the performance of MR applications, analyzing user behavior and collecting data	Google Analytics for AR, Unity Analytics

2.2 Hardware for MR

It must meet specific requirements to enable a high-quality and accurate MR experience. Indispensable elements are motion tracking sensors and cameras that ensure accurate

and fast sensing of the surroundings. Powerful computing units are key to processing large amounts of real-time data and rendering virtual content with low latency. Displays with sufficient resolution and a wide field of view are essential for the realistic display of virtual objects in the real world [33]. In the case of main wearers of MR, such as glasses, ergonomic design, light material and wireless connection contribute to comfortable use and freedom of movement. Ensuring reliable power sources is critical because MR devices often require powerful batteries or other power solutions [34]. Last but not least, compatibility with connected software and the ability to support updates and enhancements are important to maintain relevance in the rapidly changing MR technology landscape [35]. By combining these elements, it is possible to achieve a full-fledged MR experience that is accurate, interactive and immersive.

Table 2. Devices and technologies for MR

Purpose	Description	Example
Display devices	They serve to display virtual content in a real environment. These can be glasses, special head-up displays or projection devices	Microsoft HoloLens, Magic Leap One, Google Glass
Sensors and Cameras	Sensors and cameras are essential components for tracking movement, detecting the environment and interacting with the user in real time	Motion tracking cameras, sensors for sensing the surroundings, LiDAR sensors
Control devices	Control devices allow users to interact with the virtual world. These can be wireless controls, gestures or haptic devices	Controllers for MR devices, gloves with haptic feedback
Calculation units	Powerful computing units are required to process and evaluate MR content in real time	Internal computing units in MR devices, computers for delivering computing power
Connection interfaces	These interfaces allow MR devices to be connected to other devices or cloud services	USB-C ports, WiFi, Bluetooth
Batteries and Power	Portable MR devices require reliable power sources, either in the form of batteries or other energy sources	Lithium batteries, rechargeable batteries
Frames and Carriers	Frames and carriers ensure comfortable wearing of MR devices and can be designed to minimize fatigue or movement restrictions	Headset systems and belts for attaching devices, ergonomic stands
Computer systems and Server Farms	Complex MR applications and services may require powerful computing systems and server farms for computing power and data processing	Powerful computers, server equipment

Based on Table 2, we can conclude that if we want to implement MR in the educational process, we must choose a display device [36]. An overview of the most commonly used headset systems is shown in Fig. 1.

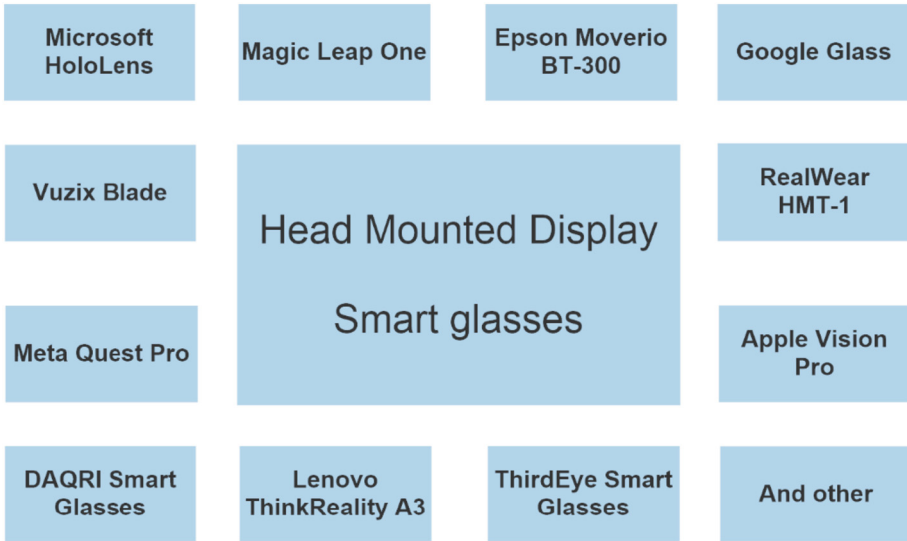


Fig. 1. Headset systems for MR

2.3 MR Implementation Methodology

It includes a series of steps and procedures that are necessary for the successful development and deployment of MR applications [37]. This methodology is often agile and iterative, emphasizing testing and getting user feedback throughout the process [38, 39]. The simplified algorithm includes the phases shown in Fig. 2.

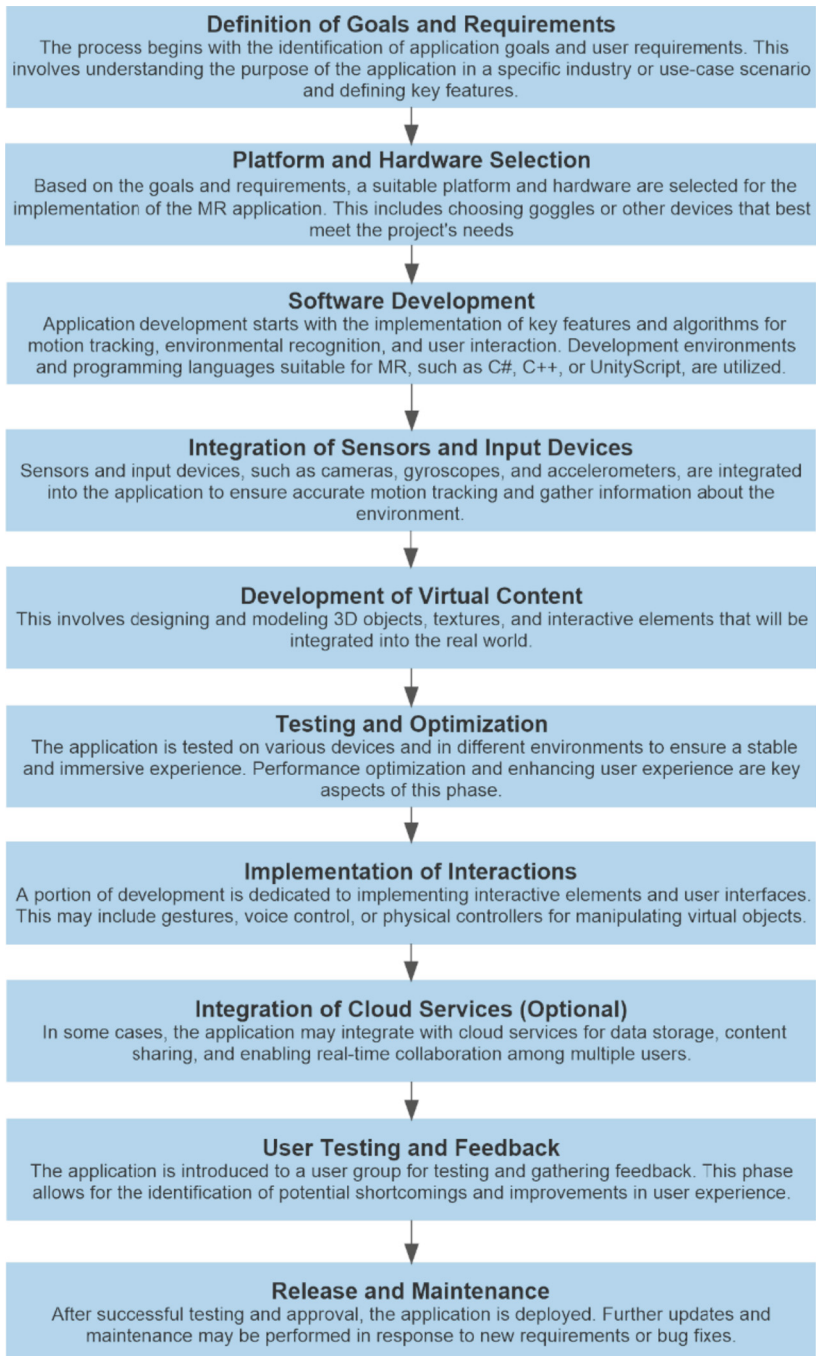


Fig. 2. Structured methodology for the creation and implementation of MR

3 Results

If we want to evaluate the created methodology, we must realize that the use of mixed reality (MR) in the education of students at universities in the context of Industry 5.0 represents a revolutionary approach that transforms traditional educational methods.

As part of Industry 5.0, where modern technologies, automation and digital transformation are integrated, MR opens up new possibilities for interactive and practical education. Through MR applications, students can simulate complex production processes, analyze digital data in real time and work with advanced technologies, thus preparing for the demanding challenges of modern industry (see Fig. 3). For example, in engineering, students could create 3D models and simulate engineering solutions in an environment that matches real industrial settings. They could also experience practical maintenance and repair scenarios in simulated production facilities through MR.



Fig. 3. Examples of current use of MR in industry

This form of education not only stimulates active participation and increased engagement of students, but also allows a safe environment for error experiences and experimentation. All in all, MR in the education of university students in Industry 5.0 represents an innovative tool that not only emphasizes theoretical knowledge, but also enables practical preparation for the diverse and dynamic challenges of the current industrial sector. Therefore, we want to analyze the main aspects of the use of mixed reality (MR) in the context of modern industry. In the field of education, we can use MR for various areas shown in Fig. 4.

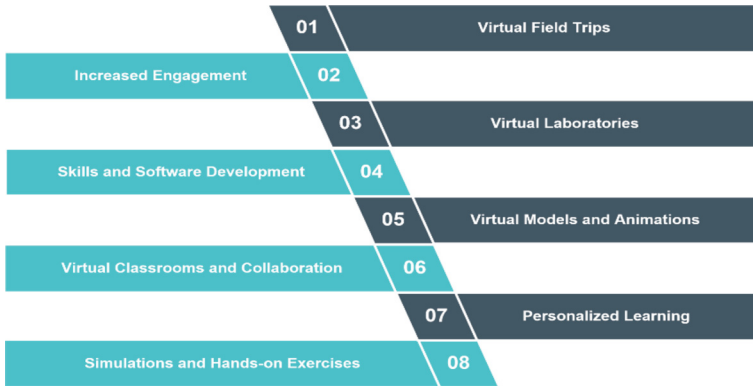


Fig. 4. The use of MR in education

Mixed reality (MR) can be used in the educational process in a variety of ways and offers students new and interactive learning experiences. Some options include virtual field trips, which allow students to visit historic sites, laboratories, museums, or other locations in a virtual environment without a physical presence, providing access to educational content that might otherwise be unavailable. MR makes it possible to create simulations for different fields such as medicine, engineering or the military, allowing students to practice different skills in a safe and simulated environment. Interactive elements of mixed reality can motivate and increase student engagement through visual and auditory cues, making learning material more interesting and memorable. In science and technology, MR can provide access to virtual laboratories where students can experiment and observe real scientific phenomena. It can also be used to create 3D models, animations and interactive visualizations, improving the understanding of abstract concepts. Virtual classrooms and collaboration in MR allow students and teachers to communicate, collaborate, share information and solve problems in real time regardless of geographic location. MR can facilitate personalized learning experiences tailored to individual student needs and learning styles. In addition, it promotes skill development and software expertise by allowing students to work with specialized software in a simulated environment. In language learning, MR can be used to improve communication skills through interaction with virtual characters and scenarios. The integration of mixed reality into the educational process offers students new and innovative learning opportunities that improve understanding and interest in the subject matter. For the sake of a comprehensive view, we must return to the scientific, technological, pedagogical and economic aspects of this problem.

In the context of education in Industry 5.0, MR plays a key role in creating authentic and immersive learning experiences. MR offers the ability to simulate complex industrial scenarios and environments, allowing students hands-on and interactive experiences in a safe and controlled environment. In this way, MR has the potential to create a bridge between theoretical education and practical training, thereby effectively responding to the needs of Industry 5.0.

One of the main questions is the effectiveness of MR in achieving educational goals. We can claim that research indicates that students who used MR achieved better results in knowledge, skills and practical abilities compared to traditional methods of education. This effectiveness is supported not only by quantitative data, but also by qualitative feedback from students and instructors who emphasize the immersive nature of MR.

The disadvantage is especially the economic aspect of MR implementation in industrial training programs. Taking into account the costs of technology, software development and professional training of personnel, today MR is unprofitable. We will see the huge potential in long-term benefits after the return of investments, with an emphasis on how MR can contribute to better preparation of the workforce in Industry 5.0.

An important point is also the future MR using in the industrial education of students. Today's generation of students spends a lot of time on mobile phones, and headsets represent the next level of mobile display unit. Future technological innovations may strengthen the role of MR in industry. This can create a market demand for the readiness of students to master the basics of technology and knowledge about MR.

All in all, MR represents a valuable and prospective educational tool in Industry 5.0. The combination of authentic learning experiences, better efficiency and prospective economic benefits underlines its key role in the current industrial context.

4 Conclusion

Mixed Reality (MR) has proven to be a revolutionary educational tool within Industry 5.0, providing unique and immersive learning opportunities for university students. In the course of this analysis, we have shown that MR not only creates a bridge between physical and virtual environments, but also profoundly affects the way education adapts to the dynamic needs of modern industry.

Its contributions in the pedagogical process are far reaching. MR stimulates the active engagement of students who can interact with virtual scenarios and experiment with advanced technologies, creating authentic learning experiences. The visual, auditory, and tactile aspects of MR make abstract concepts concrete, promoting deeper understanding and retention of information. MR software and hardware tools complement the pedagogical process, allowing students to simulate a real work environment and solve practical problems. In this way, MR not only increases the quality of education, but also effectively contributes to the preparation of students for following challenges and innovations in Industry 5.0. At the same time, however, we recognize that with these benefits come challenges, such as technological limitations and the costs of MR implementation. Nevertheless, it cannot be denied that MR represents an inherent element of modern education that reflects the needs of the digital and automated industrial environment.

The conclusion of this article shows us that MR is indeed a key educational tool in Industry 5.0. Its importance in the education and preparation of students for future work challenges in the industrial sector is evident and is still evolving. In order to preserve the relevance and effectiveness of MR in the pedagogical process, it is important to continue to monitor technological developments and adapt educational strategies to the needs of the ever-changing Industry 5.0

Acknowledgements. This work was supported by the projects VEGA 1/0268/22, KEGA 038TUKE-4/2022 granted by the Ministry of Education, Science, Research and Sport of the Slovak Republic.

References



1. Medyński, D., et al.: Digital standardization of lean manufacturing tools according to Industry 4.0 concept. *Appl. Sci.* **13**, 6259 (2023). <https://doi.org/10.3390/app13106259>
2. Gutiérrez, M., Vexo, F., Thalmann, D.: Mixed realities. In: *Stepping into Virtual Reality*. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-36487-7_6
3. Dragan, F., Ivascu, L., Ardelean, B.O.: Trends for manufacturing industry: a strategic roadmap toward Industry 5.0. In: Draghici, A., Ivascu, L. (eds.) *Sustainability and Innovation in Manufacturing Enterprises. Advances in Sustainability Science and Technology*, pp. 275–292. Springer, Singapore (2022). https://doi.org/10.1007/978-981-16-7365-8_11
4. Kašćak, J., Husár, J., Knapčíková, L., Trojanowska, J., Ivanov, V.: Conceptual use of augmented reality in the maintenance of manufacturing facilities. In: Trojanowska, J., Kujawińska, A., Machado, J., Pavlenko, I. (eds.) *MANUFACTURING 2022. LNME*, pp. 241–252. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-99310-8_19
5. Henriksen, B., Røstad, C.C., Thomassen, M.K.: Industry 5.0 – making it happen in the agri industry: the core product service platform. In: Kim, D.Y., von Cieminski, G., Romero, D. (eds.) *Advances in Production Management Systems. Smart Manufacturing and Logistics Systems: Turning Ideas into Action. APMS 2022. IFIP Advances in Information and Communication Technology*, vol. 663, pp. 424–431. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-16407-1_50
6. Dai, M., et al.: Research on holographic visualization verification platform for construction machinery based on mixed reality technology. *Appl. Sci.* **13**, 3692 (2023). <https://doi.org/10.3390/app13063692>
7. Abdulaziz, Q.A., et al.: Developing an IoT framework for Industry 4.0 in Malaysian SMEs: an analysis of current status, practices, and challenges. *Appl. Sci.* **13**, 3658 (2023). <https://doi.org/10.3390/app13063658>
8. Milgram, P., Colquhoun, H.W.: A taxonomy of real and virtual world display integration. *Mix. Real. Merging Real Virtual Worlds* **1–26**, 1999 (1999). <https://doi.org/10.1007/978-3-642-87512-0>
9. Tamura, H., Yamamoto, H., Katayama, A.: Mixed reality: future dreams seen at the border between real and virtual worlds. *IEEE Comput. Graph. Appl.* **21**(6), 64–70 (2001). <https://doi.org/10.1109/38.963462>
10. Su, S., Wang, R., Zhou, R., et al.: The effectiveness of virtual reality, augmented reality, and mixed reality training in total hip arthroplasty: a systematic review and meta-analysis. *J. Orthop. Surg. Res.* **18**, 121 (2023). <https://doi.org/10.1186/s13018-023-03604-z>
11. Skarbez, R., Smith, M., Whitton, M.C.: Revisiting Milgram and Kishino’s reality-virtuality continuum. *Front. Virtual Real.* **2**, 647997 (2021). <https://doi.org/10.3389/frvir.2021.647997>
12. Hönig, W., Milanes, C., Scaria, L., Phan, T., Bolas, M., Ayanian, N.: Mixed reality for robotics. In: *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Hamburg, Germany, 2015, pp. 5382–5387 (2015). <https://doi.org/10.1109/IROS.2015.7354138>
13. Coutrix, C., Nigay, L.: Mixed reality: a model of mixed interaction. In *Proceedings of the Working Conference on Advanced Visual Interfaces (AVI 2006)*, pp. 43–50. Association for Computing Machinery, New York (2006) <https://doi.org/10.1145/1133265.1133274>

14. Heimo, O.I., Sakari, L., Säntti, T., Lehtonen, T.: Mixed reality for industry? an empirical user experience study. In: Bi, Y., Bhatia, R., Kapoor, S. (eds.) *IntelliSys 2019*. AISC, vol. 1038, pp. 241–253. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-29513-4_17
15. Moser, T., Hohlagschwandtner, M., Kormann-Hainzl, G., Pözlbauer, S., Wolfartsberger, J.: Mixed reality applications in industry: challenges and research areas. In: Winkler, D., Biff, S., Bergsmann, J. (eds.) *SWQD 2019*. LNBIP, vol. 338, pp. 95–105. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-05767-1_7
16. Holly, F., et al.: Gaining impact with mixed reality in industry – a sustainable approach. In *Proceedings of the 2022 8th International Conference on Computer Technology Applications (ICCTA 2022)*, pp. 128–134. Association for Computing Machinery, New York (2022). <https://doi.org/10.1145/3543712.3543729>
17. Hain, V., Hajtmanek, R.: Mixed reality in the presentation of industrial heritage development. In: *IntechOpen* (2020). <https://doi.org/10.5772/intechopen.92645>
18. Golubkin, A., Pirmagomedov, R.: Analytical review of augmented and mixed reality systems in the context of Industry 4.0. *Telecom IT 4*, 1–27 (2021). <https://doi.org/10.31854/2307-1303-2021-9-4-1-27>
19. Watkins, D., et al.: Using workspace to implement digital twins in the mixed reality lab. In: *MODSIM2021, 24th International Congress on Modelling and Simulation* (2021). <https://doi.org/10.36334/modsim.2021.c1.watkins>
20. Guo, Q.: Learning in a Mixed Reality System in the Context of, Industrie 4.0. *J. Techn. Educ. (JOTED)* **3**(2), 92–115 (2015). <https://doi.org/10.48513/joted.v3i2.60>
21. Juraschek, M., Büth, L., Posselt, G., Herrmann, C.: Mixed reality in learning factories. *Procedia Manuf.* **23**, 153–158 (2018). <https://doi.org/10.1016/j.promfg.2018.04.009>
22. Alnagrat, A.J.A., Ismail, R.C., Idrus, S.Z.S.: Extended reality (XR) in virtual laboratories: a review of challenges and future training directions. In: *Journal of Physics: Conference Series*, vol. 1874, no. 1, p. 012031. IOP Publishing (2021). <https://doi.org/10.1088/1742-6596/1874/1/012031>
23. Chen, S.C., Duh, H.: Mixed reality in education: recent developments and future trends. In: *2018 IEEE 18th International Conference on Advanced Learning Technologies (ICALT)*, Mumbai, India, pp. 367–371 (2018) <https://doi.org/10.1109/ICALT.2018.00092>
24. Birt, J., Cowling, M.: Toward future mixed reality learning spaces for steam education. *Int. J. Innov. Sci. Math. Educ.* **25**, 1–16 (2017)
25. Pridhvi Krishna, M.V., Mehta, S., Verma, S., Rane, S.: Mixed reality in smart computing education system. In: *2018 International Conference on Smart Systems and Inventive Technology (ICSSIT)*, Tirunelveli, India (2018). <https://doi.org/10.1109/ICSSIT.2018.8748813>
26. Kujawińska, A., Diering, M.: The impact of the organization of the visual inspection process on its effectiveness. *Int. J. Adv. Manuf. Technol.* **112**, 1295–1306 (2021). <https://doi.org/10.1007/s00170-020-06543-9>
27. Diering, M., Dyczkowski, K., Hamrol, A.: Rating system analysis in quality engineering based on fuzzy similarity. *J. Multiple-Valued Logic Soft Comput.* **32**(3–4), 277–292 (2019)
28. Husár, J., Dupláková, D.: Evaluation of foreign languages teaching in LMS conditions by facility and discrimination index. *TEM J.* **5**, 44 (2016). <https://doi.org/10.18421/TEM51-07>
29. Cheng, J.C., Chen, K., Chen, W.: State-of-the-Art review on mixed reality applications in the AECO industry. *J. Constr. Eng. Manag.-ASCE* **146**, 03119009 (2020). [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001749](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001749)
30. Santoso, H.B., Baroroh, D.K., Darmawan, A.: Future application of multisensory mixed reality in the human cyber—physical system. *South Afr. J. Ind. Eng.* **32**(4), 44–56 (2021). <https://doi.org/10.7166/32-4-2551>
31. Husár, J., Knapčíková, L.: Implementation of augmented reality in smart engineering manufacturing: literature review. *Mobile Netw. Appl.* (2023). <https://doi.org/10.1007/s11036-023-02121-x>

32. Trojanowska, J., Żywicki, K., Varela, M.L.R., Machado, J.: Shortening changeover time—an industrial study. In: 10th Iberian Conference on Information Systems and Technologies (CISTI), pp. 1–6 (2015). <https://doi.org/10.1109/CISTI.2015.7170373>
33. Shim, J., Yang, Y., Kang, N., et al.: Gesture-based interactive augmented reality content authoring system using HMD. *Virtual Real.* **20**, 57–69 (2016). <https://doi.org/10.1007/s10055-016-0282-z>
34. Brunzini, A., Papetti, A., Messi, D., et al.: A comprehensive method to design and assess mixed reality simulations. *Virtual Real.* **26**, 1257–1275 (2022). <https://doi.org/10.1007/s10055-022-00632-8>
35. Peraković, D., Periša, M., Sente, R.E.: Information and communication technologies within industry 4.0 concept. In: Ivanov, V., et al. (eds.) *DSMIE 2018. LNME*, pp. 127–134. Springer, Cham (2019). https://doi.org/10.1007/978-3-319-93587-4_14
36. Tokorova, M., et al.: Augmented reality as a support tool in machining process. *Tem J.* **9**(1), 407–411 (2020). <https://doi.org/10.18421/TEM91-56>
37. Varela, M.L.R., et al.: Collaborative paradigm for single-machine scheduling under just-in-time principles: total holding-tardiness cost problem. *Manag. Prod. Eng. Rev.* **9**(1), 90–103 (2018). <https://doi.org/10.24425/119404>
38. Kascak, J., et al.: Implementation of augmented reality into the training and educational process in order to support spatial perception in technical documentation. In: *IEEE 6th International Conference on Industrial Engineering and Applications (ICIEA)*, pp. 583–587. IEEE, Tokio (2019). <https://doi.org/10.1109/IEA.2019.8715120>
39. Husár, J., Hrehova, S., Trojanowski, P., Wojciechowski, S., Kolos, V.: Perspectives of lean management using the Poka Yoke method. In: Ivanov, V., Trojanowska, J., Pavlenko, I., Rauch, E., Piteř, J. (eds.) *Advances in Design, Simulation and Manufacturing VI. DSMIE 2023. Lecture Notes in Mechanical Engineering*, pp. 121–131. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-32767-4_12



Lean Manufacturing in Digital Transformation of Manufacture

Agnieszka Terelak-Tymczyna^(✉)  and Beata Niesterowicz 

West Pomeranian University of Technology in Szczecin, Szczecin, Poland
aterelak@zut.edu.pl

Abstract. The development of innovative Industry 4.0 technologies and widespread digitalization have enabled manufacturers to find innovative ways to optimize production operations. One way to assess the transformation of an enterprise is the ADMA method, which involves assessing the digital maturity of the factory. The audit carried out as part of the creation of the company's roadmap aims to determine its maturity in seven areas. The roadmap recommends technologies for each transformation area and the benefits that can be obtained from their use. Various Lean Manufacturing methods can be significant at each of these stages. The article assigns Lean Manufacturing methods to each transformation, which support the development of the company in their area. Based on a literature review 15 Lean Manufacturing methods were selected, such as: Hoshin Kanri, 5S, Single-minute exchange of dies (SMED), Total Productive Maintenance (TPM), Kaizen, Modern QFD, Standardization, Plan For Every Person, Training Within Industry (TWI), Value Stream Map (VSM)/MAKIGAMI, POKA-YOKE, System PULL, One-Piece Flow, Just-in-Time (JIT), Heijunka.

Keywords: Industry 4.0 · Lean Manufacturing · ADMA method · digital transformation · digital lean

1 Introduction

Nowadays, competition between the economies of the world drives the development of their industries. Therefore, costs, product quality as well as the time of their production and delivery are becoming more and more important. The concept of Lean Manufacturing fits perfectly into this trend and is one of the commonly used methods to increase production efficiency. Lean Manufacturing focuses on optimizing production by delivering things in the right quantity to the right places at the best time to minimize waste and implement workflow. The most commonly used Lean tools are Hoshin Kanri, 5S, single-minute exchange of dies (SMED), Total Productive Maintenance (TPM), Kaizen, Value Stream Map (VSM), Just-in-Time (JIT) [6].

In recent years, the development of technologies related to Industry 4.0 has had a particular impact on the development and use of Lean Manufacturing methods [9]. The Fourth Industrial Revolution is based on the development of automation, i.e. communication of industrial systems and devices in order to obtain data allowing for the

optimization of work and processes [7]. It includes technologies such as the industrial Internet of Things (IIoT), cloud, edge computing and digital twins, as well as other defining concepts such as machine-to-machine (M2M) communications and cyber-physical systems (CPS) technologies [5, 7]. These innovative technologies support increasing efficiency at every stage of the production process.

Implementation of Industry 4.0 means integrating new technologies with existing Lean Manufacturing systems [2, 4, 8, 10, 12, 13, 15–17]. As a result of this integration, new tools are created to help increase production efficiency, called Lean 4.0 [3, 11, 13]. These methods are based on innovative technologies and are proving to be more advantageous than those adopted so far. However, also existing methods can be successfully used to develop a digital factory.

One of the methods of assessing an enterprise's readiness to implement digitalization-related transformations is conducting an audit according to Advanced Manufacturing (ADMA) recommendations [1]. This audit aims to assess the factory's digital maturity in seven areas: Transformation of Advanced Manufacturing Technologies, Digital Factory, Eco Factory, End-to-End Engineering, Human-Oriented Organization, Intelligent Manufacturing and Value Chain Oriented Open Factory.

Transformation of Advanced Manufacturing Technologies involves the use of state-of-the-art industrial equipment in factories. Factories of the Future develop their own special devices used in key stages of production and, as a result, have unique equipment.

Second transformation is when the companies use digital technologies to transform developed products and processes into real products, systems or services. All employees are supported by digital and integrated processes. Digital information flow control ensures simulation of virtual scenarios before real actions are implemented. The digital factory ensures the validity, certainty and precision of data collected in real time.

The next transformation involves the creation of Eco Factory. Sustainable production includes a flexible production system based on the availability of raw materials and auxiliary materials. Such systems are able to close the material cycle in order to optimize the efficiency of raw material consumption. The goal of the production system is to reduce energy consumption and use renewable energy sources.

The fourth transformation - End-to-End Engineering - manufacturers from the SME sector analyze customer expectations and use them as a key development factor and a starting point for all new solutions and processes. This transformation results in optimization of processes and the maximization of benefits in terms of design, production and use. Robust, high-quality products, production processes and service delivery are the result of a cross-functional and cross-functional approach to design.

The next – Human-Centered Organization - this transformation assumes that employee involvement in the company's development is very important. Individual factory workers are properly motivated and supported to fully use their talent, creativity and initiative to achieve the best possible results. The employer also enables them to develop competences and skills.

Smart manufacturing transformation can be defined as a combination of the intelligent use of human capabilities, the intelligent use of technology and the implementation

of a (self-learning) production system. The aim is to achieve maximum efficiency, flexibility and creation of new values for machine operators and workers on the production floor.

The last transformation is Value Chain Oriented Open Factory. The highest quality innovations and the most comprehensive technologies are increasingly introduced by self-organizing networks. Networks are interconnected organizations that generate, acquire and integrate specific knowledge and skills in order to co-create new solutions, products and/or technologies. Factories are evolving from single players to networked organizations that share both risk and capital.

The result of the audit is a roadmap that is a starting point for planning further steps in the digital transformation process. The report includes recommendations on the use of tools and technologies for each of the transformation areas and the benefits that can be obtained from their use. Among these tools, many Lean Manufacturing methods can be successfully used. In this article, Lean methods are assigned to individual transformations, which can be used to develop the company in appropriate areas.

2 Research Problem

Digitization of enterprises is not only the implementation of modern digital technologies, but also the optimization and improvement of both management and production processes.

One of the methodologies used to verify the level of digital maturity of the organization is the ADMA method. This method evaluates the company in terms of 7 transformations.

The authors of the article noted that in addition to the digitization process itself, the ways of optimization and improvement are also evaluated during the ADMA scan of the company. According to literature review [2, 3, 7, 10, 12, 13, 15, 16] new, especial digital technologies are implemented with existing Lean Manufacturing systems [2, 4, 8, 10, 12, 13, 15, 16]. In article [10] authors shown that to increase production efficiency and develop a digital factory a new tools are created, but also existing methods are successfully used.

3 Results

Optimization and continuous improvement are the basis of each of the techniques used in Lean Manufacturing. The principle of operation of these techniques is based on the PDCA (Plan-Do-Check-Act) cycle, which by its nature leads to the improvement of processes in the organization. To show the connections between the ADMA methodology and the implemented Lean Management techniques, an “L” matrix diagram was used. The diagram presented in Fig. 1 shows the connection of selected Lean Management techniques with individual digital transformations of the organization, consistent with the ADMA methodology.

Based on a literature review in the field of Lean Management and the ADMA methodology, the authors selected 15 techniques that are applicable and related to 7 transformations. These techniques included: Hoshin Kanri, 5S, SMED, TPM, Kaizen, Modern

ADMA	Chosen methods used in Lean Management														
	Hoshin Kanri	5S	SMED	TPM	KAIZEN	Modern QFD/Blitz QFD®	Standardization	Plan For Every Person	TWI	VSM/MAKIGAMI	POKA-YOKE	System PULL	One-Piece Flow	JiT	Heijunka
Transformation 1: Advanced Manufacturing Technologies	✓	✓	✓	✓	✓										
Transformation 2: Digital Factory	✓						✓								
Transformation 3: Eco Factory	✓						✓								
Transformation 4: End-to-End Engineering					✓	✓	✓				✓	✓	✓	✓	
Transformation 5: Human-Centered Organization	✓				✓			✓	✓						
Transformation 6: Intelligent Manufacturing	✓	✓	✓	✓	✓		✓			✓	✓	✓	✓	✓	✓
Transformation 7: Value Chain Oriented Open Factory	✓									✓					✓

Fig. 1. Matrix of connections between selected Lean Management methods and Digital Transformations in the ADMA methodology

QFD, Standardization, Plan For Every Person, TWI, VSM/MAKIGAMI, POKA-YOKE, System PULL, One-Piece Flow, JiT, Heijunka. For each of the techniques, the connection with individual transformations was determined based on their characteristics.

3.1 Transformation 1: Advanced Manufacturing Technologies

For transformation 1: Advanced Manufacturing Technologies, connections were defined between 5 Lean Management techniques, such as:

1. Hoshin Kanri - a management process that adapts the functions and activities of the organization to its strategic goals. As part of the process, a detailed plan is developed - usually annual - with precise goals, activities, schedule, responsibilities and metrics. The basic principles that guide this technique are [Guidelines for Policy Management JSQC-Std 33-001 (E):2017]:
 - Leadership: Purpose and direction should be unified, understood and applied by all employees. A transparent investment policy is implemented that corresponds to the strategic vision.
 - Catchball: Formulation of company policy takes place with close cooperation at the vertical and organizational level and with the participation of key participants in the process.
 - Priority approach: Planning focuses on the highest priority factors. Factors that have less impact on strategy are ignored when formulating policy.
 - Total people involvement: All members of the organization must be aware of their role in the organization and must actively participate in activities to achieve its goals. Employees have qualifications appropriate to operate advanced production technologies.
 - Process orientation: Importance is given not only to goals, but also to the process (understood as a means) that leads to them.

- Evidence-based management: When formulating policy, ensure that quantitative targets result from evidence-based analysis. The rapid pace of technology evolution makes it necessary to collect information and build knowledge to support investment decisions.
2. 5S - 5 steps containing a set of methods and tools aimed at establishing and maintaining high-quality workplaces, taking into account the principles of ergonomics that affect employees' health, safety and quality of work.
 3. SMED - (Single Minute Exchange of Die) a set of techniques and tools that allow for shortening the time of retooling machines, devices and production processes. The use of this method allows you to raise the standards of organizing the retooling workstation by organizing the process and all equipment related to retooling. Reducing changeover times increases the flexibility of production processes and allows for shorter order fulfillment times.
 4. TPM – (Total Productive Maintenance) allows for the creation of cooperation between maintenance and production. Under the method, operators are responsible for the maintenance of machines and devices (autonomous maintenance), and maintenance staff are responsible for planned maintenance. Cooperation organized in this way allows for improving the efficiency of even heavily used machinery and significantly reducing threats to production continuity such as failures or unplanned downtime. Improving work organization, designing and observing maintenance standards, an effective employee training system and the work improvement process allow for achieving a high level of Overall Equipment Effectiveness (OEE).
 5. KAIZEN - continuous improvement in every area of all company processes allows for building a culture based on knowledge and effective use of all company resources, in particular strengthening the potential of the company's own machinery.

3.2 Transformation 2: Digital Factory

As part of the Transformation 2: Digital Factory, the use of two Lean Management techniques was indicated:

1. Hoshin Kanri – in the context of taking into account information security management and digitalization in planning the enterprise strategy. In particular, this applies to taking into account in development plans:
 - modern digital technologies, including digital twins that will allow direct collection and exchange of data between production processes and use them for optimization and decision-making in real time;
 - using digital solutions and tools to support employees in their daily tasks;
 - implementation of information security and event management (SIEM) systems that guarantee the smoothness of production operations;
 - integration of ICT applications and digital connection of entire supply chains.
2. Standardization - in the context of creating standards related to data exchange, creating digital connections, and the method of exchanging information.

3.3 Transformation 3: Eco Factory

For Transformation 3: Eco Factory, similarly to Transformation 2, a link is indicated for:

1. Hoshin Kanri – in the context of taking into account environmental management and energy management in the planning of the company’s strategy. In particular, this applies to taking into account in development plans:
 - reducing the consumption of materials, energy, fuel, water and the amount of waste and emissions in production processes by optimizing production processes and manufactured products, using materials and energy recovery methods;
 - collecting current data on the impact of activities on the environment;
 - application of business processes and management systems that will ensure minimization of the impact of the company’s activities on the environment;
 - using innovative, ecological technologies in product design, industrial processes and logistics.
2. Standardization – in the context of active compliance with both existing and new rules, regulations and standards. Introducing standards related to responsible and sustainable development of processes and products.

3.4 Transformation 4: End-To-End Engineering

Transformation 4: End-to-End Engineering, focuses mainly on analyzing customer expectations and treating it as a development factor and a starting point for all new solutions and processes. In this context, companies should use the technique Blitz QFD®/Modern QFD.

The Blitz QFD®/Modern QFD is a process, that has nine steps and no matrices (although it may lead to matrices, such as the “House of Quality” matrix shown behind step 9).

The complete course of action in modern QFD consists of the following stages:

1. Determining the scope of the project.
2. Customer segmentation.
3. Customer process analysis.
4. Visit to the client’s gemba.
5. Analysis of customer needs.
6. Structuring the customer’s needs.
7. Analysis of the structure of customer needs.
8. Prioritization of customer needs.
9. Development of the client’s most important needs.

This method allows you to obtain products and services designed in accordance with customer expectations.

Other Lean Management techniques that may be helpful in implementing the 4 transformations may be:

1. Standardization - in order to ensure reliability and predictability, digitally supported product and process engineering standards are created. Preventive and corrective actions, product and service changes, transfer processes and production performance tests are documented and incorporated into key performance indicators for new products, processes and services.

2. Kaizen - The principles of continuous improvement are applied to both manufacturing and engineering processes. Every employee is open to new and better ways of working and is committed to continuous progress.
3. POKA-YOKE – designing products that are designed in a way that ensures their safety and failure-free operation.
4. PULL system, One-Piece Flow, JiT - to ensure production enabling the scheduling and production of products in accordance with customer orders and commissioning production for a specific order.

3.5 Transformation 5: Human-Centered Organization

Employee involvement in the company's development is an extremely important goal of Transformation 5: Human-Centered Organization. As part of this transformation, individual factory workers must be transformed into work groups with autonomy and space to fully utilize their talent, creativity and initiative (in the context of an innovative organization). The organization provides an approach to the systematic development of competences and talents through tools such as **Plan For Every Person**.

Individual employees can work on their development through various teaching techniques and are supported in assessing possible development paths. Experiences gained are disseminated through various methods, ensuring knowledge accumulation. For this purpose, you can use the **TWI - Training Within Industry** technique, which is a program supporting the development of management skills among experienced operational employees and low- and middle-level supervisors.

Hoshin Kanri and **Kaizen** techniques are also related to activities within this transformation.

Hoshin Kanri – as part of developing a strategic plan, the company should:

- provide a specific translation of goals for each team, so that teams receive tasks in areas that they can influence, implement and improve through their own initiatives;
- stimulate the company to be flexible and change-oriented. Leaders should actively promote the drive to grow by openly communicating future opportunities;
- present a clear and repeatable vision to everyone;
- define development paths for all employees;
- ensure open communication.

Kazien is the continuous improvement of the organization by employees who are open to changes. As part of the Kazien program, a plan for continuous improvement of the organization should be developed, employees should be supported in implementing their ideas and an environment open to cooperation and the activities of quality circles should be created.

3.6 Transformation 6: Intelligent Manufacturing

Intelligent production, which is the basis of Transformation 6 in the ADMA method, is a combination of the intelligent use of human knowledge and competences, intelligent technologies and the implementation of an intelligent production system. Due to the Transformation goal of achieving maximum efficiency and flexibility and creating new

values for machine operators and workers on the production floor, most of the selected Lean Management techniques are related. The use of techniques that directly improve the flexibility of production processes was selected, such as: **5S, SMED, TPM, KAIZEN**. In order to ensure quick response and adaptation to changing orders from customers, it is proposed to introduce: **PULL System, One-Piece Flow, JiT and Heijunka**. To ensure high quality of manufactured products and to fulfill First Time Right orders, it was proposed to introduce the **POKA-YOKE** method. Additionally, to eliminate waste in production processes and increase their flexibility, the value stream in processes should be mapped, for which we will use the **VSM or MAKIGAMI** technique.

However, the use of **Hoshin Kanri** will allow you to define KPIs tailored to production processes and ensure the reliability of data collected in real time, which will allow you to monitor, estimate and improve the company's performance.

3.7 Transformation 7: Value Chain Oriented Open Factory

As part of the last 7 transformation including the Value Chain Oriented Open Factory, it was proposed to implement 3 Lean Management techniques: Hoshin Kanri, TWI and VSM.

As part of Hoshin Kanri – the company should identify all stakeholders beyond the needs of the customer and supplier. Additionally, the company's strategy should include identifying and actively participating in innovation networks for a given industry.

TWI should be used not only within the plant, but also taking into account the transfer of knowledge and learning throughout the entire supply chain and innovation network.

Value stream mapping (VSM) performed for the entire supply chain will allow us to identify links that need to be improved and those from which we can obtain valuable information.

4 Discussion

The article presents the connections between the use of Lean Management methods and the ADMA method. Based on a literature review 15 Lean methods were selected, which are most applicable in each of the seven transformations of the ADMA method. These techniques included: Hoshin Kanri, 5S, SMED, TPM, Kaizen, Modern QFD, Standardization, Plan For Every Person, TWI, VSM/MAKIGAMI, POKA-YOKE, System PULL, One-Piece Flow, JiT, Heijunka. Based on the characteristics of each Lean method, was determined the connection with 7 transformations defined in ADMA method. The most widely used of Lean methods is Hoshin Kanri, because it involves developing an organizational strategy including production plans and new technologies, process orientation, leadership, total people involvement, building culture of organization. Another tool with the widest application is Kaizen and standardization. Standardization refers to four transformations: Digital Factory, Eco Factory, End-to-End Engineering, Intelligent Manufacturing, within which great emphasis is placed on developing standards related to the digitization of production processes, energy management systems and environmental standards related to technical documentation of products and standardization of

workstations and production processes. Kaizen, on the other hand, refers to continuous improvement in terms of improving production processes, machinery, products and employee development. The transformation in which we can use the most Lean Management methods is the sixth transformation - Intelligent Manufacturing. This is due to the fact that the basis of Lean Management itself is the elimination of waste in production processes, by increasing the efficiency and flexibility of these processes, building an organizational culture and creating new values for machine operators and workers on the production floor, that favors the development of the enterprise, which is the basis of the sixth transformation.

The proposals for using individual Lean methods in increasing the level of digital maturity of an enterprise presented in the article are consistent with the results presented in the literature relating to Lean 4.0 [10] and indicating the connection between the implementation of Lean methods in the implementation of the Industry 4.0 concept [2, 3, 7, 9, 11–14].

5 Conclusions

The topic of applying Lean Management methods in the context of increasing the digital maturity of an enterprise, presented in the article, in accordance with the ADMA methodology, is very important for the development of SME sector companies towards Industry 4.0. The implementation of Lean Management methods allows the company to achieve a higher level of digital maturity.

To sum up, the implementation of a wider range of Lean methods in the company allows the company to be more open to changes, including in the field of digital solutions, by:

- defining a transparent investment policy,
- increasing the flexibility of the enterprise,
- improving the efficiency of even heavily used machinery and significantly reducing threats to production continuity such as failures or unplanned downtime,
- improvement of work organization,
- design and compliance with maintenance standards,
- effective employee training system,
- continuous improvement in every area of all company processes
- increasing employees' awareness of their role in the organization
- using digital solutions and tools to support employees in their daily tasks;
- implementation of information security and event management (SIEM) systems that guarantee the smoothness of production operations;
- integration of ICT applications and digital connection of entire supply chains
- collecting current data from processes,
- the use of innovative, ecological technologies in product design, industrial processes and logistics.
- focusing on the analysis of customer expectations and treating it as a development factor and a starting point for all new solutions and processes
- employee involvement in continuous progress,
- ensuring high quality of manufactured products and fulfilling orders first time right.

References

1. ADMA Homepage. <http://www.adma.ec>. Accessed 20 Nov 2023
2. Buer, S.V., Strandhagen, J.O., Chan, F.T.S.: The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda. *Int. J. Prod.* **56**(8), 2924–2940 (2018)
3. Bueno, A., et al.: Lean 4.0 implementation frameworks: proposition using a multi-method research approach. *Int. J. of Prod. Econ.* **264**, 108988 (2023)
4. Gallo, T., Cagnetti, C., Silvestri, C., Ruggieri, A.: Industry 4.0 tools in lean production: a systematic literature review. *Procedia Comput. Sci.* **180**, 394–403 (2021)
5. Kovacs, G., Kot, S.: New logistics and production trends as the effect of global economy changes. *Pol. J. Manag. Stud.* **14**, 115–126 (2016)
6. Kumar, N., et al.: Lean manufacturing techniques and its implementation: A review. *Materials Today Proceedings* **64**(3), 1188–1192 (2022)
7. Lasi, H., Fettke, P., Kemper, H.G., Feld, T., Hoffmann, M.: Industry 4.0. *Bus. Inf. Syst. Eng.* **6**, 239–242 (2014)
8. Naciri, L., et al.: Lean and industry 4.0: a leading harmony. *Procedia Comput. Sci.* **200**, 394–406 (2022)
9. Nedjwa, E., Bertrand, R., Boudemagh, S.: Impacts of Industry 4.0 technologies on Lean management tools: a bibliometric analysis. *Int. J. Interact. Des. Manuf.* **16**, 135–150 (2022)
10. Nunes, M.L., Pereira, A.C., Alves, A.C.: Smart products development approaches for Industry 4.0. *Procedia Manuf.* **13**, 1215–1222 (2017)
11. Powell, D.J., Romero, D.: Digital lean manufacturing: a literature review. In: 2021 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Singapore, pp. 659–662 (2021)
12. Schumacher, S., Bildstein, A., Bauernhansl, T.: The impact of the digital transformation on lean production systems. *Procedia CIRP* **93**, 783–788 (2020)
13. Silvestri, L., Gallo, T., Silvestri, C.: Which tools are needed to implement Lean Production in an Industry 4.0 environment? Literature review. *Procedia Comput. Sci.* **200**, 1766–1777 (2022)
14. Solheim, A.B., Powell, D.J.: A learning roadmap for digital lean manufacturing. In: Lalic, B., Majstorovic, V., Marjanovic, U., von Cieminski, G., Romero, D. (eds.) APMS 2020. IAICT, vol. 592, pp. 417–424. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-57997-5_48
15. Tortorella, G.L., Fogliatto, F.S., Cauchick-Miguel, P.A., Kurnia, S., Jurburg, D.: Integration of Industry 4.0 technologies into total productive maintenance practices. *Int. J. Prod. Econ.* **240**, 108224 (2021)
16. Hossain, M.M., Purdy, G.: Integration of Industry 4.0 into lean production systems: a systematic literature review. *Manuf. Lett.* **35**, 1347–1357 (2023)
17. Valero, M.R., Newman, S.T., Nassehi, A.: Link4Smart: a new framework for smart manufacturing linking Industry 4.0 relevant technologies. *Procedia CIRP* **107**, 1594–1599 (2022)



The Scenario Approach to the Concept of Maintenance of Technical Systems of Urban Engineering

Andrzej Loska¹ , Waldemar Paszkowski¹ , and Robert Waszkowski² 

¹ Silesian University of Technology, Gliwice, Poland
{andrzej.loska,waldemar.paszowski}@polsl.pl

² Military University of Technology, Warszawa, Poland
robert.waszkowski@wat.edu.pl

Abstract. The work includes an overview of the possibilities and needs for implementing the exploitation decision-making process regarding the subsystems of the urban engineering system in the conditions of implementation and operation of the SmartCity concept. Based on discussions on key operational problems, in the first part of the article, the SmartMaintenance concept was proposed. Its implementation allows to maintain the exploitation potential of technical systems at an appropriate level. The second part of the article includes a proposal of scenario method as a solution of exploitation policy modeling problem. Scenarios and computer support tools built on this basis enable effective assessment of the implementation of exploitation processes, which is particularly important in long-term conditions of significant decision uncertainty. A set of supporting tools has been developed to implement the SmartMaintenance concept proposed and described in the article. The final part of the article describes the operation of one of the most important such tools - the SMOPE. This tool helps create scenarios and also contains mathematical algorithms to evaluate them.

Keywords: Scenarios · SmartCity · Exploitation · Maintenance · Decision-Making Process · Exploitation Events · Exploitation Processes

1 An Introduction

The development of urban agglomerations is now increasingly carried out taking into account the SmartCity concept. This concept involves the use of appropriate methods and tools, both technical (engineering, IT) and non-technical (organizational, economic, social), whose intended effects are the sustainable development of the urban community [4, 10].

The use of innovative, advanced methods and tools in this area allows for the development and implementation of the concept of smart cities. They are characterized by, among others: high safety, effective communication system, reliable utility supplies, etc. Research and tool solutions are focused on [5, 15]:

- creation and development of methods and tools supporting the activities of city services and residents themselves, usually focusing on several areas, such as delivery and remote measurement of utilities, transport and road traffic, or lighting, and other,
- integration methods and tools for developed and implemented intelligent subsystems, in two aspects: the tool aspect and the information/IT aspect,
- implementing and testing methods and tools in a given urban center, and then supervising their proper exploitation.

The idea of a smart city brings great benefits for residents, there are also technical problems, that require special attention both at the stage of their creation and during operation in the urban environment. A key aspect that requires attention is the process of wear and tear of the parts of the implemented devices, which directly reduces the level of reliability of exploited systems (Fig. 1).

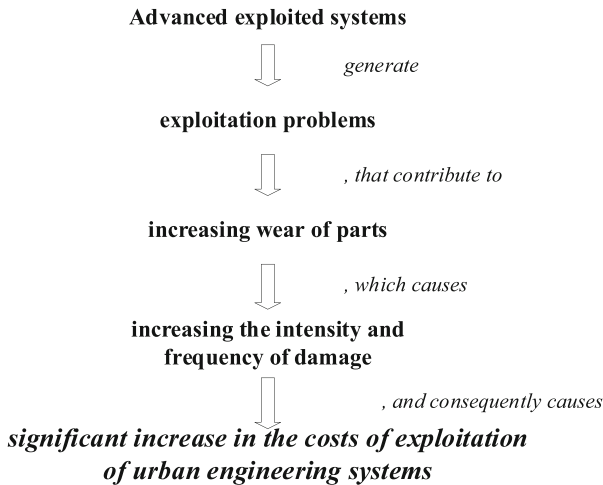


Fig. 1. The importance of exploitation problems in the development and implementation of innovative exploited technical systems [13].

The use of technologically advanced exploited systems generates, often unrecognized operational, maintenance and repair problems. This increases the wear and tear of individual components and, as a result, causes damage (unintentional events). The consequence of such a series of situations is an increase in the costs of exploited solutions, considered both in the economic and social context [1, 12].

The above conditions show the multi-aspect nature of the functioning of urban engineering devices, which cannot focus only on the benefits resulting from meeting the needs of users/residents. Engineering activities should also take into account unfavorable aspects of the use of urban engineering systems, such as aging and wear of individual elements, as well as errors in operator tasks [2]. The above arguments resulting from both the analysis and assessment of exploitation problems, as well as the multi-aspect nature of the issues discussed, became the basis for the authors to undertake research aimed at developing a methodology for modeling the decision-making process regarding the

operation of urban engineering systems, reflected in the long-term horizon. In particular, the aim of the undertaken research is to develop methods and tools that will answer the question: What decisions should be made today to ensure that the maximum exploitation potential is maintained in the future? The direct specific purpose of this article is to identify and review existing knowledge resources useful in the discussed field, as well as to present the already developed concept and partial tool solutions prepared so far.

2 Assumptions of the SmartMaintenance Concept

The research undertaken was based on the assumption that it was necessary to take into account the key features of the maintenance strategy in the construction and application of the developed urban engineering systems. This makes it necessary to develop and follow the principles of a rational exploitation policy, which should be based on assumptions based on optimization, taking into account technical, organizational, economic and normative and legal criteria [6, 13].

The authors propose the use of a concept in this area called SmartMaintenance. This concept is intended to provide comprehensive support for operational activities, taking into account both aspects related to the operation of urban engineering devices and technical services performing traffic maintenance tasks.

The SmartMaintenance concept within a SmartCity idea is presented in Fig. 2.

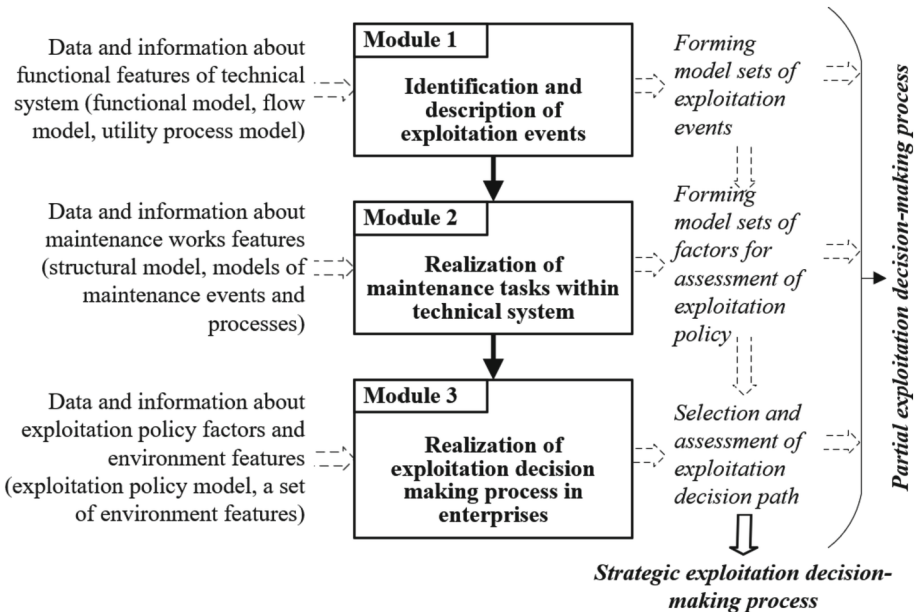


Fig. 2. The SmartMaintenance concept within a SmartCity idea [13].

The proposed SmartMaintenance concept includes three modules that refer to subsequent stages of identification and maintain of events and exploitation processes.

In this regard, we can distinguish:

1. Module 1 is a representation of tasks relating directly to exploitation events. It is assumed that an exploitation event is a state change between two classes of states. Therefore, developed models of the exploitation events should be based on the collection of:
 - data regarding the features of the state of objects along with the boundary conditions of state changes,
 - information about borderline circumstances of state changes (causes, course and effects of operational events).
2. Module 2 is a representation of tasks relating directly to exploitation processes. It is assumed that the exploitation process is, identified and ordered in time, a set of events. In this context, this module focuses directly on methods and tools for implementing and supporting operate and maintenance activities. The result of the identification and analytical tasks within this module is a set of time-dependent models of exploitation processes (diagnostic or reliability oriented). Such models should constitute the basis for developing the exploitation policy implemented in relation to the analyzed urban engineering systems.
3. Module 3 is a representation of tasks related to maintenance management. This module focuses on taking into account the features resulting from the identification and processing within modules 1 and 2 and their consolidation within the exploitation policy. The result of such ordering should be a set of guidelines for making decisions regarding both the operation of urban engineering devices and the activities of maintenance tasks.

The implementation of the decision-making process reflected in operational and maintenance activities can be considered in the context of two interrelated directions:

1. Horizontal paths in Fig. 2. These directions represent the implementation and decision support of exploitation tasks. Tasks located in this area are characterized by individuality in relation to both the object/component and the scope of implementation. Examples of tasks, that can be located on one of three paths of this type are: identification of the course and/or cause of failure, analysis of repair costs, assessment of the impact of increasing the frequency of inspections on the value of the availability index of the analyzed urban engineering device.
2. Vertical paths in Fig. 2. This direction represents the implementation of operational processes consistent with the adopted operational strategy. The tasks located in this area are characterized by comprehensiveness and organizational, technical and economic completeness in terms of the operational policy for the technical system of urban engineering. Examples of tasks that can be located in this area are: shaping the features of the operational strategy for the urban engineering system, building and assessing a set of scenarios for the development of the exploitation policy in the long-term perspective. Efficient implementation of decisions regarding the exploitation of the integrated urban engineering technical infrastructure system is the result of the synthesis of information regarding the functionality of all subsystems (modules).

The SmartMaintenance concept built in this way, allows for shaping and improving elements of the exploitation policy. In this way, it can be an organizational and technical tool for controlling and improving the reliability of urban engineering systems and their components. At the same time, imperfections and limitations can be noticed, which affect possible difficulties in applying the SmartMaintenance concept in a comprehensive form:

- high dispersion of information in available and used support systems, caused by lack of compatibility of the tools used, which are a source of information about events and exploitation processes,
- incomplete information and tool connections between individual exploitation decision (e.g. separate systems supporting identification, diagnostic, maintenance and repair tasks),
- insufficient consideration of the exploitation specificity of particular devices, as well as analytical methods and tools to support exploitation analyzes in the long term horizon.

The methods and tools used in practice, in the discussed task area, limit the possibility of using data about objects, events and processes, which are collected and processed on an ongoing basis during the operation of devices of urban engineering systems.

The methods and tools used in the discussed area do not allow full use of the information collected about objects, events and maintenance processes for the purposes of implementing the exploitation decision-making process. In the context of conducted research, there is a need to focus on analytical and decision aspects and to approach the developed methods and tools in terms of practical applications.

3 Selected Exploitation Decision-Making Problems

The key issue of operation, both in the theoretical-model and practical-industrial aspects, is the problem of making optimal decisions, the effects of which concern the used and operated technical facilities and also have a considerable influence on the participants and resources of the implemented exploitation processes⁸. It results from the assumptions of decision theory and, on the other hand, the specificity of the relationship between worker and a technical object, which is reflected in the methodology of the basis for the construction and exploitation of machines and devices, as well as the practice of industrial conditions of their operation.

The scope of decision-making problems in the operation of urban engineering devices is well recognized. The subject of selection usually concerns the shaping of features, that influence the technical and organizational environment on the operation of individual devices during their exploitation. Cyclical nature of exploitation processes makes decision-making problems predictable and repeatable. In particular, key decision-making problems arise from the constant desire to increase equipment operating periods and reducing downtime periods, while maintaining a high level of quality of works performed. Decisions made in this regard concern both engineering, organizational and economic aspects that de-fine the exploitation conditions for urban engineering devices in a specific location. This approach means that the specificity of exploitation decision problems is shaped by features that concern the variability of certain (predetermined) and uncertain features in the context of observing the results of the decision made (Fig. 3).

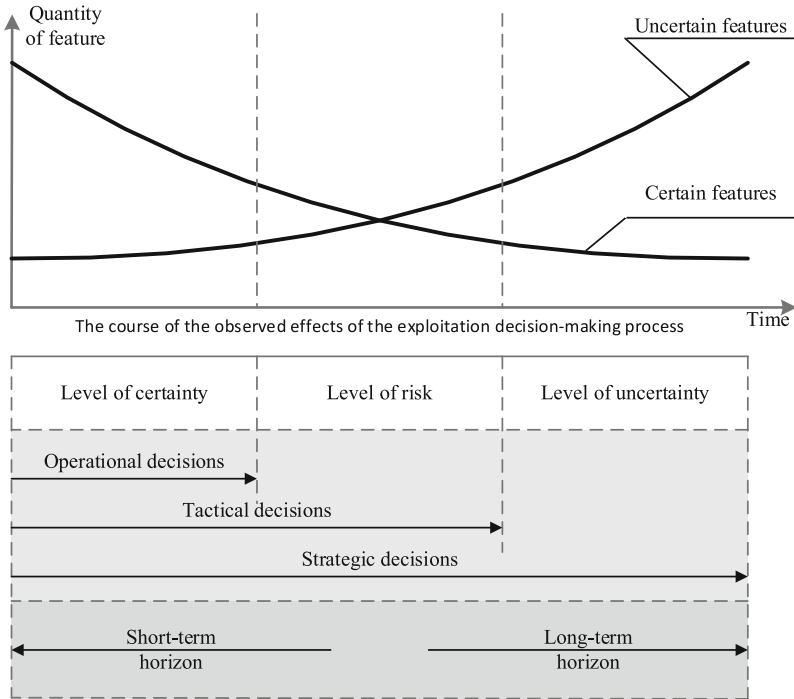


Fig. 3. The course and scope of changes of characteristics of the observed effects/consequences of exploitation decisions [13].

4 Scenario Methods in the SmartMaintenance Concept

One of the ways to solve the decision-making exploitation problems of the SmartMaintenance concept, described in the previous point, may be the use of scenario methods for modeling future exploitation variants, which will allow for the assessment and implementation of decision-making process in the long-term exploitation horizon.

Future variant modeling involves developing assumptions and images for the purpose of describe how events will unfold in a period well ahead of the current moment.

This is intended to optimally prepare and implement the decision basis by identifying and supervising the course of changes of specific features of devices and exploitation processes.

Within future modeling methods, two opposing concepts can be distinguished, where the scenario could be [11, 14, 17]:

- the forecast, which is the result of math processing as quantitative and computational form in nature,
- the vision, which is the result of a search for future characteristics, as unmeasurable descriptions and facts; a good vision is concise and comprehensible, but lacks measurability and unambiguity.

The industrial exploitation specificity described in the previous point justifies the construction of scenario models taking into account both the features that are the subject of forecasting and the descriptions that are the subject of creating a vision. The forecast may be an input element for an exploitation scenario project. In particular, the input should include a set of data and information describing the main goals of the scenario project. In addition, conclusions resulting from the procedures for developing scenarios and their verification in the area of industrial practice, in the context of the possible behavior of a selected technical object or the functioning of a maintenance organization, require reliable test data, which in this aspect should be quantitative forecasts. In turn, the vision may be one of the elements of the exit from the exploitation scenario project - showing, in a simple and understandable way to the operators-recipient, the effect of the potential events and situations showed in individual scenarios.

5 Scenario Methods and Tools in the Aspect of Exploitation Issues

The practical effect of the scenario modeling process should be a set of recommendations that respond to potential events that may occur in the exploitation cycle. This set is most often built as part of the script process, carried out according to an adopted methodology. Such a process is cyclical and iterative rather than linear and single.

There is considerable freedom and interpretative diversity in the aspects of modeling future variants, which contributed to the creation of many methods and techniques used in the implementation of scenario procedures. In this respect, three key scenario concepts can be distinguished, susceptible to modeling exploitation problems, in particular:

1. The concept of intuitive logic, which brings together those methods and procedures in which the generation of future variants is the result of a creative thinking process, based on the knowledge and experience of the participants of the scenario team based on the experience and opinions of people creating the scenario team. In this area, there are SRI, GBN, TAIDA and PBSS models [3, 7, 11].
2. The La Prospective concept, the assumptions of which are consistent with the assumptions of the intuitive logic concept, but subsequent stages are supported by mathematical models and IT tools [6, 14].
3. A probabilistic concept that is related to statistical analysis. The basis of this method is the simultaneous or separate use of two methods: the TIA (Trend Impact Analysis) and the CIA (Cross Impact Analysis) [9, 18].

6 The Way of Implementing the Exploitation Scenario Procedure in Accordance with the SmartMaintenance Concept

In the aspect of the large spectrum of ways, that can be used to exploitation scenario modeling the exploitation future (presented in the previous point), a method (course) of implementing the scenario procedure was developed, common to each of the above-mentioned concept (Fig. 4).

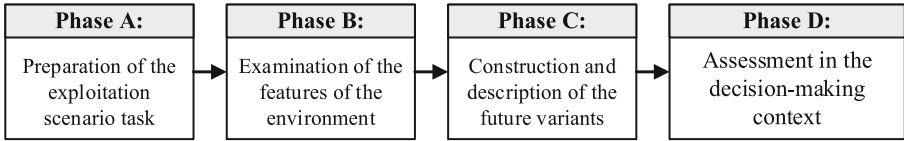


Fig. 4. Method of building and implementing the exploitation scenario procedure [11]

6.1 Phase A: Preparation of the Exploitation Scenario Task

Phase A is, on the one hand, of an orderly nature and, on the other hand, of a formal nature. The orderly nature is manifested in the need to determine the parameters of the scenario procedure, such as: target time of the analysis, methods and tools used, scope of resources. The formal nature concerns the specification of the main scenario problem, based on the identification and characteristics of the analyzed case. The main scenario problem, often expressed in the form of a focal question, is the time point, to which the effects of the scenario procedure relate.

6.2 Phase B: Examination of the Exploitation Features of the Scenario Environment

Phase B involves the identification of those features and their values that refer to both the operating conditions of the analyzed object or organization and the context of such functioning. In this case we are talking about:

- the so-called external and internal environment, or closer or further environment. The identified features, which, depending on the methodological approach, may be qualitative or quantitative, are subject to processing in order to select.
- the so-called main driving forces, among the identified external features.
- the so-called main key factors, among the identified internal features.

The result of phase B is a set of features in the form of driving forces and trends, organized using methods and tools, the selection of which is individual and adequate to the adopted goal and scope of the scenario project.

6.3 Phase C: Construction and Description of the Future Exploitation Variants

This phase is the most empirical of all phases of the scenario project. This phase involves generating and verifying a set of environmental factors, based on the features identified in phase B, and then developing a model (schematic) and narrative form of scenarios (Fig. 5). The goals set in this phase are achieved in several ways, depending on the selected or defined methodology and tool capabilities, including:

- identification of a clearly defined number of scenarios (most often - four), by selecting and differentiating several (two or three) features, that, in the analyzed conditions, show a high level of uncertainty and have a high impact on the analyzed problem,
- generating scenarios as a result of a combination of features (environmental factors), and then limiting their number in the ranking process, based on the expert assessment, or determined probability measures.

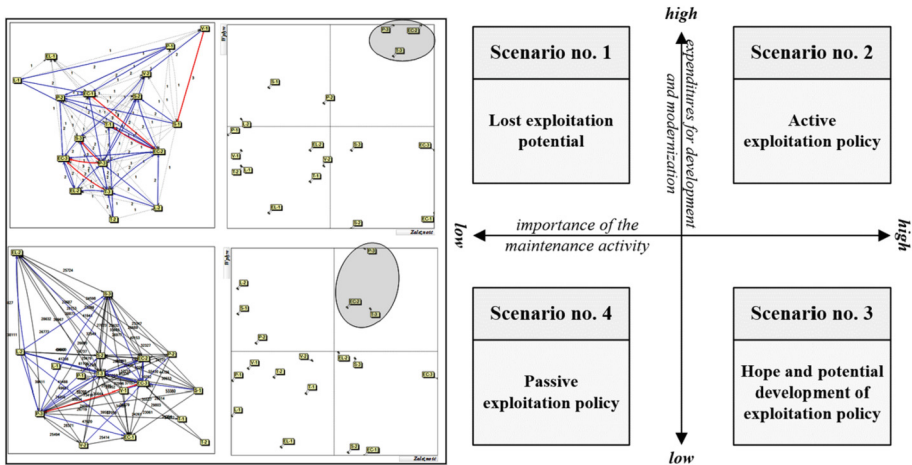


Fig. 5. An example layout of four scenarios [6].

The task concluding phase C may be to develop images of the expected future, which are called scenario content, visions of the future, or plots. This is done by conducting a process of logical and credible narration, within three aspects: the title, the course of possible events and credible and understandable end results. The content of the scenario is an extension and interpretation of the identified possible images of the future, which, using assumed narrative forms and character traits, should provide answers to the questions.

- A. What could the image of the organization under consideration or the course of the analyzed phenomenon look like in the assumed time window?
- B. What situations might be needed to achieve the result?
- C. What entities and factors may influence the assumed course of events?

6.4 Phase D: Assessment of the Decision-Making Context

This phase is transformation of a creative and rather abstract approach into practical implementation of defined guidelines in relation to the organization's strategic intentions and requirements. The great diversity of fields and areas in which scenario modeling is attempted, as well as the specificity of the analyzed problems in organizations, means that this phase is characterized by particular individualization within individual approaches and concepts. The author's analysis of classic model scenario procedures, supplemented by verification of case studies, showed that the tasks in this phase can be assigned to one of two groups:

1. Assessment of developed scenarios in the light of organizational assumptions and requirements. Such an assessment involves confirming the logical correctness as well as the compliance of the developed possible future events and situations with the laws and general principles of the surrounding real world (e.g. the laws of physics). According to the author, the most useful concepts for implementing such an assessment include: analysis and assessment of the problem in the environment of individual

scenarios, i.e. the so-called wind tunnel, trials of the future [14], analysis of the scenario learning process, i.e. examining the influence of scenarios on possibilities of organizational changes, or a subjective (survey) assessment of satisfaction and practical usefulness of scenario models in the organization or in the aspect of the situation under consideration.

2. Assessment of the effects and/or consequences of decisions for the organization. Such an assessment involves identifying the degree of coherence and correlation of the current key features of the organization's functioning with the assumptions of individual scenarios. This allows, on the one hand, to monitor changes in the actual picture of the situation and correct decisions in the direction previously determined and considered correct, and on the other hand, it allows for possible preparation for difficult and uncertain situations in given spatial and temporal conditions [16]. For the purposes of implementing such an assessment, it is necessary to define quantitative measures, which may take the form of the so-called leading indicators and signposts, i.e. early warning indicators regarding changes in driving forces, trends and maintaining direction.

Scenario assessment, which is the last stage of the procedure, is of key importance for decisions made and actions taken on this basis, as well as for possible effects observed at an expected or given point in time in the future.

The scenario assessment model should:

- aim to select a scenario for implementation,
- enable the determination of the potential of the exploitation policy of technical system, at the initial moment of applying the scenario,
- enable the assessment of the potential of the technical system at any time during its exploitation,
- enable the assessment of the convergence of changes in the exploitation policy in the context of the developed scenarios,
- enable modification of scenario assumptions during the development of the exploitation situation and changes in the characteristics of the operated technical object,
- be based primarily on the model, whose results are quantitative, and this allows for mutual comparison of scenarios, as well as relating the features of the scenarios to the features of the operational policy.

From a mathematical point of view, the assessment of scenarios should be adapted to the assessment of the operational policy (exploitation potential) implemented for the selected technical system. In this regard, there are several possibilities:

1. Use of assessment methods derived from scenario applications. Key scenario concepts, in addition to descriptions of scenario construction procedures, also include proposals for evaluation measures. For example, the CIA (Cross Impact Analysis) or TIA (Trend Impact Analysis) methods mentioned in point 5 are directly mathematical and refer directly to statistical models that should be used in the assessment of the developed scenarios. It is also possible to use quantitative variant methods, which are built on the basis of expert assessments, which are then objectified in the area of constructed trees or networks. Examples of methods belonging to this group are AHP (Analytical Hierarchy Process) and Delphi [6].

2. Use of assessment methods derived from exploitation applications. Exploitation assessment methods make it possible to determine the exploitation potential and, above all, changes in this potential of a technical system during its working. In this respect, two groups of measures can be identified:
 - diagnostic measures, which are a set of features (usually in the form of time series) as a result of observing selected symptoms,
 - exploitation measures, which are a set of indicators, as a result of the observation of selected events and exploitation processes.

In the discussed area, the exploitation measures seem to be particularly important and valuable. They take into account not only changes in the features of the object, but also organizational and economic changes in the environment of the operated technical system. The specificity of many exploitation indicators (including MTBF, OEE and KPI), as well as their reliability (statistical) nature, are more directly adapted to the specificity of the scenario structure.

7 Scenario Module of Exploitation Policy

A key practical aspect of the scenario methodology is the possibility and need for computer support of selected tasks of the developed procedure. An example of a supporting tool is the SMOPE system, which is an important part of the research. The diagram of structural and functional connections of SMOPE parts is shown in Fig. 6.

SMOPE's mission is to:

- possibility of effective implementation of the exploitation policy modeling methodology and the exploitation scenario modeling methodology,
- supplementing the scenario procedure with analytical solutions,
- verification (confirmation) of the correctness of the developed models and procedures.

The concept of the SMOPE module directly reflects the course of calculations and the visualization of their results carried out within the scenario methodology. It is a tool built in object-oriented technology, which allowed defining connections between the most important elements within the source code. The objects mentioned are defined on the basis of layers separating separate structures of input data, output information and procedures.

Activities carried out using SMOPE can be divided to the three-layer system. The data layer, which in this case has the nature of a data warehouse. The idea of such a solution is based on the assumption of purposeful use of the company's existing data resources without interference or modification of the IT solutions used in the company. Therefore, the data warehouse developed using the MySQL relational database management system, through the SQL data exchange mechanisms in the SQL:2003 standard, enables ongoing collection of data that:

- can be obtained from a system supporting the handling of exploitation events and processes operating in the enterprise (CMMs/EAM class system),
- can be entered into the database directly within SMOPE, using mechanisms for building the exploitation policy and scenario models.

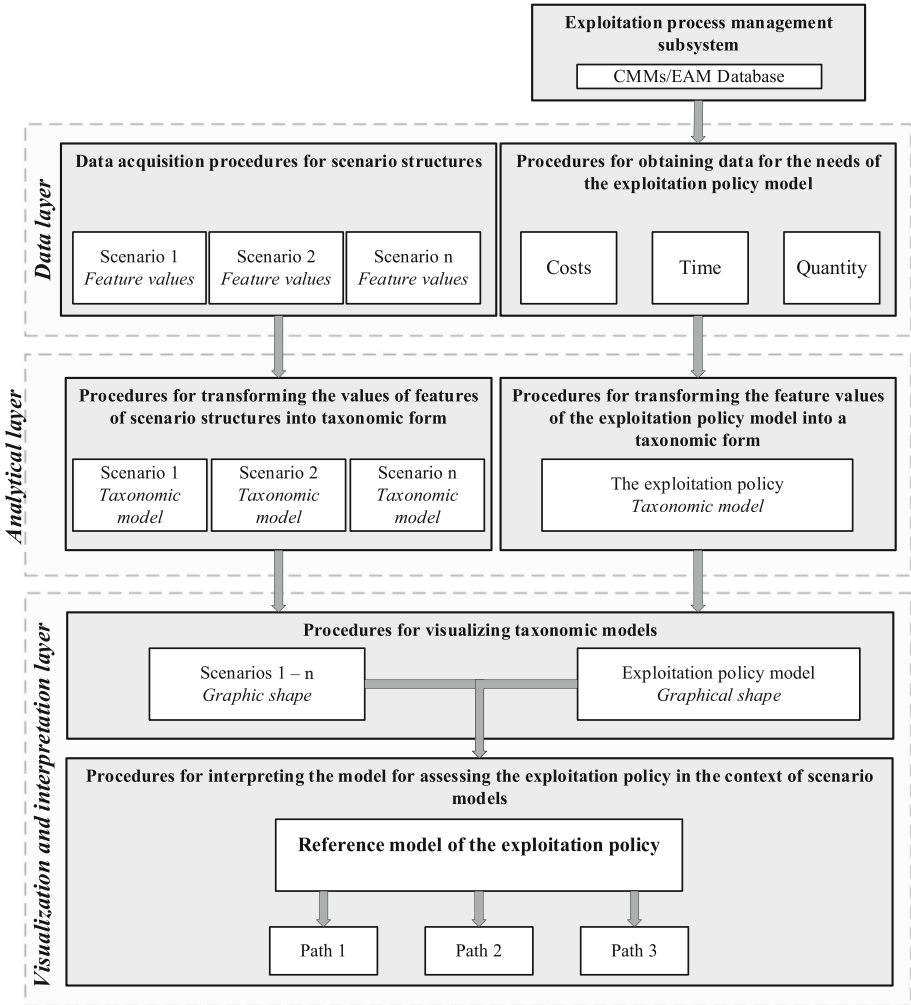


Fig. 6. Diagram of structural and functional connections in the SMOPE system [13].

In addition to the function of defining and storing the structure of built models, the tools included in the data layer enable the use of space for data and information for the purposes of conducting all calculations, storing intermediate and final results, as well as visualizing the results of conducted analyses.

The analytical layer, which in structural terms includes a set of algorithms interpreted using the PHP scripting programming language version 5.2.4. The task of the tools included in this layer is to implement procedures enabling the determination of individual taxonomic measures.

The visualization and interpretation layer is based on mechanisms developed using JavaScript, using the w2ui, jQuery libraries, CSS and HTML, allows you to generate

the results of assumptions made and calculations performed, in terms of numerical and tabular summaries, as well as graphic layouts.

8 Summary and Conclusions

This article is the result of the authors' research on the methodology of maintenance management of technical systems. It is an attempt at a synthesis covering the issues of shaping and supporting the decision-making process of exploitation of urban engineering systems using scenario techniques.

The concept of using scenario models, dedicated to the specific implementation of operational processes in conditions of significant decision uncertainty, allows for expanding the methods of shaping and assessing the operational future with methods that take into account alternative multi-threaded sets of continuous in time or discrete images of reality. Developed in this way the exploitation scenario modeling methodology, based on the resources of assumed and predicted future data on the implementation of processes, adopts a new approach to the decision-making procedures in maintenance management processes.

In order to assess the correctness and usefulness of the concept proposed in the article, a tool environment was developed - the SMOPE computer module. This module allows you to support and implement the scenario procedure according to the adopted technical and organizational assumptions.

The conducted research confirmed the possibility and validity of using scenario methods in the area of management in maintenance of machines and devices. However, according to assumptions, specificity and methodological and tool limitations, it should be noted, that:

- scenario modeling methods describe equivalent images of the exploitation future,
- exploitation scenarios are not direct maintenance tasks procedures, but constitute a set of indications for developing an exploitation policy,
- scenario modeling methods are largely uncertain, especially in the long-term perspective, therefore the created scenarios are dynamic and change discreetly over time.

It is worth noting, that although the presented solutions are considered in the content of the work in the limited context of urban engineering systems, the developed methodology is universal, which can be extended to technical systems of other classes (e.g. technical production systems or technical transport systems).

The environment of the technical system being used is important in the scenario methodology, therefore it is advisable to conduct further research on taking into account the context methods [8]. Research in this area is currently being conducted and the results will be presented in future publications.

References

1. Antosz, K., Jasiulewicz-Kaczmarek, M., Machado, J., Relich, M.: Application of Principle Component Analysis and logistic regression to support Six Sigma implementation in maintenance. *Eksploracja i Niezawodność – Maint. Reliabil.* **25**(4), 174603 (2023)

2. Górny, A.: Industry 4.0 - safety guidelines in the construction of technical devices. In: *Theory and Practice in Modern Computing: Vision 2025 in the Era of Pandemic*, 39th IBIMA Computer Science Conference, pp. 130–138 (2022)
3. Guo, J., Li, Y., Du, B.G., Wang, K.P.: Multi-objective fuzzy partial disassembly line balancing considering preventive maintenance scenarios using enhanced hybrid artificial bee colony algorithm. *Expert Syst. Appl.* **237**(Part C), 121681 (2024)
4. Gupta, N.: Smart cities challenges, technologies and trends. *Front. Big Data* **6**, 1258051 (2023)
5. Janik, A., Ryszko, A., Szafranec, M.: Scientific landscape of smart and sustainable cities literature: a bibliometric analysis. *Sustainability* **12**(3), 779 (2020)
6. Jasiulewicz-Kaczmarek, M., et al.: Application of MICMAC, Fuzzy AHP, and Fuzzy TOPSIS for evaluation of the maintenance factors affecting sustainable manufacturing. *Energies* **14**, 1436 (2021)
7. Jia, Q., Liu, Y., Ren, S., Zhu, K.Q.: Taxonomy of abstractive dialogue summarization: scenarios, approaches, and future directions. *ACM Comput. Surv.* **56**(3), 1–38 (2023)
8. Przystałka, P., Kalisch, M., Timofiejczuk, A.: Genetic optimization of meta-learning schemes for context-based fault detection. In: Timofiejczuk, A., Łazarz, B.E., Chaari, F., Burdzik, R. (eds.) *ICDT 2016*. ACM, vol. 10, pp. 287–297. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-62042-8_26
9. Kozłowski, E., Borucka, A., Oleszczuk, P., Jałowicz, T.: Evaluation of the maintenance system readiness using the semi-Markov model taking into account hidden factors. *Eksploracja i Niezawodność – Maint. Reliabil.* **25**(4), 172857 (2023)
10. Lai, C.S., et al.: A review of technical standards for smart cities. *Clean Technol.* **2**(3), 290–310 (2020)
11. Lindgren, M., Bandhold, H.: *Scenario Planning: The Link Between Future and Strategy*. Palgrave Macmillan, New York (2009)
12. Loska, A., Paszkowski, W.: Geometric approach to machine exploitation efficiency: modelling and assessment. *Eksploracja i Niezawodność – Maint. Reliabil.* **24**(1), 114–122 (2022)
13. Loska, A., Paszkowski, W.: SmartMaintenance - the concept of supporting the exploitation decision-making process in the selected technical network system. In: Burduk, A., Mazurkiewicz, D. (eds.) *ISPEM 2017*. AISC, vol. 637, pp. 64–73. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-64465-3_7
14. Ringland, G.: *Scenario Planning: Managing for the Future*. John Wiley & Sons, Ltd., Chichester (2006)
15. Stecuła, K., Olczak, P., Kamiński, P., Matuszewska, D., Duc, H.D.: Towards sustainable transport: techno-economic analysis of investing in hydrogen buses in public transport in the selected city of Poland. *Energies* **15**(24), 9456 (2022)
16. Sun, B., et al.: Failure-based sealing reliability analysis considering dynamic interval and hybrid uncertainties. *Eksploracja i Niezawodność – Maint. Reliabil.* **23**(2), 278–284 (2021)
17. Wu, Z.Y., Chen, Q.X., Mao, N., Xu, G.N., Gola, A.: Two scenario-based heuristics for stochastic shift design problem with task-based demand. *Appl. Sci.* **13**(18), 10070 (2023)
18. Zelinka, D., Amadei, B.: Systems approach for modeling interactions among the sustainable development goals part I: cross-impact network analysis. *Int. J. Syst. Dyn. Appl.* **8**(1), 23–40 (2019)



Manufacturing Line-Level Root Cause Analysis and Bottleneck Detection Using the Digital Shadow Concept and Cloud Computing

Jan Dąbrowski¹, Tomasz Bartkowiak² , Piotr Wierzchowski¹,
and Dariusz Dąbrowski¹

¹ Ilabo sp. z.o.o., Warsaw, Poland

² Poznan University of Technology, Poznan, Poland

tomasz.bartkowiak@put.poznan.pl

Abstract. The paper introduces a method for online detection of root-cause machine and bottleneck identification in manufacturing systems, aiming to enhance reliability and productivity. The study addresses the interconnected nature of manufacturing systems, emphasizing the impact of equipment faults on overall performance of the line. Existing fault propagation methods are discussed, highlighting the need for a comprehensive approach considering the entire production process. The proposed root-cause algorithm utilizes a digital shadow concept, analyzing machine states and historical data to identify the primary source of faults. The study focuses on machine workstates, distinguishing between internal and external causes, thus determining the root-cause machine affecting the entire line. A Gantt chart-based approach considers the relative timing of events, enhancing accuracy in root-cause determination. Bottleneck detection methods are presented, including analysis of active periods and an arrow method based on machine blockages and starvations. The study showcases a cloud-based system, LogiX, for real-time data processing and visualization, integrating Industry 4.0 principles. A case study evaluates the proposed methods using an 8-h shift period in a bottle filling&packaging line. Root-cause analysis achieved an 89.23% detection efficiency, demonstrating practical applicability. Bottleneck detection methods, both active period analysis and the arrow method, identified the Labeller as the potential bottleneck. In conclusion, the paper provides a valuable contribution to manufacturing system optimization, offering a systematic on-line approach to root-cause identification and bottleneck detection. The proposed methods exhibit promising results, with potential applications in enhancing overall equipment effectiveness and production efficiency.

Keywords: root-cause analysis · bottleneck · digital twin · cloud computing · industry 4.0

1 Introduction

Manufacturing systems encompass human workers, machinery, materials, and information. These systems transform resources into finished or semi-finished products [1]. Equipment, a vital component of a manufacturing line, significantly influences quality

and cost. Its reliability is crucial for a company's competitiveness. Detecting and rectifying equipment faults is a key approach to enhance reliability, necessitating understanding the failure propagation path [2, 3].

Current fault propagation methods mainly focus on individual pieces of equipment [1, 4, 5]. These methods involve qualitative or quantitative analysis of equipment faults based on causality and prior probability (such as FMEA [6], FMECA [7], and FTA [8]). They identify the root cause and propagation path by examining the physical connections among subsystems, components, or their subparts. In other words, a single fault, through these connections, can impact other subsystems, components, or subparts, leading to their breakdown or malfunction. As a result, the overall equipment performance can deteriorate, and the device may cease to function altogether. For a complex manufacturing line, single equipment becomes a node in the equipment network. If a fault occurs in any equipment, the resulting performance degradation or failure ripples forward and backward through the production process. Consequently, the upstream process accumulates work-in-process (WIP), while the downstream process experiences a shortage of WIP. This imbalance leads to a partial or complete loss of production capacity across the entire manufacturing system. The detection of the corresponding states of the equipment, i.e., blocked or starved which are the consequences of the failures of either downstream or upstream equipment is a primary concern of this study.

Identifying the root-cause equipment from which the failure propagated to the line level is a crucial aspect of finding bottlenecks in the system. The bottleneck is a process in a chain of processes, such that its limited capacity reduces the capacity of the whole chain [9]. The presence of the bottleneck leads to low throughput of the entire line and results in the asynchronous operation of all the machines [10]. There exist various methods for identifying bottlenecks in manufacturing. The first group involves the creation of a mathematical formulation of the entire process, which in most cases is either difficult or impossible for complex production system [11, 12]. Other, simulation-based techniques, entail developing a discrete-event system (DES) model of the process [13]. The advantage of this approach lies in its ability to ascertain the real-time status of machines, assess the capacity utilization of each buffer, and monitor every product moving through the system at any specific time [14]. This method also enables a comprehensive analysis of system bottlenecks and allows testing various improvement scenarios to gauge their effectiveness [15, 16]. Another group of methods is based on a close examination of buffers. In the average waiting time method, the time the product waits in the buffer before it is processed by the downstream machine is an indicator of the bottleneck. On average, the longer it takes the products to leave the buffer, the more likely the following machine is a problem. Analyzing the inter-arrival time can also help to detect the bottleneck. A bottleneck tends to be less frequently starved or blocked by other machines as there will be a queue in front of the bottleneck and an empty buffer downstream. Based on that observation, a variance of the inter-arrival time can be indicative of the potential problem as the for the non-bottleneck the material flow is disturbed (which is evident in high variance), while for the bottleneck the flow is even (low variance) [10, 17, 18]. The other group of methods involves analyzing the machine state: active or inactive periods as well as being starved or blocked. An active state for a machine is when it is either currently processing the material or it has the ability to do so (it is neither blocked nor

starved) but due to its failure, it cannot operate. The inactive periods take into account “starved” and “blocked” states [19–23].

Finding the root-cause of the problem has been recently adopted into the concept of digital twin. Papacharalampopoulos et al. developed an approach for identifying the measured values that may negatively affect the production performance by eliciting historical data with the aid of Key Performance Indicators. They showed that a digital twin for real time management of production alarms was feasible [24]. Oliveira et al. demonstrated an automated method for finding the root causes of problems in complex manufacturing systems [25].

The main purpose of this work is to demonstrate a method that allows the determination of the root-cause machine which reduces the performance at the line level. The secondary objective is to determine the bottleneck which contributes the most to the reduced performance of the manufacturing system. In the paper, we introduced a system which uses a digital representation of machines and production lines, which is based on the Industry 4.0 concept of digital shadow [26, 27]. In the presented case, the models are fed by a one-way data flow with the state of an existing physical object and a change in state of the physical object leads to a change in the digital object [28].

The paper is structured as follows: introduction with literature review, methods, results and conclusion. Methods section describes the architecture of the system and principles of the proposed root-cause algorithm. It also covers two bottleneck detection methods: active period and arrow method. Results section includes a case of the real FMCG manufacturing line. It presents the exemplary results of the root-cause analysis and the detection of the machine that is considered to be the bottleneck in the system. The summary and future work is given in the last section.

2 Methods

2.1 System Architecture

In this work, we use a self-developed cloud-based system – LogiX for on-line data registration, processing and visualization from real manufacturing equipment. The architecture of the system is briefly summarized in Fig. 1. Data acquisition begins with components installed on the edge, on premise, in the local factory network. This can be done using a proprietary LogiX Gate service (an edge connector to LogiX system) which can run on an industrial PC, Raspberry PI class device or other solution supporting JavaScript runtime. The system handles various communication protocols in parallel - Modbus, OPC, HTTP and SQL. It listens for any change in the values of input signals and sends them to the cloud-based processing. Alternatively other edge components can be used as long as they produce messages in compatible format, i.e. LogiX can consume messages originating from Microsoft IoT Edge.

Messages from the edge are in standardized JSON messages delivered from industrial standard OPC UA PubSub JSON format as specified in part 14 of the OPC UA specification or a simple JSON telemetry format with Azure Time Series Insights [29]. In the cloud, data is received by platform-managed event ingestion service - Azure IoT Hub and published to Kafka topic (Fig. 2). Messages are partitioned inside the topic based on the source publisher and processed by a cluster of LogiX Processing Engines.

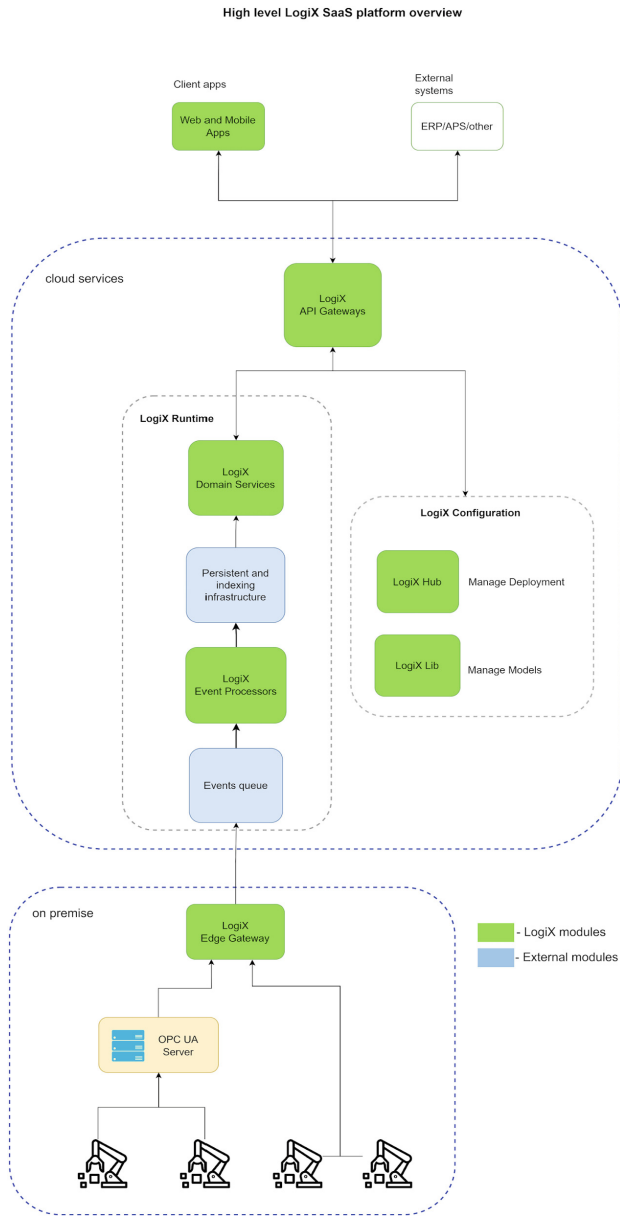


Fig. 1. Architecture of the LogiX system

It has been implemented as a state-of-the-art complex event processing engine and it is intended to process huge amounts of events in near real-time speeds. Users can configure custom rules as simple expressions or complex scripts using C# language and executed by Roslyn compiler [30].

Processing rules, signals configuration along with factory structure and supporting parameters are maintained in dedicated Domain Services (LogiX Lib and LogiX Asset Inventory). All data, both incoming raw signals and information augmented by the Processing Engine are saved in dedicated storage services: SQL Database for relational queries, Time Series for fast access to temporal data and File (blob) storage for files (i.e. video files). LogiX backend components supporting domain and client applications are decomposed into separate microservices dedicated to specialized subdomains (i.e. Production Order Management, Asset inventory, Reporting/Notifications, User Administration etc.). They are deployed as containers using Azure Kubernetes Cluster. This processing architecture is visualized in Fig. 2.

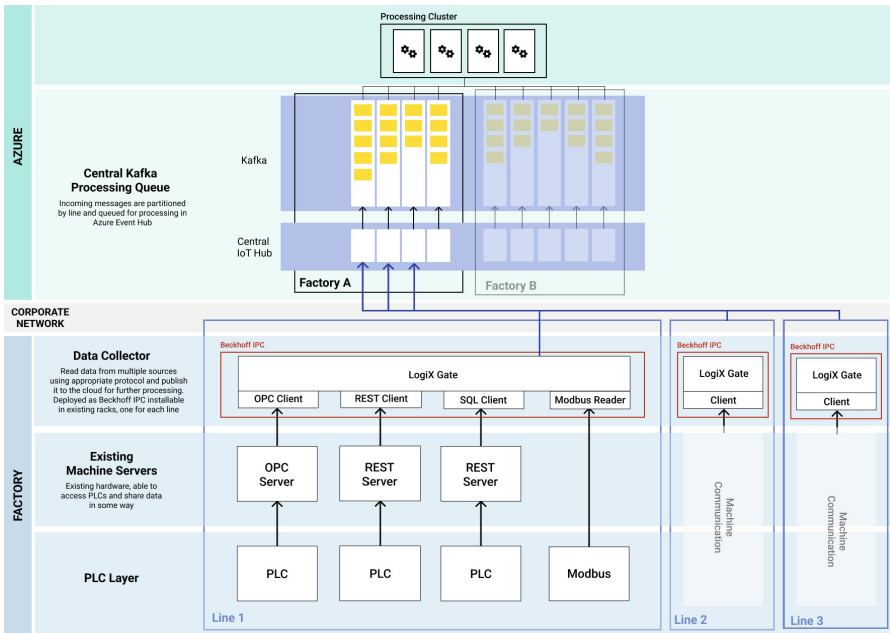


Fig. 2. Architecture of the data processing system

2.2 Root-Cause Algorithm

Finding the root cause of a line-level stop in a chain of machines requires deeper knowledge about the statuses of individual machines. In the proposed system all of the machines define two properties for each stop:

1. What is the stop on the machine itself?
2. What is the potential root cause?

We consider 3 work states of internal nature where the machine downtime was not caused by any upstream or downstream interference in the line: failure, lack of components and stop by operator.

Failure state is usually directly identified by the sensor on the machine itself or triggered internally by a machine controller. It means that something prevents the machine from normal operation (e.g. a fault of some part). Lack of Components (also called Material Shortage) state is usually also directly identified by the sensor on the machine itself. In the event of that state occurring, a machine cannot produce because some component (e.g. caps) is missing. Stop by operator state is a result of manual operator intervention in machine operation, preceded by pressing stop or safety button. It is usually done on purpose to resolve an ongoing failure. When the system spots a pattern that a failure is followed immediately by a stop by operator, the former becomes the root cause of the latter. All those three events become a potential root cause for that machine and can propagate to the others.

Holdup and Idle states occurring on the machine indicate that the root cause is outside of the machine. Holdup state appears when a machine has to stop because its subsequent buffer or machine is full or stopped. This suggests that the root cause is a downstream machine. Idle state is an event happening when a machine has to stop because its preceding buffer is empty or the previous machine is stopped, indicating that the root cause is to be sought upstream.

Considering the entire manufacturing line, each machine may at the same moment be holdup or starved or stopped by an operator or due to its internal failure or lack of material for processing. From the line perspective and in-depth analysis of OEE losses the critical is to determine the state of the base availability (BA) machine and its root cause, which is then associated with the state of the entire line [31]. This makes it important to determine what was the external cause when the base machine stops due to an upstream or downstream problem. In the proposed method a focus is given to the holdup state analysis. Nonetheless, the same mechanism can be applied for idle state, but with the opposite search direction.

To find a root cause for the holdup, we analyze all stoppages for machines downstream, and look for events which can be classified as the root cause. All of the other states are “transparent”, i.e. there is no “bouncing” the other way: if we are looking for the cause of a holdup, we never look at the machines before the BA machine even if one of the downstream machines is in the idle state. Let us consider a simple line consisting of four machines: Filler (BA machine), Capper, Labeller and Palletizer. Figure 3 shows an example of the search sequence to determine the original root cause of the Filler holdup which was caused by the failure of the Palletizer.

If there was no breakdown at this point of time, the Holdup state would not be associated with any external root cause (Fig. 4).

In order to take into account the behavior of buffers (i.e. the failure propagation requires to block the machine output which often happens when a buffer gets full) and shorter reaction times, we will take into consideration the entire period starting from the maximum reaction time (x) and ending at the moment when a stoppage began - or even a while after the stoppage started (y) which would allow detecting a situation when the machine controller did not “report” a breakdown as fast as it should have. The whole period ($x + y$) is analyzed, and the first event in this period of time will take precedence and become the root cause (Fig. 5).

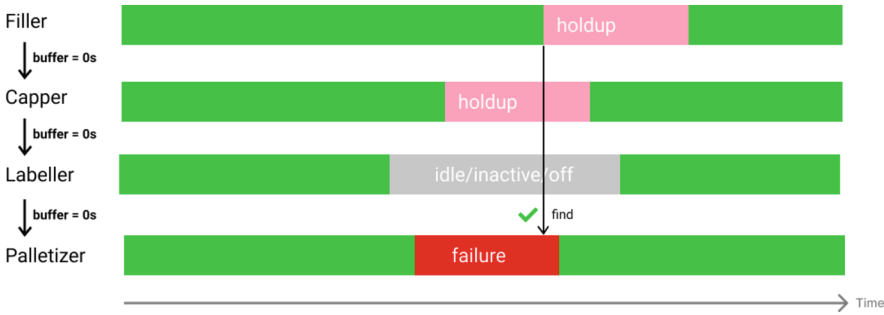


Fig. 3. Gantt chart illustrating the search sequence to determine the root cause of the hold state of the Filler – a failure of Palletizer.

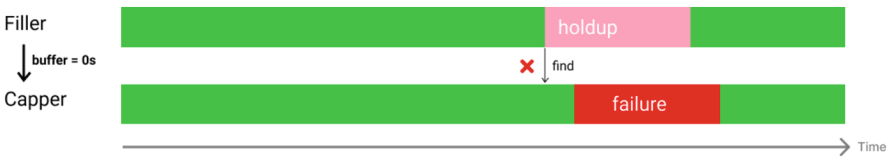


Fig. 4. Gantt chart the situation where the cause of the holdup state was not determined

In a chain of many machines, it is vital to observe the relative delay of stoppages from the beginning of the observed reaction time (marked in pink range of +1 s/+5 s in Fig. 6). Using that relative time, it is possible to indicate the stoppage that began first as the root cause because a stoppage that occurred relatively later could be a consequence of the problem rather than its cause.



Fig. 5. Gantt chart showing the situation where two potential failures happened within $x + y$ time window

The time that has passed starting from the set “reaction time” is more important than the order of machines (Fig. 6).

Specifying buffer delays is especially important when working with long lines. In that case root causes can take some time to propagate through machines. An example of two independent failures on Palletizers propagated to two separate holdup states on Filler is shown in Fig. 7.

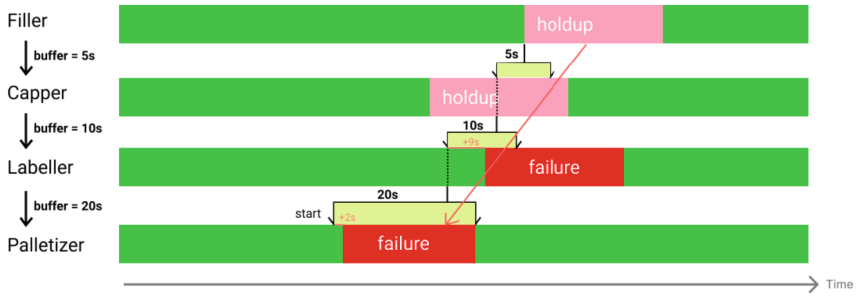


Fig. 6. Gantt chart depicting a sequence of events which were considered in the root-cause determination. Please note that failure on Labeller was not preferred as the time sequence is of higher priority than line layout

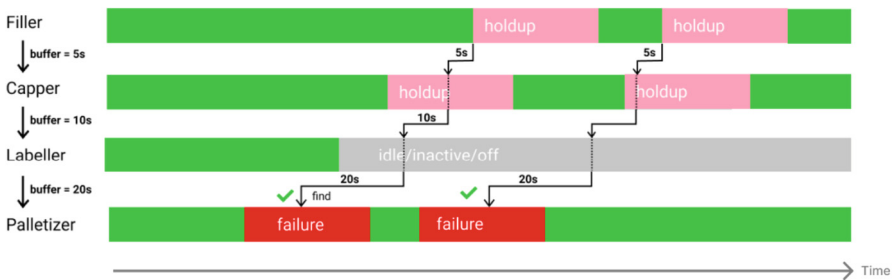


Fig. 7. Gantt chart illustrating two independent failures which propagated to Filler as two separate holdups

2.3 Bottleneck Detection

In the proposed system, two bottleneck detection methods are implemented. They both take into account the periods in which a machine is active, i.e. it is processing or it is down due to failure excluding interruption states. Those interruptions involve stopping the machine due to downstream blocking or upstream starving by other machines. The first method can either be based on examining the longest average active period or the highest percentage of active time, which are both associated with the potential bottleneck [20, 21]. In short, a machine operating at a pace closest to its own maximum capacity has very little idle capacity to use. Both approaches are briefly visualized in the form of a Gantt chart in Fig. 8 for an exemplary system consisting of three machines working in the line. Each active period is identified and either average value or the total share of active period is calculated. A potential bottleneck is associated with the machine that has the highest average active period time or its share (percentage). This method requires a history of states collected for a representative amount of time (a shift, day, or longer). On-line detection of a bottleneck at any given moment is not possible as the representative observation period is required.

In the second method, if the time the machines are blocked or starved is known, the bottleneck machine can be easily identified by comparing the numbers for each subsequent pair in the system [32]. This method derives its name from arrows which are

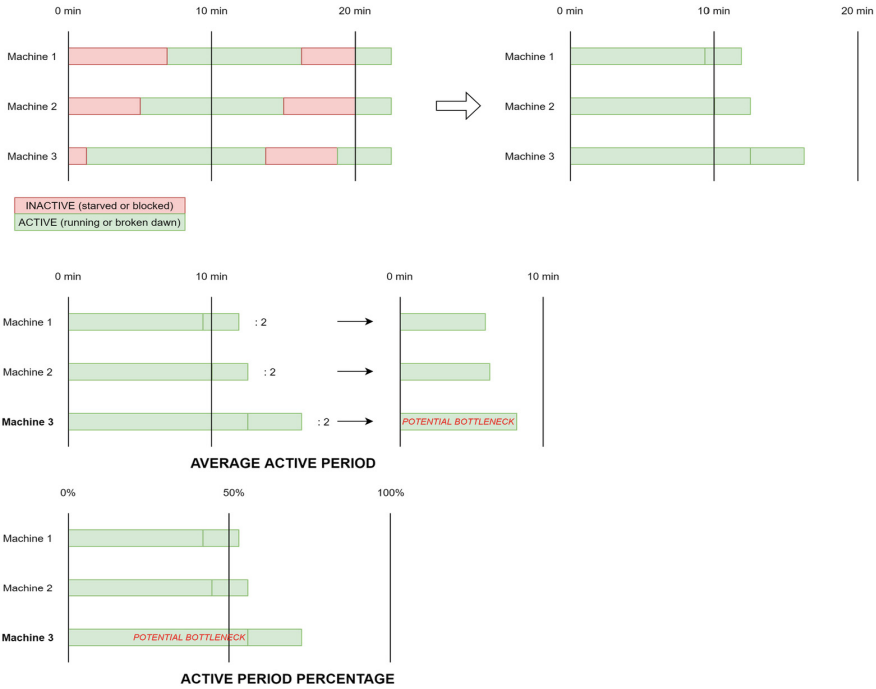


Fig. 8. Visualization of average active period and active period percentage methods

drawn from the larger to the smaller value of the blocking and starving total timeshares for every two machines. If the arrows point to the same resource, it is a potential bottleneck (Fig. 9).

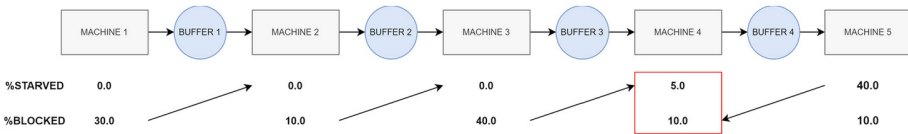


Fig. 9. Bottleneck detection with arrow method

3 Case Study

3.1 Root-Cause Analysis

The basis for the analysis was data registered over an 8 h shift period at a bottle filling&packaging line. The architecture of that line is serial. The line consists of six subsequent machines: bottle sorter, filler, plug capper, capper, labeller and packer. The machines are connected with conveyors which can accumulate products and serve as buffers. The exemplary results indicating the detection of two different root causes of the line downstate is presented in Fig. 10.



Fig. 10. Gantt chart with indicated root-cause of the problems: a) failure of labeller which propagated to all upstream machines including base machine and b) failure of bottle selector starved all downstream machines – including filler.

In the observed period, the root-cause machine was detected correctly in 58 out of 65 cases. This added up to 89.23% of detection efficiency. The performance evaluation was conducted onsite together with the industrial partner who is responsible for the daily operations of that line. The method is primarily based on the fixed propagation times between machines. Those values were assumed by trial-and-error while tuning the system and considering the most common propagation time between each machine.

3.2 Bottleneck Detection

The same observation period was considered for bottleneck detection analysis. The input data is a list of events and work states for each machine in the line, together with their timestamps. Six different states were already automatically assigned based on the implemented set of rules for the line: **failure**, **holdup**, **idle**, **lack**, **stop** and **work**. **Work**, **stop**, and **failure** are here considered as **active states**, while the others (idle, lack, and holdup) fall into the definition of **inactive**. The summary of states (in percent) from the

analyzed period is given in Table 1. Bottle selector was not connected properly to the system and was excluded from the analysis.

Table 1. The share of all analyzed states as identified by the system

State	Filler	Plugcapper	Capper	Labeller	Packer
failure	21.10%	3.85%	4.64%	10.12%	11.18%
holdup	17.10%	17.35%	16.04%	5.32%	0.01%
idle	0.00%	15.53%	13.18%	0.00%	45.32%
lack	2.07%	0.00%	0.42%	0.00%	0.00%
stop	9.23%	0.00%	3.36%	6.33%	2.93%
work	50.51%	62.26%	62.36%	78.32%	40.56%

The results of the active period method are summarized in Table 2. The potential bottleneck is detected as the Labeller. The same potential cause of the bottleneck, i.e. Labeller, is detected by the arrow method (Fig. 11).

Table 2. The results of bottleneck detection method which bases on active period analysis

Machine	Average active period [min]	Active period percentage
Capper	110.64	70.4%
Filler	20.51	80.8%
Labeller	167.49	94.7%
Packer	6.78	54.7%
Plugcapper	89.98	67.1%

This can be explained by the fact that subsequent machine – Packer has much greater processing capabilities and can operate at higher rates when compared to all other upstream machines. Labeller, however was never noticed to be starved meaning that there were always products available in the feeding conveyor for labelling. In order to improve the efficiency of the line, the primary focus should be given to either decrease its downtime due to failure or lack of material states or to increase its processing rate.

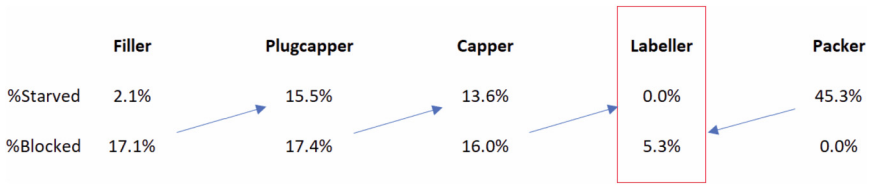


Fig. 11. Results of bottleneck detection using arrow method

4 Conclusions

In the paper, we presented the online detection method for the determination of the root-cause machine which reduces the performance at the line level. The method is based on fixed propagation times between machines which are estimated as the most common propagation times. This simplification makes it easier to be implemented in the industrial practice but at the cost of accuracy. The accuracy can be potentially improved by considering instantaneous machine speeds and the current contents of the accumulating conveyors. The effect of the long-lasting interference is present until accumulation of the products on the conveyors returns to zero. Nonetheless the achieved accuracy of the method is above 80% is acceptable from the industrial practice and can be considered a good rough determination of the root-cause machine in the entire manufacturing line. Further work will involve the development of the method that takes into account the long-lasting effect of the chain of historic downtime events (multiple not single) which eventually propagate to the line level. Further improvements will also include the analysis of current buffer contents what should lead to the creation of on-line bottleneck detection in the form of the automated version of “bottleneck walk” method. The estimation of the number of products which have accumulated in the buffers at a time can be done using vision system. On-line detection of the potential bottleneck can create an opportunity to immediately and accurately react to the exact problem which causes the current inefficiency in the process.

To expand the analysis, we showed the method that allows the determination of the potential bottleneck in the system. A good compliance between the methods which are based on active period analysis with the arrow method was noted. The arrow method requires the knowledge of idle and holdup states of each machines, which is usually not available from Manufacturing Execution or SCADA system, especially online. The presented LogiX system collects all the information to automatically determine all the machines workstates at any given time. Using that knowledge, in the considered case study, we correctly identified that Labeler was the bottleneck machine. The presented system has already been successfully implemented in multiple factories from various FMCG companies. The potential benefits of the method as implemented here using the concept of digital shadow and cloud computing is the accurate detection of the source of inefficiency in the manufacturing system. The described solution can be generalized to complex parallel or hybrid production line which operate in the FMCG, Pharma or automotive industry.

Acknowledgements. This research was financially supported by the National Center for Research and Development, project titled: “Self Learning Factory – Recommendation Engine built based on artificial intelligence with video based production events recognition and utilizing global production machines libraries” (POIR.01.01.01-00-0542/20).

References

1. Hou, Z., Yu, Z.: Two-layer model of equipment fault propagation in manufacturing system. *Qual. Reliab. Eng. Int.* **37**, 743–762 (2021). <https://doi.org/10.1002/qre.2761>
2. Li, L., Ni, J.: Reliability estimation based on operational data of manufacturing systems. *Qual. Reliab. Eng. Int.* **24**, 843–854 (2008). <https://doi.org/10.1002/qre.959>
3. Lins, I.D., Moura, M.D.C., Zio, E., Droguett, E.L.: A particle swarm-optimized support vector machine for reliability prediction. *Qual. Reliab. Eng. Int.* **28**(2), 141–158 (2012). <https://doi.org/10.1002/qre.1221>
4. Huang, S., et al.: Fault propagation analysis of computer numerically controlled machine tools. *J. Manuf. Syst.* **70**, 149–159 (2023). <https://doi.org/10.1016/j.jmsy.2023.07.006>
5. Xia, W., Wang, Y., Hao, Y.: Modeling failure propagation to analyze the vulnerability of the complex electromechanical systems under network attacks. *Physica A* **613**, 128514 (2023). <https://doi.org/10.1016/j.physa.2023.128514>
6. Wang, L., Dai, W., Luo, G., Zhao, Y.: A novel approach to support failure mode, effects, and criticality analysis based on complex networks. *Entropy* **21**, 1230 (2019). <https://doi.org/10.3390/e21121230>
7. Hecht, M., Baum, D.: Failure propagation modeling in FMEAs for reliability, safety, and cybersecurity using SysML. *Procedia Comput. Sci.* **153**, 370–377 (2019). <https://doi.org/10.1016/j.procs.2019.05.091>
8. Kabir, S.: An overview of fault tree analysis and its application in model based dependability analysis. *Expert Syst. Appl.* **77**, 114–135 (2017). <https://doi.org/10.1016/j.eswa.2017.01.058>
9. Su, X., Lu, J., Chen, C., Yu, J., Ji, W.: Dynamic bottleneck identification of manufacturing resources in complex manufacturing system. *Appl. Sci.* **12**, 4195 (2022). <https://doi.org/10.3390/app12094195>
10. Roser, C., Lorentzen, K., Deuse, J.: Reliable shop floor bottleneck detection for flow lines through process and inventory observations. *Procedia CIRP* **19**, 63–68 (2014). <https://doi.org/10.1016/j.procir.2014.05.020>
11. Leporis, M., Kráľová, Z.: A simulation approach to production line bottleneck analysis. In: *International Conference Cybernetics and Informatics*, Vysna Boca, Slovak Republic (2010)
12. Yu, C., Matta, A.: Data-driven bottleneck detection in manufacturing systems: a statistical approach. In: *2014 IEEE International Conference on Automation Science and Engineering (CASE)*, pp 710–715. IEEE (2014)
13. Żywicki, K., Bartkowiak, T., Kujawińska, A.: Application of a simulation model to the prognosis of material loss in wood processing. *PLoS ONE* **16**, e0246325 (2021). <https://doi.org/10.1371/journal.pone.0246325>
14. Ericson, A.: *Bottleneck Detection in Manufacturing a Throughput Case Study at SCANIA CV*. Chalmers University of Technology (2017)
15. Bartkowiak, T., Pawlewski, P.: Reducing negative impact of machine failures on performance of filling and packaging production line - a simulative study. In: *2016 Winter Simulation Conference (WSC)*, pp 2912–2923. IEEE (2016)
16. Jasiulewicz-Kaczmarek, M., Bartkowiak, T.: Improving the performance of a filling line based on simulation. *IOP Conf. Ser. Mater. Sci. Eng.* **145**, 042024 (2016). <https://doi.org/10.1088/1757-899X/145/4/042024>

17. Betterton, C.E., Silver, S.J.: Detecting bottlenecks in serial production lines – a focus on interdeparture time variance. *Int. J. Prod. Res.* **50**, 4158–4174 (2012). <https://doi.org/10.1080/00207543.2011.596847>
18. Lagershausen, S., Tan, B.: On the exact inter-departure, inter-start, and cycle time distribution of closed queueing networks subject to blocking. *IIE Trans.* **47**, 673–692 (2015). <https://doi.org/10.1080/0740817X.2014.982841>
19. Li, J., Meerkov, S.M.: *Production Systems Engineering*. Springer, Boston (2009). <https://doi.org/10.1007/978-0-387-75579-3>
20. Roser, C., Nakano, M., Tanaka, M.: A practical bottleneck detection method. In: *Proceeding of the 2001 Winter Simulation Conference (Cat. No.01CH37304)*, pp 949–953. IEEE (2001)
21. Roser, C., Nakano, M., Tanaka, M.: Shifting bottleneck detection. In: *Proceedings of the Winter Simulation Conference*, pp 1079–1086. IEEE (2002)
22. Subramaniyan, M., Skoogh, A., Gopalakrishnan, M., Salomonsson, H., Hanna, A., Lämkuill, D.: An algorithm for data-driven shifting bottleneck detection. *Cogent Eng.* **3**, 1239516 (2016). <https://doi.org/10.1080/23311916.2016.1239516>
23. Thürier, M., Stevenson, M.: Bottleneck-oriented order release with shifting bottlenecks: an assessment by simulation. *Int. J. Prod. Econ.* **197**, 275–282 (2018). <https://doi.org/10.1016/j.ijpe.2018.01.010>
24. Papacharalampopoulos, A., Giannoulis, C., Stavropoulos, P., Mourtzis, D.: A Digital twin for automated root-cause search of production alarms based on KPIs aggregated from IoT. *Appl. Sci.* **10**, 2377 (2020). <https://doi.org/10.3390/app10072377>
25. e Oliveira, E., Miguéis, V.L., Borges, J.L.: Overlap in automatic root cause analysis in manufacturing: an information theory-based approach. *Appl. Sci.* **13**, 3416 (2023). <https://doi.org/10.3390/app1306341>
26. Bauernhansl, T., Hartleif, S., Felix, T.: The digital shadow of production – a concept for the effective and efficient information supply in dynamic industrial environments. *Procedia CIRP* **72**, 69–74 (2018). <https://doi.org/10.1016/j.procir.2018.03.188>
27. Bergs, T., Gierlings, S., Auerbach, T., Klink, A., Schraknepper, D., Augspurger, T.: The concept of digital twin and digital shadow in manufacturing. *Procedia CIRP* **101**, 81–84 (2021). <https://doi.org/10.1016/j.procir.2021.02.010>
28. Kritzinger, W., Karner, M., Traar, G., Henjes, J., Sihm, W.: Digital Twin in manufacturing: a categorical literature review and classification. *IFAC-PapersOnLine* **51**, 1016–1022 (2018). <https://doi.org/10.1016/j.ifacol.2018.08.474>
29. Mahnke, W., Leitner, S.-H., Damm, M.: *OPC Unified Architecture*. Springer, Heidelberg (2009). <https://doi.org/10.1007/978-3-540-68899-0>
30. Vasani, M.: *Roslyn Cookbook: Compiler as a Service, Code Analysis, Code Quality and More*. Packt Publishing, Birmingham (2017)
31. Aleš, Z., Pavlů, J., Legát, V., Mošna, F., Jurča, V.: Methodology of overall equipment effectiveness calculation in the context of Industry 4.0 environment. *Eksplatacja i Niezawodność – Maint. Reliabil.* **21**, 411–418 (2019). <https://doi.org/10.17531/ein.2019.3.7>
32. Roser, C., Nakano, M.: A quantitative comparison of bottleneck detection methods in manufacturing systems with particular consideration for shifting bottlenecks, pp 273–281 (2015)



3D Printing in Non-planar Layers as a New Tool for Increasing the Quality of FDM Production

Jakub Kaščák^(✉) , Marek Kočiško , Jozef Török , and Adrián Vodilka 

Technical University of Kosice, Presov, Slovakia
jakub.kascak@tuke.sk

Abstract. In nearly every domain today, additive technologies are advancing, particularly in the realms of technical execution and materials. The outcome of these processes is a faster, more economically efficient, and more precise production of models tailored to meet the material requirements arising from their intended purposes. However, all this progress shares a common denominator - the methodology of creating models in planar layers. All Fused Deposition Modeling (FDM) devices, regardless of their construction type, are capable of actively engaging the 'Z' axis in the printing process, not only after completing all perimeters at a specific height. Current software solutions now enable the modification of the process of generating planar layers into a form wherein non-planar surfaces are created in models through active movement along the 'Z' axis during the entire creation phase. The result of this activity is a model with coarse planar layers that serve as a foundation for creating the eventual non-planar surface. This publication intends to elucidate the process of modifying G-code for printing in non-planar layers for specific samples intended for further research. These samples aim to explore potential alterations in force distribution within the non-planar layers of various material types in the subsequent research phase.

Keywords: FDM · fused deposition modeling · 3D printing · additive manufacturing · non-planar printing

1 Introduction

The FDM technology remains one of the most prevalent methods for additive manufacturing of plastic or composite models. Its dominance in this realm is attributed to its accessibility, low economic demands, and a widespread community of users congregating around projects such as RepRap. Among the numerous advantages of this technology is the extensive array of materials available for producing 3D models, known for their mechanical and environmental stability.

FDM technology has found application in manufacturing functional prototypes from plastic materials with mechanical properties that closely respond to various requirements resulting from their further use. It is also utilized in producing molds and visual prototypes. The printing duration for a model ranges from several minutes to several tens of hours, contingent upon the size and complexity of the printed object, as well as the operational parameters of the device [1, 2].

1.1 The Current State of Non-planar Plastic Layering Technology

The current endeavor addressing this issue is undertaken by the Center for Additive Manufacturing at the University of South Carolina. Within their research on expanding the possibilities of additive manufacturing through robotics, the research specifically focuses on the non-planar layering of thermoplastic materials. In the application of this technology to robotic arms, an independent revolver-type printing head has been designed. Comprising three hotends (Fig. 1), tailored to printing conditions, its fundamental operational principle lies in maximizing time efficiency achieved through varying layer heights in the printing process and employing a combination of non-planar and planar layers.

Essentially, this involves individual printing heads equipped with nozzles of varying diameters, actively interchanged during the manufacturing process [3].

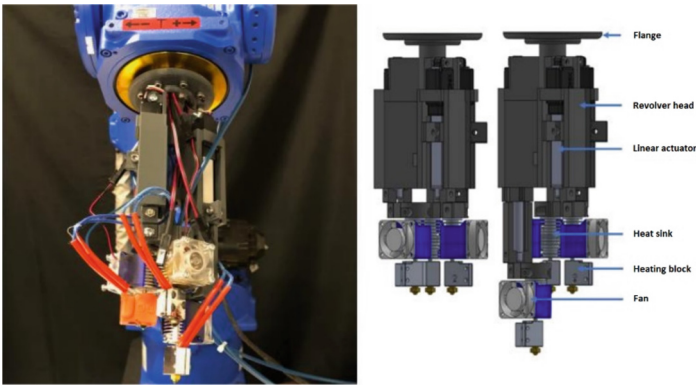


Fig. 1. The print head adapted for printing non-planar surfaces using a robotic arm [4]

In Fig. 2, various types of non-planar surfaces created by a robotic arm are depicted. Their fundamental concept revolves around forming a non-planar base that mirrors the surface of the supporting model. Instead of the customary infill referring to the percentage value of the interior fill known in the creation of models by FDM devices planar-layered plastic is used in this case. As mentioned earlier, this planar layering serves as a support for the upper non-planar surfaces [3].

The application of FDM technology to robotic arms is a current topic significantly fostering advancements in this technological domain. Similar studies and conceptual solutions notably contribute to increasing interest in non-planar printing. From the standpoint of ongoing research in materials, mechanical properties of models, development of constructions, and software, non-planar printing holds an indispensable position [3].

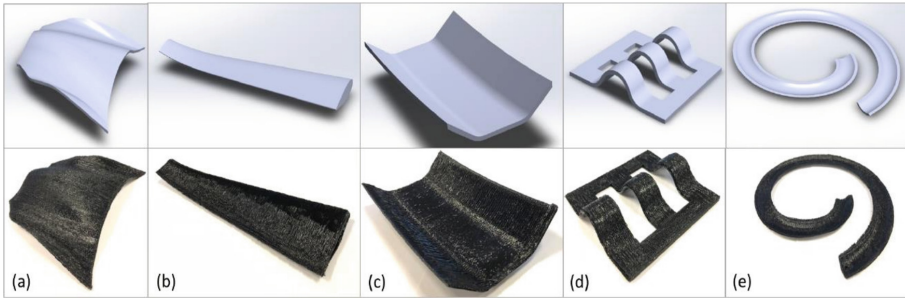


Fig. 2. Examples of non-planar models printed using this method [5]

2 Overview of FDM Technology-Current Challenges in FDM Production Quality

As mentioned earlier, the publication focuses on the possibilities of altering the method of material layering using FDM devices. It briefly provides an overview of the current state and capabilities of contemporary FDM devices while articulately describing the intention and method of generating G-code for modified non-planar samples. To achieve this, the Rhinoceros software is employed. The publication delineates the process of execution and the operational aspects of the software, followed by the subsequent verification of sample production. In its concluding phase, the publication presents the prospective direction of research.

Despite the availability of FDM technology since 1989, its most significant growth has been observed in the past decade. The anticipated growth in this sector of industrial production is estimated to reach \$34.8 billion by 2025. This projection anticipates a planned growth rate of 27% annually within this timeframe [4]. However, despite continuous development and expansion, this technology has notable limitations. One of these limitations is that all devices available in the market create models from bottom to top and solely in planar layers. The utilization of this method results in elements of FDM devices that are structurally and aesthetically similar, hindering the adoption of alternative material layering techniques.

2.1 Fundamentals in FDM Technology

The 3D printing process can be divided into three fundamental stages, encompassing all necessary steps from the conception or creation of a CAD model to its processing and the creation of the final print [3, 6].

- **Pre-production (pre-manufacturing)**
This stage, similar to any 3D printing technology, involves the conversion of the object into a three-dimensional computer-aided design (CAD) model and its export, usually to the STL/3MF format. The requisite software generates the modeling trajectory, material consumption, and estimated time [3, 7].

- Model Creation

The initial steps in fabricating real 3D objects using FDM technology involve creating a virtual model. Various necessary models are available, directly relating to the product's characteristics. One option is a 3D model database accessible during the production of existing CAD models. Another possibility involves digitizing real objects, and the third encompasses creating a model on a PC using appropriate software. With the increasing prevalence of additive manufacturing technologies, every CAD program now offers the option to export a virtual model in a suitable format, further enabling its processing within G-code. Among the processable formats are stereolithography (STL), OBJ, and the 3MF format. STL is generally considered the standard. OBJ and 3MF formats contain additional information beyond the model's geometry, such as color or information about models with different components [3, 8].

- Slicing

To process files into a format understandable by FDM devices, numerous software tools are available. Some are developed by the device manufacturer, while others are not device-specific, allowing for general utilization. These programs can be categorized into two basic groups. The first comprises paid and unpaid programs, often bundled with specific device types, restricting extensive intervention into operational parameters and resulting programs. The second category includes open-source programs. These programs allow significant intervention into operational parameters and process conditions, along with the script, facilitating precise manipulation of information. Evaluated programs include Cura and Simplify3D. These programs enable all necessary modifications of parameters for custom devices [3].

- Production (Manufacturing)

G-code essentially refers to a numerical control language commonly employed in computer-aided manufacturing (CAM). It is also utilized to control FDM devices. G-code contains commands and information guiding the machine. These commands dictate, for instance, the tool's movement speed and its final position. In the context of FDM devices, the tool represents the printing head. G-code also governs other parameters besides speed and position. It contains information on all device operating parameters, read from a file during operation. In the past, creating and controlling machines using commands was more complicated. Currently, numerous generators automatically create this code for predefined devices [3, 9, 10]. For instance, the utilization of G-code in FDM devices includes commands like 'G1 X100 Y100 Z100 E10 F2400,' indicating the movement of the printing head to coordinates $x = 100$, $y = 100$, $z = 100$. In FDM devices, there's linear interpolation during movement, meaning that the speed in axes isn't consistent. This ensures the printing head reaches the target coordinate at the same time. The 'E' command, regarding FDM devices, implies extruding 10 mm of thermoplastic material at a maximum speed of 2400 mm/min. The 'G1' command at the beginning of the line in the relevant part of the G-code enables the simultaneous execution of these steps. In practice, this line could be interpreted as the approach of the printing head from a reference point at coordinates $x = 100$, $y = 100$, and $z = 100$, while extruding 10 mm of material at the maximum extrusion speed of 2400 mm/min.

- Model Creation

The method involves melting thermoplastic polymer in filament form, which is gradually fed into the extruder, where it melts and is extruded through the printing head, depositing layer upon layer onto a flexible substrate. The filament partially liquefies due to the extruder temperature, maintained close to the melting temperature of the material used. As the ambient temperature is significantly lower, the material solidifies rapidly. The printing head moves in the X and Y axes, precisely extruding and depositing material in thin layers onto the substrate. After applying a specific layer, the head moves upward in the Z-axis and continues applying the subsequent layer. The result of layering solidified material onto the preceding layer is a plastic 3D model. The FDM process necessitates the use of support structures for most models with overhanging geometry. This involves using an additional, typically water-soluble material, enabling relatively easy removal of support structures after completion [3, 4].

- **Post-production**

After modeling, various finishing operations are often required based on the product's nature and use. Modifications may involve mechanical or chemical removal of support structures [3]. Depending on the material and FDM device type, several types of supports are known. The most common supports are generated by FDM devices with a single printing head, utilizing the same support material as the model material. They differ only in preset parameters used during their creation. Such support is challenging to remove, particularly from complex-shaped models, often causing mechanical damage to the model during removal. Devices with multiple printing heads or devices allowing material combination during production offer a different approach to support creation. These devices replace the model's material in the print area with support material. This permits the use of various support materials, subsequently removable using different methods, such as dissolving the support material in a special emulsion, water, or completely burning it during the sintering process.

2.2 Non-planar Layer 3D Printing Technique

Concerning the application of FDM technology on robotic arms or other atypical constructions inspired by these arms, a fundamental question arises: considering the current state, precision, manufacturing method, and implementation of new materials, is it necessary to approach the production of models from a different perspective? Given the current trends and advancements in this technology, the improvement of operational production parameters, and its application to sophisticated device types, innovation within the manufacturing process itself becomes essential. One direction in which FDM technology is evolving involves altering the approach to generating paths for printing heads or changing the method of material layering. The current method of generating tool paths involves dividing the created object into planes corresponding to the layer's height. Essentially, each perimeter is created first in the X and Y axes, and only after completion does the shift occur in the Z-axis. This layering method has been used from the invention of FDM technology to the present day. This process indicates that FDM devices, commonly called as 3D printers, operate realistically in 2.5 axes during their operation, as visible in Fig. 3. Such a method of material layering is associated with the characteristic state of the surface finish of prints and their varying properties concerning their orientation to the device's coordinate system during printing [11].

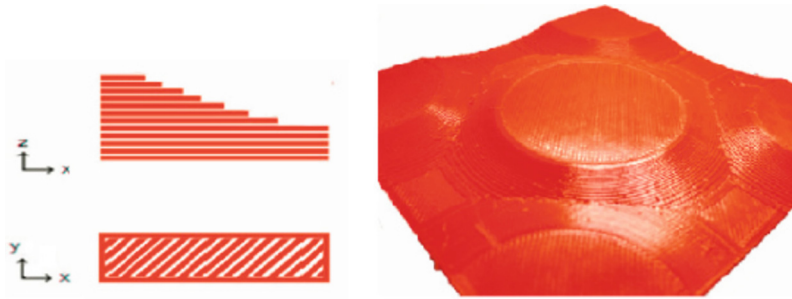


Fig. 3. The method of generating individual layers in the planar printing mode [3]

Presently, only narrow groups of researchers within institutions and companies are delving into this issue, specializing in FDM technology. One of these companies is Autodesk. This company, known as a leader and pioneer in CAD/CAM and CAE software, has held an official registration for Patent No. US10005126B2 since July 2018. This patent describes the so-called ‘Systems and methods for enhanced 3D printing.’ Among these methods is the utilization of non-planar material layering as depicted in Fig. 4 [1].



Fig. 4. The method of generating individual layers in the non-planar layering mode [3]

This printing method involves modifying the slicer program. As previously mentioned, the generation of tool paths for the printing head occurs in planar layers, necessitating the active involvement of the Z-axis during the printing process. This function is active within the generation of G-code only in specific situations, such as movement to reference points using device rapid traverse or printing in a specialized mode for creating thin-walled models through spiralization and continuous printing of a single perimeter. Hence, the required function is already implemented within the Slicer program but remains inactive during the standard manufacturing of models [12, 13].

2.3 Utilizing Rhinoceros and Grasshopper for Non-planar Layer G-code Generation

Currently, the only option offering a change in the material distribution method is the so-called variable layer height feature [14, 15]. It is integrated into the functionalities of various slicers such as PrusaSlicer, Simplify3D, and MeshMixer. Its principle lies in the variable layer height range for different perimeters. The layer height of models is lower in areas requiring more detailed finishing or increased precision, while in areas without functional or intricate surfaces, the layer is higher, even coarser. A significant advantage of this feature is the extreme reduction in the time required for producing prints.

<pre> ; Planar G-code for a block with a curved top G1 X0 Y0 Z0 ; Move to the starting point at the base G1 F3000 ; Set the feedrate to 3000 mm/min ; Loop for each layer for (layer = 1; layer <= total_layers; layer++) { G1 Z[layer_height] ; Move to the next layer height ; Loop for each line in the layer for (line = 1; line <= lines_per_layer; line++) { ; Print a line across the layer G1 X[line_length] E[extrusion_amount] } } </pre>	<pre> ; Non-Planar G-code for a block with a curved top G1 X0 Y0 Z0 ; Move to the starting point at the base G1 F3000 ; Set the feedrate to 3000 mm/min ; Loop for each layer for (layer = 1; layer <= total_layers; layer++) { ; Calculate the non-uniform layer height based on the block's curvature G1 Z[non_uniform_layer_height] ; Move to the next layer height based on the curve ; Loop for each line in the layer for (line = 1; line <= lines_per_layer; line++) { ; Adjust movements based on the curved top surface G1 X[line_length] Y[curved_movement] E[extrusion_amount] } } </pre>
---	--

Fig. 5. The difference between planar and non-planar processing of G-code

For the creation of non-planar layers or G-code for FDM devices, as seen in Fig. 5 in comparison to the typical planar G-code, a series of programs within the Rhinoceros software and its Grasshopper plugin are utilized. This plugin essentially functions as a visual programming language and graphical algorithm editor. Grasshopper enables users to parametrically create and manipulate complex 3D models by visually connecting various components instead of using traditional programming code. Widely used in architecture, engineering, and other fields, it offers flexibility in creating and manipulating designs [16, 17].

Therefore, it can be concluded that currently, there is no slicer capable of ‘plug and play’ processing of non-planar surfaces and adjusting the positioning of the FDM device’s head [18, 19]. For this purpose, an improvised slicer is designed within the graphical interface of the Grasshopper plugin. This, in combination with a series of add-ons, allows us to identify and work with non-planar surfaces on models imported into the Rhinoceros 7.0 software interface.

Figure 6 illustrates the first two ‘clusters,’ characteristic for all slicers, essentially forming a network of dependencies and functions that are concealed within the simplified and aesthetically designed user interface of common slicers. As depicted in the figure, it represents the basic process parameters for the printing process. In this representation, they appear as numerical sliders allowing for value editing. Additionally, they are complemented by logical functions, as seen in the option to use functions like skirt/brim or filament retraction (Fig. 7).

The following two clusters contain additional information about cartesian-type devices, such as the ability to edit the print bed size, import the used model, or set operational temperatures for the print bed and extruder. The last section of this prepared program provides a preview of the G-code and the option to export it in the required format.

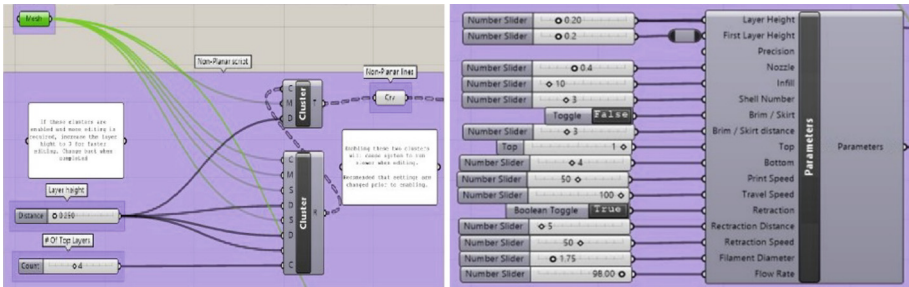


Fig. 6. Basic definitions in the Grasshopper plugin

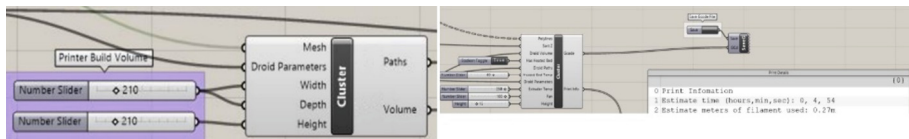


Fig. 7. Additional parameters and finalization of the G-code

The result of this arrangement and the use of add-ons like Droid, Pufferfish, and others is an improvised slicer capable of recognizing and editing the selected number of top non-planar surfaces of imported models. Figure 8 illustrates the import of the first sample. However, in this instance, it represents a misprint since the slicer only works with non-planar surfaces highlighted in red. The part of the model intended to be printed using the standard method is ignored.

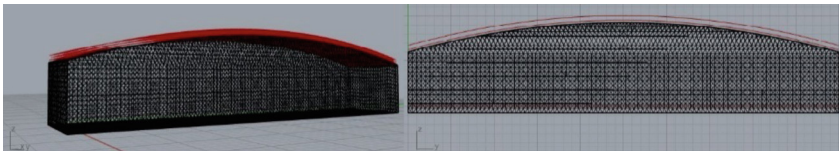


Fig. 8. Test object, displaying trajectory only in the non-planar section

Within this constructed slicer, several samples with non-planar surfaces were tested across various FDM devices into which the resulting G-code was imported. In connection with this process, the following shortcomings were identified:

- Limitations arising from working with the slicer:
 - The slicer disregards the planar part of the model if it represents the majority of its volume.
 - It divides the planar and non-planar parts into two separate G-codes with different coordinate systems.
- Limitations arising from working with Rhinoceros software:

- The absence of a global coordinate system poses challenges in setting references for FDM devices.
- Limitations arising from importing the generated G-code into the FDM device and the printing process:
 - Inconsistent reference point coordinate system between software and hardware.
 - Similar issues in dividing the non-planar and planar parts of the model, resulted in multiple coordinate systems and erroneous attempts to print parts outside the print bed.
 - When the model is split into planar and non-planar sections, the device with automatic calibration initiates a calibration process, causing collisions with the already printed planar part of the model.

By addressing all these limitations, the aim was to enhance the functionality of the prepared slicer in a ‘plug-and-play’ format. This implementation allows the generation of both planar and non-planar parts as a single unit on any imported model. The model is automatically placed at the center of the coordinate system, regardless of changes in print bed dimensions or other parameters. Due to these modifications resulting in a unified G-code with a single reference, these models no longer trigger an undesired calibration process.

3 Results

After optimizing the CAD model processing for the FDM device, several samples were printed. The selected parameters for the output device, i.e., for the entire printing process, are listed in Table 1. As observed, the parameters used in both variations were identical, and the output was produced using the same FDM device, namely the Prusa mk3s+ type.

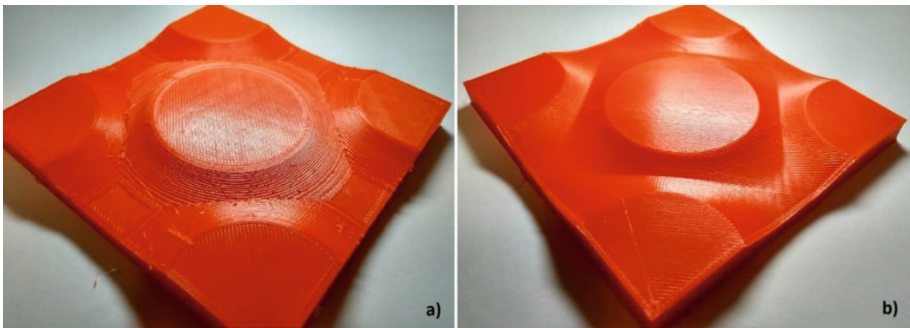
One of the results is depicted in Fig. 9 b). For comparison, the model produced using the planar method, i.e., standard printing, is also displayed. As evident, the difference in the quality of the surface finish is strikingly distinct. The top layers created using the non-planar method appear more cohesive, free from aesthetic flaws and exhibit a less rough surface characteristic.

After appropriate adjustments, optimizing the process and its applicability to any non-planar surface of a CAD model is feasible. The only remaining limitation lies in the design of the print head, constrained by the angle between the print bed and other components of the printing head. From the experiment, it is evident that this value is set at 22.5 to 25°, depending on the type of device used. Another limitation is the fact that the print nozzle is designed to be perpendicular to the surface; therefore, excessively steep non-planar trajectories will also affect the final quality of the prints.

Among other differences in the preparatory and production phases, including slicer processing speed, print speed, and material consumption, as visible in Table 2. As evident, while the slicer is optimized in terms of its functionality, the actual operational efficiency shows a significant increase in the time required for generating the G-code. A similar trend is observed in the time needed for printing. One positive aspect, however, is the lower material consumption.

Table 1. Selected parameters for the 3D printing process

Print parameters	Planar print	Non-planar
Layer height	0.2 mm	0.2 mm
First layer height	0.2 mm	0.2 mm
Nozzle diameter	0.4 mm	0.4 mm
Infill	10%	10%
Number of shells	2	2
Number of top layers	3	3
Print speed	50 mm/s	50 mm/s
Retraction distance	5 mm	5 mm
Retraction speed	50	50
Filament diameter	1.75 mm	1.75 mm
Flow rate	105%	105%

**Fig. 9.** The result and comparison with the planar execution**Table 2.** The table assessing critical areas

	Planar print	Non-planar
Slicer processing speed	5 s	223 s
Print time	7524 s	11340 s
Material consumption	40.67 g	35.94 g

4 Conclusion

The article introduces with the current state of technology and an innovative approach to the method by which trajectories for FDM printer heads are generated. It describes the present state of utilizing robotic arms in combination with non-planar material layering

and elucidates the possibilities and relevance of the topic. The theoretical segment dissects individual phases characteristic of working with software and hardware intended for creating models through layering plastic.

The analysis of these phases highlights the possibility of changing material distribution, which is also outlined in the patent labeled US10005126B2. In line with this realization, an alternatively structured slicer is prepared within the practical solution, enabling work with non-planar surfaces. Subsequently, this slicer is further developed within the Rhinoceros software plugin named Grasshopper, whose graphical programming interface, aided by a series of add-ons, facilitates the creation of an improvised slicer. After the initial version is crafted, its analysis ensues, detailed in subsequent sections of the publication. These phases are then subjected to optimization in three stages. The first and second stages characterize the distinct operating principles of this developed slicer and the Rhinoceros software, from which all characteristic elements for CAD models and their manipulation are derived. The third stage involves the identification and subsequent resolution of deficiencies arising from importing the G-code into the output device, specifically the Prusa mk3s+.

Upon eliminating these drawbacks, a series of 11 models is created, subject to further monitoring and analysis. Summarizing the entire practical segment in Table 2, which describes or compares a model with three top non-planar layers to a model produced using the standard procedure. The results indicate the potential for material savings with this method, yet its downside lies in extending the entire process. The third compared parameter was the time taken by the slicer to process the model and prepare it according to instructions for the FDM device. Due to its non-optimized user interface and the use of a series of modules supplementing its functions, this process tends to be protracted.

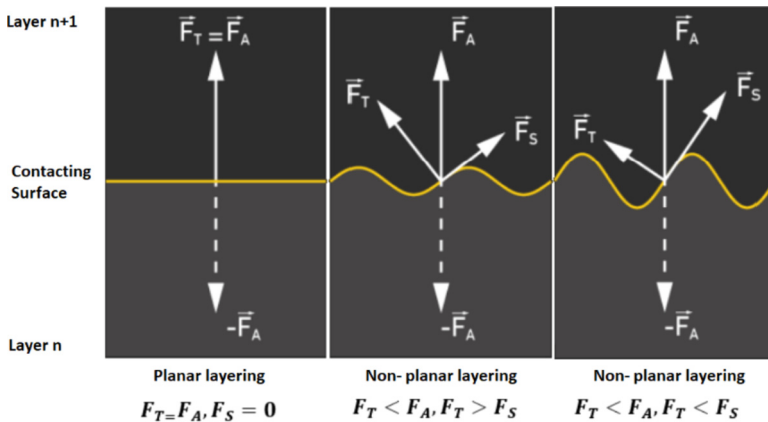


Fig. 10. The depiction of the assumption of the change in the cutting force component F_s depending on the layer displacement inferred by forces during the tensile test [20].

In any case, the intention to create a slicer for non-planar material layering, designed for ‘plug and play’ usage, or model import and utilization, is successful. The future

re-search direction will revolve around the comparison and analysis of non-planar surfaces. As depicted in Fig. 10, with a non-planar surface, there is an anticipated change in force distribution. This phenomenon characterizes the further research direction in this field.

Acknowledgments. This work was supported by the projects VEGA 1/0026/22, and KEGA 004TUKE-4/2022 granted by the Ministry of Education, Science, Research and Sport of the Slovak Republic.




References

1. Ahlers, D.: 3D printing of nonplanar layers for smooth surface generation, Master thesis, MIN-Fakultät, University of Hamburg, str. 13-19 (2018)
2. Gibson, I.: Additive Manufacturing Technologies. Springer, New York (2014). 978-1-4939-2112-6
3. Kašćak, J., et al.: Design of an atypical construction of equipment for additive manufacturing with a conceptual solution of a printhead intended for the use of recycled plastic materials. *Appl. Sci.* **11**(7), 2928 (2021). <https://doi.org/10.3390/app11072928>
4. Bhatt, P.M., Malhan, R.K., et al.: Expanding capabilities of additive manufacturing through the use of robotics technologies: a survey. *Elsevier-Addit. Manuf.* **31**, 100933 (2019). 2214-8604
5. Chua, C.K., Leong, K.F., Lim, C.S.: *Rapid Prototyping: Principles and Applications*. World Scientific, London (2003)
6. Wojciechowski, S., Przystacki, D., Chwalczuk, T.: The evaluation of surface integrity during machining of Inconel 718 with various laser assistance strategies. *MATEC Web Conf.* **136**, 01006 (2017)
7. Vitković, N., et al.: Extra-articular distal humerus plate 3D model creation by using the method of anatomical features. *Materials* **16**(15), 5409 (2023). <https://doi.org/10.3390/ma16155409>
8. Stojković, J.R., et al.: An experimental study on the impact of layer height and annealing parameters on the tensile strength and dimensional accuracy of FDM 3D printed parts. *Materials* **16**(13), 4574 (2023). <https://doi.org/10.3390/ma16134574>
9. Varela, M.L.R., et al.: Collaborative paradigm for single-machine scheduling under just-in-time principles: total holding-tardiness cost problem. *Manag. Prod. Eng. Rev.* **9**(1), 90–103 (2018). <https://doi.org/10.24425/119404>
10. Kujawińska, A., Diering, M.: The impact of the organization of the visual inspection process on its effectiveness. *Int. J. Adv. Manuf. Technol.* **112**, 1295–1306 (2021). <https://doi.org/10.1007/s00170-020-06543-9>
11. Yoon, Y.J., Yon, M., et al.: Development of three-nozzle extrusion system for conformal multi-resolution 3D printing with a robotic. In: DETC/CIE International Design Engineering Technical Conferences and Computers and Information in Engineering Conferences, Anaheim. DETC2019-98069 (2019)
12. Bhatt, P.M., Kabir, A.M., et al.: A robotic cell for multi-resolution additive manufacturing. In: ICRA-International Conference on Robotics and Automation (2019). 978-1-5386-6027-0
13. Kašćak, J., Husár, J., Knapčíková, L., Trojanowska, J., Ivanov, V.: Conceptual use of augmented reality in the maintenance of manufacturing facilities. In: Trojanowska, J., Kujawińska, A., Machado, J., Pavlenko, I. (eds.) *Advances in Manufacturing III*, vol. 2 – Production Engineering: Research and Technology Innovations, Industry 4.0, pp. 241–252. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-99310-8_19

14. Trojanowska, J., Husár, J., Hrehova, S., Knapčková, L.: Poka Yoke in smart production systems with Pick-to-Light implementation to increase efficiency. *Appl. Sci.* **13**(21), 11715 (2023). <https://doi.org/10.3390/app132111715>
15. Husár, J., Hrehova, S., Trojanowski, P., Wojciechowski, S., Kolos, V.: Perspectives of lean management using the Poka Yoke method. In: Ivanov, V., Trojanowska, J., Pavlenko, I., Rauch, E., Piteř, J. (eds.) *Advances in Design, Simulation and Manufacturing VI, DSMIE 2023. LNME*, pp. 121–131. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-32767-4_12
16. Shembekar, A.V., Yoon, Y.J., et al.: Generating robot trajectories for conformal three-dimensional printing using nonplanar layers. *J. Comput. Inf. Sci. Eng.* **19**, 031011-1 (2019)
17. Diering, M., Dyczkowski, K., Hamrol, A.: Rating system analysis in quality engineering based on fuzzy similarity. *J. Multiple-Valued Logic Soft Comput.* **32**(3–4), 277–292 (2019)
18. Kong, X., Gosselin, C.M.: Type synthesis of 3T1R 4-DOF parallel manipulators based on screw theory. *IEEE Trans. Robot. Autom.* **20**(2), 181–190 (2004)
19. Şap, S., Uzun, M., Usca, Ū.A., Giasin, K., Wojciechowski, S.: Investigation on microstructure, mechanical, and tribological performance of Cu base hybrid composite materials. *J. Market. Res.* **15**, 6990–7003 (2021)
20. Sweeney, C.B., et al.: Welding of 3D-printed carbon nanotube-polymer composites by locally induced microwave heating. *Sci. Adv.* **3**, e1700262 (2017)



Potential of Graph Database Visualization of the Supplier Network to Increase Resilience in Multi-tier Supply Chains

Erwin Rauch¹ , Ali Asghar Bataleblu¹ , Michaela Golser¹, Asja Emer¹, and Dominik T. Matt^{1,2} 

¹ Industrial Engineering and Automation (IEA), Faculty of Engineering, Free University of Bozen-Bolzano, Bolzano, Italy

aliasghar.bataleblu@unibz.it

² Fraunhofer Research Italia, Innovation Engineering Center, Bolzano, Italy

Abstract. Since Covid and the following bottlenecks in material supply companies are highly sensitive regarding the vulnerability of their supply chains. Delayed deliveries, failures of sub-suppliers, and supply shortages are only a few of the problems arising over the last years in global markets. This work deals with the potential of graph database systems in terms of increasing transparency and resilience in manufacturing supply chains. For the research, an open-source solution is tested for its functionality so that small and medium-sized enterprises (SMEs) can also benefit from the advantages of such systems. The goal is to find out if such systems are suitable in the case of multi-tier supply chains. The more sub-suppliers there are between the manufacturer and the raw material producer, the more difficult it is for a company to manage the entire supply chain. In this work, the supplier network is exemplarily visualized using a NoSQL database focusing on graph-based data models. Queries are designed and tested facilitating the user to search for specific criteria and critical situations within the supplier network. The results in this research suggest that there is considerable potential for increasing resilience as supply chain managers can use such tools to act based on the results instead of reacting when problems are already materializing along supply chains.

Keywords: Sustainable Manufacturing · Resilience · Graph Database · NoSQL · Multi-Tier Supply Chain · Sustainability

1 Introduction

The upstream supply chain of companies, extending beyond their direct suppliers, is gaining increased attention from investors and customers, facing stricter regulation by governments, and attracting growing interest from civil society [1]. Increased supply chain transparency is demanded from companies, and reasons for supply shortages and delays should be justifiable. However, many companies lack knowledge about their sub-suppliers and their supply chain, leading to communication challenges [2]. Monitoring suppliers requires companies to [1]:

- Understand which information is of importance.
- Investigate what data might be available.
- Evaluate which data is best suited to meet defined information needs and access the sources of that data.

Supplier networks have expanded over decades due to extensive and strategic global outsourcing by companies. Initially, linear supply chains have evolved over time into complex, extensive supplier network structures with numerous sub-suppliers distributed around the world [3]. In literature, the degree of distinction from sub-supplier to direct supplier up to the buyer is conveyed by designations such as Tier 1, Tier 2, and so on. Tier 1 is the direct supplier to the buyer, and Tier 2 supplies Tier 1. A Tier 2 for one purchased part can simultaneously supply another purchased part as Tier 1 or provide as Tier 4 in the supply chain for a third item [4]. Value-adding partners can work together multilaterally, resulting in a multi-tier supplier network [5]. The concept of Tier-n Management originates from automotive logistics. Fundamentals identified by the scientific community for a supply chain management concept, such as “complex supply chains” and “network-like relationships,” as well as goals like cost reduction and quality advantages, also apply to Tier-n Management [6]. Multi-Tier Management is gaining increasing importance in the academic context [7].

The latest COVID-19 pandemic has led to disruptions in global supply chains, posing significant challenges for companies. Procurement managers and supply chain managers, due to the limited transparency and asymmetric power distribution within their global supply chains, faced high risks. Such supply chains are referred to be vulnerable [8]. The software-based solution discussed in this work aims to help companies (and especially SMEs) enhance the resilience of their supplier network and stimulate further research in this area. This resilience is described as the ability of a supply chain to respond resiliently to external influences, unexpected changes, and disruptions, to mitigate impacts and return to the initial state promptly [9].

2 Literature Review

2.1 Supply Chain Integration

Supply chain integration is defined by Dodel as “optimizing supply relationships through cross-company collaboration in a partnership environment with collaborative data and information sharing [5]”. Optimizing this collaboration is becoming increasingly important, both practically and theoretically, in the global value chain [10]. A functioning supply chain must be responsive and cost-effective in its entirety. It must also be able to adapt, have a clear direction, and be agile. An adaptive supply chain requires flexible network relationships and a focus on change management. Adaptability also involves constant collection of information about customer needs and continuous development. Defined role models and responsibilities as well as extended, shared performance measures are essential [11]. According to Lee, the most stable supply chains are agile, and adaptive, and ensure that the interests of all participating companies are aligned.

A supply chain adapts to its environment by establishing different supply chains for various product lines. For highly customized products with low quantities, suppliers deliver in close proximity to the Original Equipment Manufacturer’s (OEM) main

markets. However, for standard products with high quantities, production takes place in low-cost countries [12]. Flexibility is ensured by using the same components and production processes for different products. As an OEM, you are in constant data exchange with your supply partners, allowing you to respond promptly to fluctuations in customer demand, among other things. Adaptability requires building resilience so that the supply chain can quickly return to its initial state while proactively mitigating future disruptions [13].

According to Lee, agility also means completing products only after customer preferences are known, with C-parts always in stock to avoid delays in the product manufacturing process. This enables quick responses to external influences and disruptions, such as epidemics, natural disasters, and human or mechanical failures [12]. In January 2021, 17 years after the publication of his Triple-A Supply Chain Theory, Lee provides examples from various industries, such as “fast fashion” in the apparel industry. Agility is now supported by the Internet of Things (IoT), big data, and artificial intelligence (AI) to respond to disruptions and changes in real-time [13]. Combining agility with robustness ensures real-time responses to risk scenarios [13].

Lastly, Lee discusses aligning the interests of all supply chain partners. Each receives the same access to forecasts, sales data, and plans from the OEM. A crucial point is that every supplier understands their role and responsibilities to avoid conflicts. The goal is to optimize the entire supply chain, as each partner strengthens the whole chain through their individual profit maximization [12]. The alignment is refocused on innovative business models and current value propositions. For example, defining the conditions for efficient wholesale contracts and prices, negotiated directly by the OEM or the suppliers, to increase the order quantity, reduce the price, and maintain stability [13].

In contemporary manufacturing systems, while the adoption of lean manufacturing principles is perceived as essential for sustaining competitiveness on a global scale [14], the supply chain partners within a supply chain, their connections, and their dependencies on each other are not always known. It starts with raw material suppliers who provide raw materials to processing companies in mutual dependencies. Manufactured components are then transferred to module suppliers, who, in turn, deliver to manufacturers or OEMs that sell to retailers. In retail, there are different connections with end customers who ultimately use the manufactured product referring to these interactions as a Polycentric Supply Chain, as depicted in Fig. 1 [15].

2.2 Multi-tier Management and Supply Chain Resilience

The term “Tier Management” originates from the automotive industry and refers to the hierarchy levels within a supplier network. In the example of Fig. 1, Tier 1 corresponds to module suppliers. A component supplier is referred to as Tier 2, and a raw material supplier is labeled as Tier 3. However, a Tier 3 can also supply a Tier 1 as a Tier 2, creating a multi-tier network. The challenge for companies is to find ways and organizational structures that generate both control and integration possibilities for the tiers into the corporate culture of the OEM [11].

Multi-Tier Management is particularly gaining importance in the context of sustainability. Companies must demonstrate that there is no child labor or other forms of labor exploitation within the supply chain. All Tier-n entities are required to adhere to the

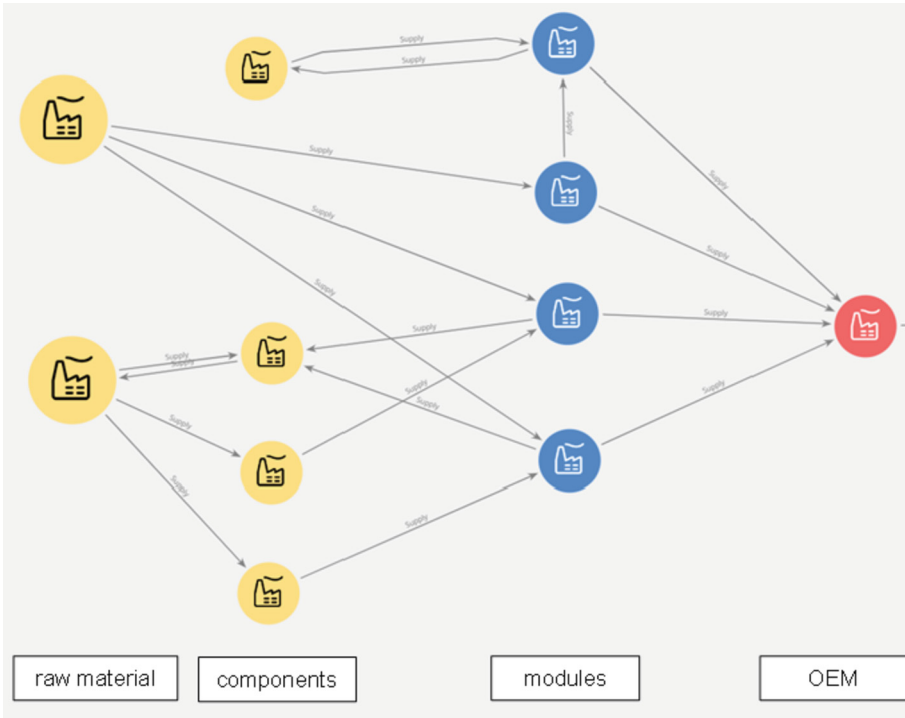


Fig. 1. Polycentric Supply Chain (own representation/illustration).

regulations of a Triple Bottom Line, which means achieving a specified level of social, economic, and ecological sustainability [16].

Every chain is only as strong as its weakest link, and this also applies to a supply chain. The supply disruption of a supplier, whether as a raw material supplier or an outsourced coater, can lead to significant damages, up to a halt in production at the OEM [10]. In general, risks in the supply chain that occur at a specific node can disrupt the entire operation of that node or parts of it. Nodes represent connections to other companies. Risks include market fluctuations, communication difficulties between different cultures, reliability risks, capacity risks, political instability, and many more.

Various approaches are theoretically situated for conducting risk assessments, such as scoring models using conjoint analysis, analytical hierarchy processes for identifying disruptive factors, and methodologies for measuring the impact of potential disruption. However, these are not the focus of this work [17].

In summary, supply chain risk management aims to develop strategies for the assessment, treatment, identification, and monitoring of risks in supply chains. Some theories aim to conduct audits directly with suppliers so that OEMs and Tier-n entities can collectively recognize and assess risks [18].

In general, the vulnerability of a supply chain is “the term used to describe the extent to which a supply chain is susceptible to a specific or unspecified risk event,” while the resilience of a supply chain demonstrates “the ability of a supply chain to overcome

vulnerability.” Nakatani [19] describes vulnerability as a concept that represents a “lack of robustness or resistance to various threats that arise both within and outside the boundaries of a supply chain system”.

Once the boundaries of a supplier network are reached due to environmental influences, insolvencies, etc., supply chain resilience is considered a measure of the ability to respond resiliently to these external impacts and return to the original state in a short period [9]. A supplier is considered critical when it weakens or disrupts the supply chain. In principle, any supplier within a chain can become critical. However, to preselect those that are considered particularly susceptible to disruption, some aspects should be considered and classified. Firstly, the product and supplier structure is significant. Both structures must be linked to identify all material flow relationships. The alignment of material flow and procurement volume plays a crucial role. Once a supplier appears multiple times in the supply chain at different positions, they are already considered more critical than a supplier that appears only once in the supply chain [20].

3 Research Methodology

3.1 Gap Analysis and Research Objectives

This work aims to test database models for simplified visualization of supplier networks to enhance reactivity along supply chains. The exemplary model is examined based on typical questions and problems supply chain managers are facing. The theoretical objective is to test a generalizable database model implemented in Neo4j graph database software for visualizing multi-tier supplier networks to increase transparency and reactivity within supply chains. Currently, there are only a few works related to transparent design or visualization of supplier networks. This work, therefore, should inspire other researchers to conduct further research, especially in the field of applied research.

From an industrial perspective, an IT-supported instrument in the form of a graph database model with visual features for digital modeling and representation of the multi-tier supply chains of a company is to be tested. By introducing such a database model, companies can elevate the transparency of their own supplier network to a new qualitative level. Such visualization of various players in supply chains should enable a sustainable increase in the resilience and reactivity of supply chains. The generalization of the model developed as a generic case study company allows further dissemination and application in industrial enterprises.

Based on the described challenges, the following main research question (RQ) arises:

RQ: “How can the resilience of multi-tier supply chains be increased in companies (and especially SMEs) through the transparent and digital visualization of supplier networks?”.

3.2 NoSQL Databases

Relational databases operate according to a rigid table schema in which each record is defined [21]. The structure can be thought of hierarchically as a tree. A database management system must manage significantly growing amounts of data. The more tables

this creates, the longer it takes to execute desired information, changes, or commands. To ensure this, multi-model databases are created that combine advantages from different NoSQL (Not only SQL) and SQL. In general, a NoSQL differs from a SQL database in that it is schema-less, sharding, replicated, and usually licensed for free [21]. With a replicated computer architecture, parallel evaluation methods are applied and horizontal scaling is used [22]. Basic approaches in NoSQL are distinguished between graph-oriented, document-oriented, key-value-oriented, object-oriented, and column-oriented databases [23, 24]. In the context of this work, graph-oriented is described in more detail.

These are schema-free and can have an arbitrary structure due to this. Graph algorithms are used for graph databases and the linkage between objects is considered in particular. Graph databases are used to store, retrieve, and manage information using a graph. An entity is modeled as a node with edges. The connection points between nodes represent the relationships between objects [25]. Creating the relationships between objects through the edges does not create rigid structures and does not limit the possibility of different data types [26]. Nodes and edges can have attributes and for an edge, the relation can be determined for a given direction [22]. The graph database is expressive, easy to understand, and can be conceptualized, making it an ideal choice for data analysis. Furthermore, graph databases are characterized by traversal-like queries that visualize unanticipated findings with relatively straightforward inputs [27].

3.3 Neo4j Open Source Graph Database

Neo4j is one of the most popular graph databases and has been available as a free download since 2010. The graphs are stored internally and queries can be designed using the developed language called Cypher. Since 2015, the descriptive query language has also been used with other graph databases [23]. Cypher provides graph pattern matching, a schema definition language, and path length comparison. Neo4j facilitates the discovery of complicated connected structures through simple queries [28]. It maintains indexes for retrieving nodes with specific labels. In addition, Neo4j allows the creation of indexes on properties of nodes with a particular label, as well as additional index structures, for full-text indexing and global indexing of all properties. In Neo4j, nodes and edges can be assigned specific properties. Nodes are referred to as “nodes” in technical language [29].

Graph databases, with their ability to handle complexity, large datasets, and intricate relationships, allow organizations to visualize the supply chain from end to end and optimize it in an intelligent, integrated way. Graph databases make it easy to model recursive relationships, for example, and can help companies anticipate bullwhip effects, pinpoint potential bottlenecks, and prepare for disruptive events [30].

4 Results from Visualization of Multi-tier Supply Chains Using Neo4j Graph Database

4.1 Premise

The following illustrations are based on a real example of multi-tier supply chains from industry. The example reflects a typical situation of many companies and only serves to illustrate the functions and potentials of Neo4j and graph databases for the visualization of supply networks.

4.2 Modeling of the Neo4j Database

To represent the supplier network, a corresponding database model is initially designed. An entity-relationship model is derived. For entity types and relationship types, a table is formulated as a.csv file. The different attribute features are grouped together as column headers:

- **Company ID:** Each company is assigned an identifiable ID in the form of a number, allowing for clear differentiation between individual companies.
- **Company Name:** The company name of the supplier is listed.
- **Location:** For this attribute, the production locations of the companies are given in the format “State XYZ.”
- **Process:** The respective manufacturing process or the designation of the purchased part (e.g., C-parts) is described here. A supplier can be associated with multiple different processes.
- **Tier:** For direct suppliers to the OEM, the designation “1” is used, which represents Tier-1. Sub-suppliers are marked as “others,” and main product groups are labeled as “Commodity.” For sub-suppliers, a specific Tier-n number cannot be provided, as the same supplier can deliver at different points along a supply chain for various components or services. The classification “OEM” appears only once and represents the OEM explicitly.

To represent the relationships between objects, a “relationship.csv” file is used. This table is structured as follows:

- **From:** In this attribute, a CompanyID number from the Companies.csv file is specified for each row. It describes the respective company that acts as a supplier.
- **To:** The second attribute describes, using a CompanyID, the corresponding company that receives goods or services.
- **Type:** The third attribute is defined as “supply” in each row, representing the act of supplying.
- **pq:** The individual attribute features are specified as a number, indicating how many different components are delivered as a flow of goods within the connection.

Within the relationship.csv, mutual relationships are listed. A company can supply multiple Tier-n entities and be supplied by multiple entities. Each connection is specified in a separate row within the table. To test user features, various queries are programmed as JSON. Various executions are displayed through “Search phrases.” These are display functions based on companies.csv and relationship.csv.

4.3 Functionality Testing: Search Phrases

In total, 6 different query possibilities are simulated and tested. These queries allow for displaying individual companies, supply chains, and networks, among other options.

Search Phrase 1: “show tier1 belongs to commodity \$name”

After entering “Show tier1 belongs to commodity” plus the name of a main commodity group, all tier-1 of this commodity group will appear. The corresponding tier-1s are displayed with their respective properties from the companies.csv file. Figure 2 shows the search phrase “show tier1 belongs to commodity” for Commodity 1 within the exemplary graph database.

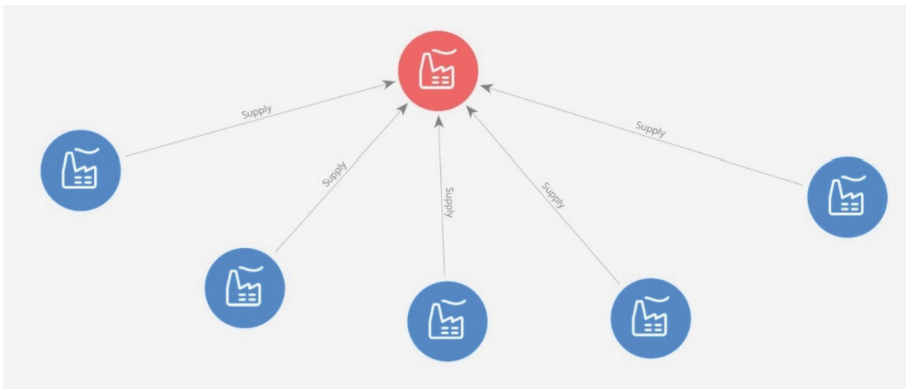


Fig. 2. Search Phrase “show tier1 belongs to commodity” in Neo4j.

All five Tier-1 of the product group “Commodity 1” with Company ID, Company-Name, production location, and corresponding processes are displayed. The properties are displayed when the corresponding Tier-1 is selected by mouse click. Figure 3 shows an example of the information obtained from the companies.csv file.

companyID	5
location	Slovakia
Name	Tekno Metallic sro
process	Machining, Casting, Raw Material
tier	1

Fig. 3. Information clicking on details in Neo4j.

Search Phrase 2: “show the shortest path from commodity \$commodity to leaf”

This displays the shortest supply chain within the selected commodity group. Figure 4

shows an example of the input “show the shortest path from commodity to leaf based on Commodity 2”. The user can see that the shortest supply chain within commodity 2 contains three links. Red always corresponds to the commodity as the graphical output. Blue represents the Tier-1 and yellow corresponds to the Tier-n.

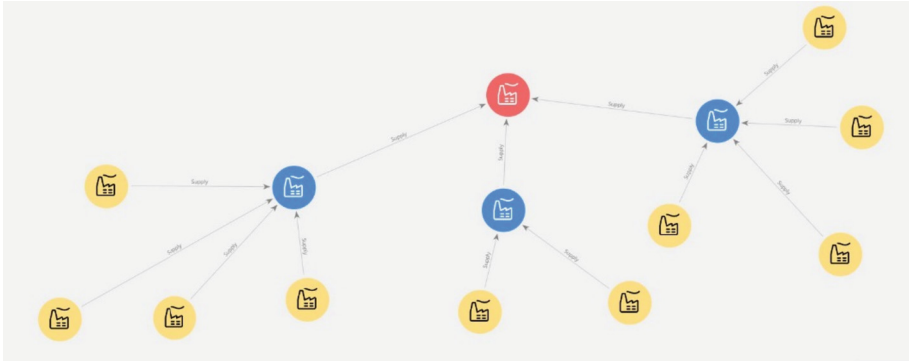


Fig. 4. Graphical output for search phrase 2 - shortest supply chain in Neo4j.

Search Phrase 3: “show \$process”

The user can display all companies within the entire supplier network that carry out the desired process in-house or supply certain components. Figure 5 shows an example of all suppliers who produce steel and use a blast furnace for this purpose. For each query in the graph database, the desired supplier can be selected by mouse click to get the same information as shown in Fig. 3.

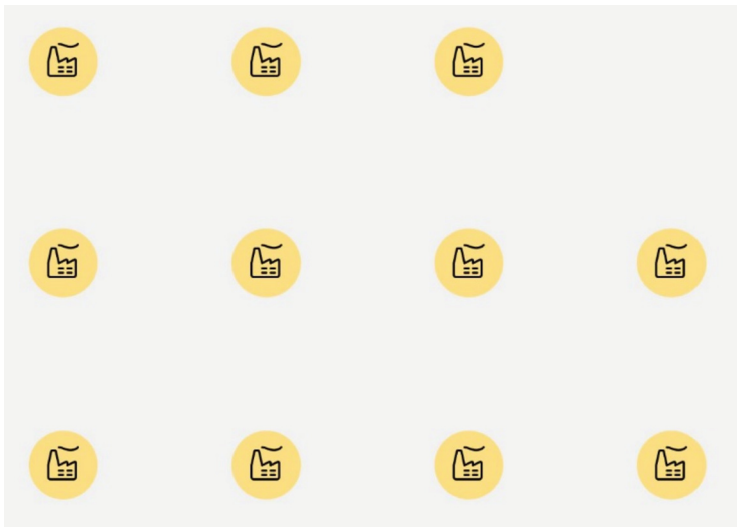


Fig. 5. Search Phrase “show blast furnace process” in Neo4j.

Search Phrase 4: “show country \$location with supplier”

When entering the desired state, the supply chain is indicated/visualized, which is supplied by the state in question. In Fig. 6, the query for Country 1 is visualized as a graph network. All yellow sub-suppliers are located in Country 1 and supply three tier-1s directly. This query is particularly helpful in the case of environmental disasters. Tier-1s are assigned to two different commodity groups. Shown in green is the OEM.

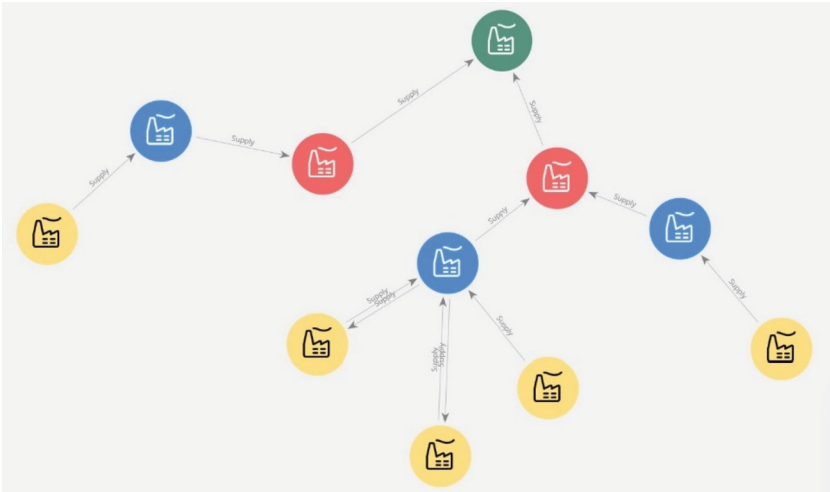


Fig. 6. Search Phrase “show Country 1 with supplier” in Neo4j.

Search Phrase 5: “show relations where more than \$elements elements are supplied”

This Search Phrase shows the user all relationships where more or equal components than the entered number are the subject of delivery. Figure 7 shows all connections between suppliers where more than 5 different components are supplied. Three tier-1s receive 5 different components from one sub-supplier. This could mean, that these 5 parts are always the same and at the same time two Tier-1 are dependent on one sub-supplier. Otherwise, a Tier-1 might follow a dual source strategy.

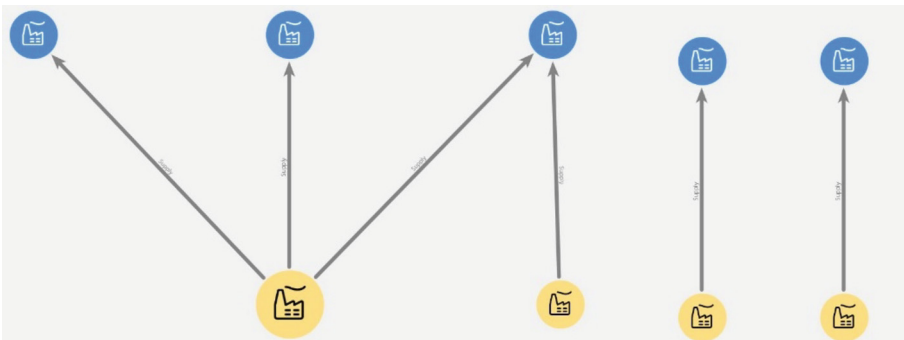


Fig. 7. Search Phrase “show relations where more than 5 elements are supplied”.

Search Phrase 6: “show critical nodes”

The user has the possibility to generate a network that includes sub-suppliers that supply more than e.g. three additional tier-n. This allows the user to see at a glance with which suppliers the possibility of a dual source strategy should be discussed to increase the resilience of the multi-tier network.

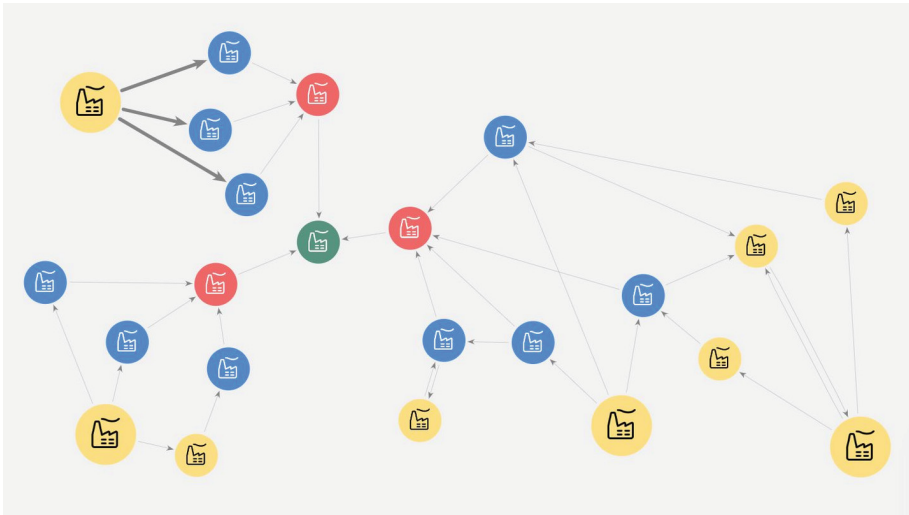


Fig. 8. Search Phrase “show critical nodes”.

Figure 8 shows four tier-n's found to be critical, which supply three other tier-n's in parallel. These are identifiable by the size of the nodes. The material group at the top left of the picture is a mechanical assembly. Here, one sub-supplier supplies three tier-1s at the same time. The wide arrows indicate that more than five different components are the subject of the delivery. At the bottom left, the Commodity 4 is shown. Here, the user can see that two tier-1s receive raw material directly and one tier-1 obtains raw material through a distributor. In Commodity 5 – in the image on the right – two sub-suppliers are connected to four tier-1s at the same time. All tier-1s receive their raw material from the same supplier. On the far right of the picture, a tier-n is shown that offers the material analogously for two tier-1s.

5 Discussion

The visualization of the investigated networks holds a lot of information for the user by using the predefined/-programmed search phrases (queries). The expertise on individual supply chains and the network at hand can be obtained by simple conditions and by entering a Search Phrase. Through the different possibilities of the search (here in this work 8 possibilities were tested, whereby still many more can be inserted) analyses and investigations along the multi-tier value chain can be visualized very intuitively and

thereby risks can be identified and simplified. This holds great potential for companies. A big advantage especially for SMEs is the fact that Neo4j is a free open-source solution. For example, by entering “show critical nodes”, all sub-suppliers that supply at least two other suppliers or tier-1 are displayed. This view helps the user to perform risk analyses. For example, possible strategies can be discussed together with the corresponding tier-1. The points of security of supply can play an important role and possibly a dual source strategy can be considered.

To summarize the following advantages can be identified in the proposed/applied methodology using graph database visualization compared to traditional non-visual analysis:

- User-friendly representation and thus easier interpretation of visual data compared to data in tabular form;
- Easy identification of the length of a supply chain for different commodities;
- Easy identification of suppliers with competencies in certain processes for support of the procurement and supplier selection;
- Easy identification of countries, supply chains, commodities with potential risks (e.g. political situation)
- Easier identification of dependencies of single suppliers along the whole supply chain and thus easier definition of critical nodes or supply chains.

As a limitation can be mentioned that the installation of Neo4j and the programming of the Search Phrases is not that user-friendly without basic know-how in the software and database systems. Especially for SMEs, this could create problems as long Search Phrases are not predefined in a generic template model adapted to the individual SME company. However, an introduction to the basic programming functions of Neo4j is needed. As a suggestion there is added that the entry in the software using tutorials provided by the software company makes it easier for SMEs to start using this tool. Additionally, constant updates of the software are required to keep the software working consistently. During updates, inconsistencies may occur regarding the input of a Search Phrase. When this happens, Neo4j reports an error in the code, which means that this existing program code must be adjusted. In general, the average end user (especially in SMEs) has no knowledge of Neo4j programming and cannot proceed without expert assistance, which shows a limitation for applying Neo4j graph database to SME companies.

Further additional challenges and drawbacks associated with the proposed software solution (and similar also for other solutions in the field) could be issues related to scalability and stability or data security. Using the tool in one single case or plant might be still quite easy. In case of larger companies or companies with several geographically distributed subsidiaries such issues need to be addressed already in advance before deciding for a specific software tool.

As practical challenges might be added that it takes a significant effort in sense of time and training of human resources to use such a tool in real-world manufacturing companies.

A general limitation of this research is, that no quantitative parameters or studies are elaborated to prove that graph database visualization tools help increasing resilience in

manufacturing. Therefore, there is further research needed to quantify the potential and to define measurable parameters.

6 Conclusions

Based on the visualizations of the search phrases in the graph-based database, multi-tier supplier strategies can be derived. These include, for example, dual source strategies to find short-term solutions in the event of supply bottlenecks. The actions derived from the transparent visualization of multi-tier supplier networks increase the resilience of supply chains and ultimately the resilience of the entire network against external and internal obstacles.

For the implementation in manufacturing companies, the requirements for the entire system must be defined. Criteria such as user interaction, interface requirements, and setup of the database are fundamental here. Finally, data security for suppliers and manufacturers in particular should be examined and defined for a possible implementation in a company.

The outcome of this research shows the potential laying in the use of (open) software tools and especially in using graph database visualization tools for increasing resilience in multi-tier supply chains. This research is especially addressed to practitioners in the field showing, based on some practical examples, how these tools are adding value. However further research based on real industrial case studies in different sectors needs to be done for investigating specific challenges to be solved with further research. A specific focus should be given in further case study research to measure and investigate the quantitative impact of this methodology towards resilience in manufacturing companies.

Acknowledgments. This project has received funding from the European Union's HORIZON-MSCA-2021-SE-01 program under the Marie Curie grant agreement No. 101086487. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union.



References





1. Hofstetter, J.S.: Extending management upstream in supply chains beyond direct suppliers. *IEEE Eng. Manage. Rev.* **46**(1), 106–116 (2018)
2. Lambert, D.M., Cooper, M.C., Pagh, J.D.: Supply chain management: implementation issues and research opportunities. *Int. J. Logistics Manag.* **9**(2), 1–20 (1998)
3. Sawik, T.: A two-period model for selection of resilient multi-tier supply portfolio. *Int. J. Prod. Res.* **58**(19), 6043–6060 (2020)
4. Tsay, A.A.: Designing and controlling the outsourced supply chain. *Found. Trends® Technol. Inf. Oper. Manag.* **7**(1–2), 1–160 (2014)
5. Dodel, J.-H.: Supply Chain Integration: Verringerung der logistischen Kritizität in der Automobilindustrie. *Schriften zum europäischen Management*. Deutscher Universitätsverlag, Wiesbaden (2004). <https://doi.org/10.1007/978-3-322-81720-4>. Accessed 21 Feb 2023
6. Göpfert, I., Braun, D., Schulz, M.: *Automobillogistik*. Springer, Wiesbaden (2013). <https://doi.org/10.1007/978-3-658-01582-4>

7. Mena, C., Humphries, A., Choi, T.Y.: Toward a theory of multi-tier supply chain management. *J. Supply Chain Manag.* **49**(2), 58–77 (2013)
8. Zunk, B.M., Woschank, M., Reinisch, M.G., Weller, S.B.: Management of critical lower-tier suppliers in global networks: practical relevance, literature review, and management perspectives. *IEEE Eng. Manage. Rev.* **48**(4), 181–194 (2020)
9. Schmid, M.: Unternehmerische Rohstoffstrategien: Zum Umgang mit kritischen Versorgungssituationen. *Supply Chain Management, Beiträge zu Beschaffung und Logistik*. <https://doi.org/10.1007/978-3-658-29007-8>. Accessed 30 Sept 2023
10. Kolmykova, A.: *Supply Chain Integration: Entwicklung eines Integrators für die globale Supply Chain*. Springer, Wiesbaden (2015). <https://doi.org/10.1007/978-3-658-02664-6>
11. Erhun, F., Kraft, T., Wijnsma, S.: Sustainable triple-A supply chains. *Prod. Oper. Manag.* **30**(3), 644–655 (2021)
12. Lee, H.L.: The triple-A supply chain. *Harv. Bus. Rev.* **82**(10), 102–113 (2004)
13. Cohen, M.A., Kouvelis, P.: Revisit of AAA excellence of global value chains: robustness, resilience, and realignment. *Prod. Oper. Manag.* **30**(3), 633–643 (2021)
14. Matt, D.T.: Template-based production system design. *J. Manuf. Technol. Manag.* **19**(7), 783–797 (2008)
15. MBR. The New AAA Supply Chain. *Management and Business Review*. <https://mbrjournal.com/2021/01/26/the-new-aaa-supply-chain/>. Accessed 22 Jan 2023
16. Werner, H., Werner, H.: Einfluss von Führungskonzepten auf die Gestaltung der supply chain. In: *Supply Chain Management: Grundlagen, Strategien, Instrumente und Controlling*, pp. 97–132 (2017)
17. Sauer, P.C., Seuring, S.: A three-dimensional framework for multi-tier sustainable supply chain management. *Supply Chain Manag. Int. J.* **23**(6), 560–572 (2016)
18. Han, J., Shin, K.: Evaluation mechanism for structural robustness of supply chain considering disruption propagation. *Int. J. Prod. Res.* **54**(1), 135–151 (2015)
19. Fan, Y., Stevenson, M.: A review of supply chain risk management: definition, theory, and research agenda. *Int. J. Phys. Distrib. Logist. Manag.* **48**(3), 205–230 (2018)
20. Nakatani, J., et al.: A graph theory-based methodology for vulnerability assessment of supply chains using the life cycle inventory database. *Omega* **75**(2), 165–181 (2018)
21. Schröder, M., Wegner, K.: *Logistik im Wandel der Zeit—Von der Produktionssteuerung zu vernetzten Supply Chains*. Springer, Wiesbaden (2019). <https://doi.org/10.1007/978-3-658-25412-4>
22. Piepmeyer, L.: *Grundkurs Datenbanksysteme: Von den Konzepten bis zur Anwendungsentwicklung*. Hanser, Munich, Wien (2011)
23. Fasel, D., Meier, A.: *Big Data*. Springer Fachmedien Wiesbaden, Wiesbaden (2016)
24. Khasawneh, T.N., AL-Sahlee, M.H., Safia, A.A.: SQL, NewSQL, and NoSQL databases: a comparative survey. In: *2020 11th International Conference on Information and Communication Systems (ICICS)*, pp. 013–021. IEEE (2020)
25. Rai, A., Miraz, M.M.I., Das, D., Kaur, H.: SQL injection: classification and prevention. In: *2021 2nd International conference on Intelligent Engineering and Management (ICIEM)*, pp. 367–372. IEEE (2021)
26. Truică, C.-O., Apostol, E.-S., Darmont, J., Pedersen, T.B.: The forgotten document-oriented database management systems: an overview and benchmark of native XML DODBMSes in comparison with JSON DODBMSes. *Big Data Res.* **25**(2), 100205 (2021)
27. Ivanova, T.S., Ivanov, E.A.: Research and development of the method of investigating the possibility of transformation relational databases to NoSQL. In: *Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus)*, 26–29 January 2021, St. Petersburg, Moscow, Russia, pp. 2090–2093. IEEE (2021)
28. Syed, S., et al.: Document oriented graphical analysis and prediction. *Stud. Health Technol. Inform.* **270**, 183–187 (2020)

29. Sakr, S., Zomaya, A.Y.: Encyclopedia of Big Data Technologies. Springer, Cham (2019). <https://doi.org/10.1007/978-3-319-77525-8>
30. Neo4j. Supply Chain Intelligence: Future-Proof Your Supply Network. <https://neo4j.com/blog/supply-chain-intelligence/>. Accessed 29 Oct 2023



A Racing Approach: The Evolution of Racing Techniques, A Systematic Literature Review

Hugo Silva¹, André S. Santos¹ , Leonilde R. Varela² , Magdalena Diering³ ,
and Khrystyna Berladir⁴ 

¹ Polytechnic Institute of Porto, Porto, Portugal

² University of Minho, Guimarães, Portugal

³ Poznan University of Technology, Poznan, Poland
magdalena.diering@put.poznan.pl

⁴ Sumy State University, Sumy, Ukraine

Abstract. Selecting the right values for an algorithm's parameters usually is a difficult, critical, and time-intensive endeavor. Though parameters can be traditionally adjusted in an empirical way, recent research indicates that automated tuning methods can frequently identify superior parameter configurations. In this sense, Racing Techniques emerge as a method of tuning hyperparameters and finding the best configurations for an algorithm. It is a time and resource efficient method. One of the more explored techniques in racing is the F-Race.ones. This work is a systematic literature review. The first section provides the context surrounding Racing Techniques. The second section explores the literature currently available on overall Racing Techniques and F-race, introducing all the essential concepts. The third section presents the research problem. The fourth section relates case studies of other works, being complemented by a bibliometric review that shows the growth of the concepts presented. The fifth and last section completes the work with the future paths for Racing Techniques, where opportunities arise in different fields of study, and provides the conclusions drawn.

Keywords: Parameter optimization · Racing techniques · F-race

1 Introduction

The world is demanding quicker, faster and better results. This is applicable not only to people's day to day lives, but also to almost every industry in the current era. Historically, improvements were made by empirical knowledge and trial-and-error approaches, such that in 2006 Vanschoren [1] claimed that the majority of the time, around 90%, dedicated to algorithm development was dedicated to find the optimal parameter values [2].

As such, developments in parameter optimization have been made during the last decades. First, Parameter optimization is the process of finding the optimal values for the parameters of a machine learning model that maximize or minimize a given objective function [3]. The concept of parameter optimization is increasingly relevant, as explored throughout this paper, given its applicability in developments in machine learning. One

of the most famous methods for parameter optimization are racing techniques. These are algorithms that compare a set of candidates based on their performance on a subset of data or objective function, and then eliminate the inferior ones until only the best one remains. Racing techniques can reduce the number of evaluations needed to find the optimal solution, as they can quickly discard the bad candidates and focus on the promising ones. Moreover, racing techniques can adapt to different types of problems and handle noise and uncertainty in a robust way. This concept is detailed in the Sect. 2.

This paper is structured as follows: the Sect. 1 introduces the work and the context around Racing Techniques, parameter optimization and metaheuristics; the Sect. 2 offers an overview of inferential statistics, along with every concept related to this topic and also to racing techniques, being portrayed as a literature review; the Sect. 3 explains the research problem seeks to address and answer; the Sect. 4 presents the results obtained through a bibliometric research and case studies; the Sect. 5 analyses the limitations of the research, the future paths and the conclusions that the authors take from this work.

2 Literature Review

This section dives into the existing literature related to the Racing Techniques, which can be defined as a group of methods associated with parameter optimization [4].

First, it is important to fully understand the definition of parameters. As for the classification, three classes emerge: numerical, categorical, and conditional. Normally, categorical parameters are presented as discrete choices and alternative procedures. These types of parameters may or may not be organized. For numerical parameters, these are typically divided into continuous or integer values. There are also continuous parameters converted into the integer form, named quasi-continuous parameters. Frequently, conditional parameters arise from certain values assumed by categorical parameters. As its name suggests, they depend on the condition of other parameters [5].

Ultimately, an optimization procedure aims to find a space of feasible configurations or the optimal configuration among a fixed number of candidate configurations [6]. It is easy to conclude that this universe of possible configurations grows continuously with the increase of the number of parameters assumed as input.

Structurally, this section is subdivided into two phases: first, an explanation of the statistical inference principles needed to properly perform and explore Racing Techniques are presented; secondly, a broad overview of Racing Techniques is displayed, along with a deep overview of the famous F-Race and Iterated F-Race techniques.

2.1 Statistical Inference

A possible explanation for statistics is that of a tool used for translating data and problems to tangible information, which may help managers and leaders make the best decisions. It is divided into two main areas: descriptive and inferential [7]. The first can be understood as a characterizer of data, revealing indicators such as average or dispersion [7]. As for the second, inferential statistics emerge from the difficulty and cost in studying all the population and, as such, sampling became an attractive and efficient option to replace studying the entire population [7]. It is basically a projection applied to the universe

being studied, based only on the results obtained from analyzing a sample. In order to properly apply inferential statistics, it is highly recommended to use the biggest sample size possible, as well as applying randomness every time is possible [8].

A concept highly associated with inferential statistics are the hypothesis tests. These can be defined as affirmations that seek to understand the relations between variables [8]. After having the problem properly defined, hypothesis tests invoke two possible affirmations: the null hypothesis, H_0 , which affirms that there is no relation between variables, or the alternative hypothesis, H_1 . Then, the p-value is calculated, which will indicate, by the comparison with the trust level if the null hypothesis should be rejected or not [9].

Still related to inferential statistics, there are two types of tests: parametric and non-parametric. The first assume some aspects, such as: normality, which should be tested if the sample size is inferior to 30, otherwise normality is assumed [10]; independency between data; inexistence of outliers [11]; equal variance between groups. These are the most desirable type of tests, due to having improved sensitivity to relations between variables.

Contrarily to parametric tests, non-parametric tests do not require these assumptions, and can be applied to every case [12]. There can be made an equivalence association, present in Table 1:

Table 1. Equivalence between parametric and non-parametric tests

Parametric tests	Non-Parametric tests
One-way ANOVA	Kruskal-Wallis
Paired t-test	Wilcoxon Sign-Rank
Repeated measures ANOVA	Friedman's two-way analysis of variance by ranks

Specifically, for Racing Techniques, two of these tests are used: Wilcoxon Sign-rank test for candidate pairs, and Friedman's test for general applications [6]. The first tests if there are differences between two groups, following the procedure: pair the data; calculate and rank the differences; assign positive or negative signs to ranks; sum all the ranks; determine significance; analyze and take conclusions [13]. For the second, it serves as an extension of the first, that can be applied to more than two groups [14].

2.2 Racing Techniques, F-Race and Iterated F-Race

The racing approach appeared as a development over a simpler approach, the brute-force approach. This approach had two big disadvantages: the number of evaluations has to be defined before beginning the procedure, and resources are allocated equally to poor and good performing configurations [5]. The racing approach can be defined as an algorithm that iteratively evaluates target configurations on different problem instances from a defined set, which recurs to statistical tests to eliminate the worst-performing candidates and end up with the best contender [15]. The comparison between the brute-force approach and the racing approach is presented in Fig. 1, where the curve reveals the racing

procedure, highlighting the decrease of candidates with the increase of instances, and the brute-force approach represented by the rectangle area, meaning that the candidate number does not vary with the increase in instances of the tests.

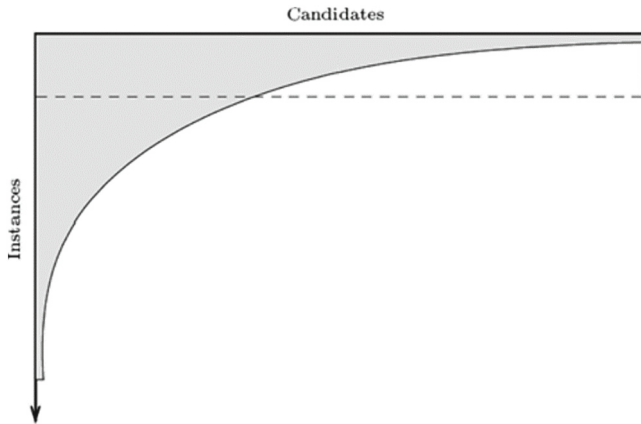


Fig. 1. Brute-force approach vs Racing approach [5]

The first racing technique was introduced by Hoeffding. Based on this authors' inequality, it uses learning boxes and evaluates their errors on a group of instances and, using nonparametric tests related to the true error, it eliminates the configurations that show the lower bound of the true error worse than the upper bound of the best candidate [16].

One of the most famous variants of the racing techniques is the F-Race, proposed by Birattari et al. [6]. It is defined as a procedure, constituted by a concise structure of steps, with the goal of simplifying the evaluation and filtering of candidate configurations. Through a selected number of sample instances, a candidate or set of candidates are selected in order to fit various [6] stochastic inputs that can be introduced into the parameters [6]. The aim is to select the ones that can provide robustness to the system. It uses statistical tests to validate its results, inducing the algorithm to eliminate the worst-performing configurations [17]. The decider in the selection process is the non-parametric Friedman rank-based test (equivalent to the parametric One-way ANOVA with repeated variances), which determines if the space of configurations show no significant performance difference. In this sense, a null hypothesis is made, which supposes that there is no difference between configurations. In case the null hypothesis is rejected, which means that some configuration(s) perform better than others, post-hoc tests between the outliers and the underperforming are executed [15]. This procedure has two possible endings: either the computational budget reaches its established limit, or until a predefined number of candidates is reached [5]. The general steps to applying this type of procedure is presented in Table 2.

The basic approach for F-Race has its limitations. Maybe the biggest is related to the number of configurations, especially when the procedure includes a full factorial design [15]. This ends up decreasing the size of the configuration space. In this regard, newer

Table 2. Steps of the racing procedure

Step	Phase	Description
I	Setup	Define candidate configurations, metrics, and budget
II	Evaluation	Run the configurations and evaluate their results
III	Statistical Testing	Perform statistical tests, such as Friedman's ranked based test
IV	Exclusion	Eliminate worst-performing configurations
V	New Run	Repeat Steps II, III and IV
VI	Selection	The remainder(s) configuration(s) is selected as the most fit to the instances sampled

techniques like Iterative F-Racing were developed, which are more robust and diminish these limitations [17].

Iterative F-Race, proposed by Balaprakash is based on, as the name suggests, an iterative procedure that starts with applying a probabilistic model, which can be explained as the sampling of a set of candidate configurations [5], followed by a standard F-Race procedure. After one instance is finished, its results update the probabilistic model [15], improving the algorithm each time a new instance is presented. This method contains the assumption that all the considered parameters are numerical [17]. It is also essential to define the number of iterations that the algorithm should run, considering the budget, and set of candidates [5].

3 Research Problem

This paper seeks to explore the evolution of Racing Techniques, being defined as a systematic review of the literature.

In earlier sections, the topics of statistical inference and racing methods were introduced and explained. Initially, a bibliometric research is conducted on the aforementioned topic to trace its evolution and emphasize its significance within the academic and industrial universes. The research was based on the top 500 articles, journals, or papers related to racing techniques from the Web of Science. The Biblioshiny software, a feature of Bibliometrix, was employed for this analysis. However, it's worth noting that the software's timeline starts in 1992, preventing the analysis of earlier developments. Conclusively, the paper delves into selected case studies from two perspectives: a concise overview of the research, followed by the insights derived by the respective authors.

4 Results

Having already presented the literature review needed to understand the concepts being discussed, as well as having the research problem explained, this section dives into the results of this work. It can be interpreted as a still photograph of the evolution of Racing Techniques in the modern era, the 2020's.

First, a bibliometric research is performed, highlighting the relevance and growth of this parameter optimization technique in academia. Subsequently, a set of case studies is elaborated upon in two aspects: an initial overview of the study, and the subsequent conclusions drawn by the authors from their research.

4.1 Bibliometric Research

Beginning this study in 1991, Fig. 2 presents the main information regarding the “Racing Techniques”, in the context of parameter optimization. It can be concluded that it has been growing year after year, with an average annual growth rate just shy of 7%.



Fig. 2. Racing techniques main information

Geographically, the country that contributed more to the development and research of Racing Techniques was the USA, followed by China and India, Fig. 3. Europe has also contributed prominently.

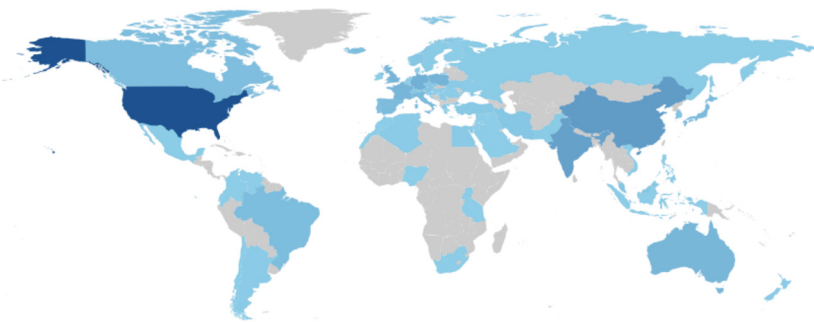


Fig. 3. Contribution by country

As for the words and expressions associated with the topic being analyzed, Fig. 4 shows that performance is the main key word, followed by parameters, diagnosis, design, exercise, and many others.

Table 3. (continued)

Study	Description	Conclusions
A unified race algorithm for offline parameter tuning [19]	<p>This work introduces a new racing algorithm that seeks to optimize the performance of a give metaheuristic. It innovates in how it is structured, starting with the choice of candidate configurations, using the Latin Hypercube Sampling technique. Then, using the paired signed rank test, is eliminates the worst performing configurations. Finally, it creates new configurations that guarantee better performance, based on the biased sampling distribution method</p> <p>To test this algorithm, an industry problem was proposed, within the context of a multinational company, with the goal of minimizing the number of containers necessary to load every selected item. This test involved 20 instances and a tuning budget of 24 h. The performance of uRace was compared to the George and Robinson 1980's algorithm, as well as the Bischoff, Janetz and Ratcliff 1995's algorithm</p>	The paper concludes that the new algorithm based on the racing methodology can be applied to deterministic and stochastic problems. It may even be applied to simulations. The results highlight the advantage in performance uRace is able to provide, even in real-world scenarios, due to this algorithm outperforming the other two mentioned. This allowed to save 5–15% on pallet and container usage
Iterated racing algorithm for simulation-optimization of maintenance planning [20]	<p>With the goal of reducing operational costs, a maintenance planning problem is proposed to optimize the NPV (Net Present Value) of assets in a company. Recurring to a simplified VME tool, the user seeks to determine the best maintenance dates to maximize the NPV. This indicator acted as the metric for the entire work. For this, iterative Racing is proposed, using statistical tests to compare solutions</p> <p>The experiments are benchmarked on 175 instances, that had a variety of seven problem sizes, based on the number of components in evaluation. The two parameters evaluated were population size and truncation rate. For each run, 500000 simulations were executed, given that each run was replicated 25 times. The metrics that evaluated the racing algorithm were the number of races during a run and the number of solutions evaluated per race. Finally, the authors used Friedman's test and Holm's procedure to verify statistical significance within the tests</p>	This paper concludes that population size is the factor that influences the algorithm's performance the most. It also concludes that, for larger problems, a wider exploration of the search space is recommended. As a broader conclusion, this paper demonstrates the robustness and effectiveness of iterated racing techniques, given that the algorithm parameters are properly selected around the problem's context and demands

5 Future Paths and Conclusions

Following all the context and concepts portrayed in this paper, it can be concluded that parameter tuning is a deal breaker in the performance of metaheuristic. Typically, and because the research is not yet extensive, the setting of parameters is usually fixed from the initial stage or set specifically in previously selected instances [18]. This paper seeks to fill the gap of systematic research that exists in the literature.

The future of techniques such as F-Race lie in their optimization and implementation in various scenarios. It has the potential to be compared to methods such as the Taguchi-based approach, an important concept of areas such as design of experiments [21, 22], as it was described in one previous case study. This specific case suggests that allocating more time and resources to the early phases of the procedure, which means increasing the number of iterations before the first elimination process, may lead to a decrease in

the probability of losing good candidates [18]. Another clear future path highlighted by this work, but is present in many others, is the hypothesis of mixing parameter-tuning strategies [18]. This may lead to effectively decreasing the negative aspects of the strategies being mixed.

There are also many alternative models and techniques that can complement, and even replace, the application of Racing Techniques in some cases. Some recent developed alternatives: In-Time Over-Parametrization, which explores the training deep neural networks [23, 24]; Surface Parametrization, which uses the quasi-conformal (QC) theory to define appropriate parameter settings [25, 26].

It is also possible to implement metaheuristics to parameterize a system, although it may not be as usual. Some of the most established metaheuristics are: Evolutionary algorithms, a recent development based on the biological evolutionary theory, using concepts like selection and mutations [27]; Simulated annealing, based on a metallurgical concept, a method of space searching to find the optimal solution, considering the candidates from the worse to best [28, 29]; Bayesian optimization, that explores a map created by hyperparameters, which gives way for a probabilistic model to be established and ends up with the hyperparameters with most potential [30].

With all the information presented in this work and considering the evolving context of increasing competitiveness in many fields, it is clear that now, more than ever, there is not much margin for resources to be spent on empirical testing, which usually take more time to get to an optimal solution than parameter tuning models, because it may lead to serious damage in businesses. There is a lot of open space for new research and development. As such, it is expected that parameter optimization techniques will grow even further and will be implemented vigorously in industrial situations in the next decades.

To conclude, the main result found in this paper is that racing techniques are being applied in many fields, as evidenced in the Sect. 4's bibliometric research, and forecast is for it to grow, both in increase in use, as well as the creation of new and improved techniques.

Acknowledgment. The research was partially supported by the Polish National Agency for Academic Exchange within the project “Digitalization in mechanical engineering” (agreement no. BNI-UE-2023-2).

References




1. van Rijn, J.N., Holmes, G., Pfahringer, B., Vanschoren, J.: Algorithm selection on data streams. In: Džeroski, S., Panov, P., Kocev, D., Todorovski, L. (eds.) *Discovery Science: 17th International Conference, DS 2014, Bled, Slovenia, 8–10 October 2014, Proceedings 17, DS 2014*. LNCS, vol. 8777, pp. 325–336. Springer, Cham (2014). https://doi.org/10.1007/978-3-319-11812-3_28
2. Adenso-Diaz, B., Laguna, M.: Fine-tuning of algorithms using fractional experimental designs and local search. *Oper. Res.* **54**(1), 99–114 (2006)
3. Hutter, F., Kotthoff, L., Vanschoren, J.: *Automated Machine Learning: Methods, Systems, Challenges*. Springer, Cham (2019). <https://doi.org/10.1007/978-3-030-05318-5>

4. Becker, S., Gottlieb, J., Stützle, T.: Applications of racing algorithms: an industrial perspective. In: Talbi, E.G., Liardet, P., Collet, P., Lutton, E., Schoenauer, M. (eds.) *Artificial Evolution, EA 2005*. LNCS, vol. 3871, pp. 271–283. Springer, Cham (2005). https://doi.org/10.1007/11740698_24
5. Birattari, M., Kacprzyk, J.: *Tuning Metaheuristics: A Machine Learning Perspective*, vol. 197. Springer, Cham (2009). <https://doi.org/10.1007/978-3-642-00483-4>
6. Klazar, R., Engelbrecht, A.P.: Parameter optimization by means of statistical quality guides in F-Race. In: *2014 IEEE Congress on Evolutionary Computation (CEC)*, pp. 2547–2552. IEEE (2014)
7. Fisher, M.J., Marshall, A.P.: Understanding descriptive statistics. *Aust. Crit. Care* **22**(2), 93–97 (2009)
8. Byrne, G.: A statistical primer: understanding descriptive and inferential statistics. *Evid. Based Libr. Inf. Pract.* **2**(1), 32–47 (2007)
9. Berger, R.W., Benbow, D.W., Elshennawy, A.K., Walker, H.F.: *The Certified Quality Engineer Handbook*. ASQ Quality Press (2006)
10. Kwak, S.G., Park, S.-H.: Normality test in clinical research. *J. Rheum. Dis.* **26**(1), 5–11 (2019)
11. Ghosh, D., Vogt, A.: Outliers: an evaluation of methodologies. In: *Joint Statistical Meetings* (2012)
12. Sahu, P.K., Pal, S.R., Das, A.K.: *Estimation and Inferential Statistics*. Springer, Cham (2015). <https://doi.org/10.1007/978-81-322-2514-0>
13. Bagkavos, D., Patil, P.N.: Improving the Wilcoxon signed rank test by a kernel smooth probability integral transformation. *Stat. Probab. Lett.* **171**, 109026 (2021)
14. Morgan, G.A., Gliner, J.A., Harmon, R.J.: Selection of inferential statistics: an overview. *J. Am. Acad. Child Adolesc. Psychiatry* **41**(4), 478–481 (2002)
15. Hoos, H.H.: Automated algorithm configuration and parameter tuning. In: Hamadi, Y., Monfroy, E., Saubion, F. (eds.) *Autonomous Search*, pp. 37–71. Springer, Cham (2012). https://doi.org/10.1007/978-3-642-21434-9_3
16. Maron, O., Moore, A.: Hoeffding races: accelerating model selection search for classification and function approximation. In: *Advances in Neural Information Processing Systems*, vol. 6 (1993)
17. Balaprakash, P., Birattari, M., Stützle, T.: Improvement strategies for the F-Race algorithm: sampling design and iterative refinement. In: Bartz-Beielstein, T., et al. (eds.) *Hybrid Metaheuristics: 4th International Workshop, HM 2007, Dortmund, Germany, 8–9 October 2007, Proceedings 4, HM 2007*. LNCS, vol. 4771, pp. 108–122. Springer, Cham (2007). https://doi.org/10.1007/978-3-540-75514-2_9
18. Gümüş, D.B., Özcan, E., Atkin, J., Drake, J.H.: An investigation of F-Race training strategies for cross domain optimisation with memetic algorithms. *Inf. Sci. (N Y)* **619**, 153–171 (2023)
19. van Dijk, T., et al.: A unified race algorithm for offline parameter tuning. In: *Proceedings of the Winter Simulation Conference 2014*, pp. 3971–3982. IEEE (2014)
20. Lacroix, B., McCall, J., Lonchamp, J.: Iterated racing algorithm for simulation-optimisation of maintenance planning. In: *2018 IEEE Congress on Evolutionary Computation (CEC)*. IEEE (2018)
21. Silva, H., Santos, A.S., Varela, L.R., Trojanowska, J., Berladir, K.: Design of experiments: an overview and future paths. In: Burduk, A., Batako, A., Machado, J., Wyczółkowski, R., Antosz, K., Gola, A. (eds.) *Advances in Production, ISPEM 2023*. LNNS, vol. 790, pp. 328–341. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-45021-1_25
22. Diering, M., Dyczkowski, K., Hamrol, A.: Rating system analysis in quality engineering based on fuzzy similarity. *J. Multiple-Valued Logic Soft Comput.* **32**(3–4), 277–292 (2019)
23. Liu, S., Yin, L., Mocanu, D.C., Pechenizkiy, M.: Do we actually need dense over-parameterization? In-time over-parameterization in sparse training. In: *International Conference on Machine Learning*, pp. 6989–7000. PMLR (2021)

24. Pavlenko, I., et al.: Using regression analysis for automated material selection in smart manufacturing. *Mathematics* **10**(11), 1888 (2022). <https://doi.org/10.3390/math10111888>
25. Choi, G.P.T., Lui, L.M.: Recent developments of surface parameterization methods using quasi-conformal geometry. In: *Handbook of Mathematical Models and Algorithms in Computer Vision and Imaging: Mathematical Imaging and Vision*, pp. 1–41 (2022)
26. Kaščák, J., Husár, J., Knapčáková, L., Trojanowska, J., Ivanov, V.: Conceptual use of augmented reality in the maintenance of manufacturing facilities. In: Trojanowska, J., Kujawińska, A., Machado, J., Pavlenko, I. (eds.) *Advances in Manufacturing III*, vol. 2 – *Production Engineering: Research and Technology Innovations, Industry 4.0*, pp. 241–252. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-99310-8_19
27. Doerr, B., Eremeev, A., Horoba, C., Neumann, F., Theile, M.: Evolutionary algorithms and dynamic programming. In: *Proceedings of the 11th Annual Conference on Genetic and Evolutionary Computation*, pp. 771–778 (2009)
28. Zhou, E., Chen, X.: Sequential Monte Carlo simulated annealing. *J. Global Optim.* **55**, 101–124 (2013)
29. Pavlenko, I., Verbovyi, A., Neamtu, C., Ivanov, V., Ciszak, O., Trojanowska, J.: Fractional-order mathematical model of single-mass rotor dynamics and stability. *Alexandria Eng. J.* **76**, 91–100 (2023). <https://doi.org/10.1016/j.aej.2023.06.024>
30. Falkner, S., Klein, A., Hutter, F.: Combining hyperband and Bayesian optimization. In: *NIPS 2017 Bayesian Optimization Workshop*, December 2017



The Impact of PLM Systems on the Digital Transformation of Manufacturing Companies

Jan Duda¹ , Sylwester Oleszek² , and Krzysztof Santarek³ 

¹ Cracow University of Technology, Cracow, Poland

² Transition Technologies PSC S.A., Łódź, Poland
sylwester.oleszek@gmail.com

³ Warsaw University of Technology, Warsaw, Poland

Abstract. The present business landscape, particularly in the era of Industry 4.0, is characterized by dynamic development, global collaboration, and intense competition for customers. To navigate these challenges successfully, companies must establish mechanisms for close and effective cooperation. Concurrently, ongoing projects for the development and production of innovative products are imperative. However, the seamless integration of various business and IT systems used daily by a company is essential to achieve these goals. Among the pivotal IT systems, alongside established CAx and ERP solutions, Product Lifecycle Management (PLM) systems play a crucial role.

Implementing a PLM system poses a significant challenge for enterprises, as each implementation project follows a unique path. There is no universally established and proven method for successful PLM system implementation, given the diverse applications and varying levels of complexity and integration with other systems within an organization. Identifying the benefits derived from PLM systems is intricate due to their extensive application across different company areas.

The literature lacks concrete information, including figures, on the effects of implementing PLM systems. This paper aims to address this gap by presenting the characteristics of PLM systems and their role in modern enterprises. It delves into the implementation procedure, offering examples and effects in design, construction, technology departments, and the supply chain of enterprises operating globally, including those in Poland.

Keywords: Digital transformation of enterprises · Industry 4.0 technologies · implementation project · Product Lifecycle Management (PLM)

1 Introduction

The conceptualization and implementation of Industry 4.0 methodologies and technologies in manufacturing enterprises give rise to various challenges, encompassing both technical and organizational dimensions. Frequently, the digital transformation of enterprises unfolds within the existing IT systems that support enterprise management, including ERP, SCM, CRM, PLM systems, and others.

Product Lifecycle Management (PLM), as a conceptual framework, entails overseeing the entire life cycle of a product—from conception and design through production, operation, to its eventual end-of-life stages involving recycling or disposal. PLM systems serve as advanced and sophisticated IT tools, constituting a distinct class of systems that practically implement this concept. They integrate multiple applications employed to manage specific product development processes throughout the entire life cycle, covering aspects such as design, production, operation, and disposal. Consequently, PLM systems harmonize people, data, processes, and systems by collecting, storing, integrating, and ensuring the consistency and timeliness of product information. This information is then disseminated to various organizational units and other participants in the product life cycle [1]. Notably, PLM systems, especially in the context of Industry 4.0, play a pivotal role in the digital transformation of enterprises. Their significance stems from several key factors:

- **Repository of Valuable Information:** As a repository of structured and ordered product data, PLM systems constitute a fundamental component (pillar) of the digital transformation of the enterprise.
- **Environment for Industry 4.0 Technologies:** PLM systems provide an environment where Industry 4.0 technologies such as IoT, VR/AR, AI, 3D printing, and simulations are actively employed.
- **Integration Tool:** They serve as a tool for seamlessly integrating various Industry 4.0 technologies.
- **Hub for Information Processing:** PLM systems act as a central hub for storing, processing, and distributing information collected through the utilization of Industry 4.0 technologies.
- **Effective User Interface:** They serve as an effective, efficient, and attractive interface for users of PLM systems.
- **Creation of Conditions for Implementation:** PLM systems contribute to creating technical, organizational, and social conditions conducive to the successful implementation of Industry 4.0 technologies and the broader digital transformation of enterprises. This involves employee training, fostering awareness of the importance and possibilities of digital transformation, cultivating a “digital” enterprise culture, and enhancing overall readiness for digital transformation and the assimilation of Industry 4.0 technologies.

The article aims to elucidate the intricate process of implementing PLM systems in manufacturing enterprises and analyze the subsequent changes in enterprises that lacked such systems previously. It outlines the general characteristics of PLM systems, the requirements that companies must meet in the era of Industry 4.0, and the process of implementing PLM systems. Key arguments presented in the article are illustrated with examples showcasing the implementation of PLM systems in manufacturing enterprises.

2 Characteristics of PLM Systems

Product Lifecycle Management (PLM) is both a business strategy and a method aimed at effectively managing the processes of design, production, operation, and disposal of products throughout their entire lifecycle—from the initial product idea to its final

moments [2]. Additionally, this term denotes a category of information systems utilized for the comprehensive management of a product's lifecycle and related data and information [3]. PLM systems amalgamate numerous applications that, when operating within a unified environment, enable the holistic management of all aspects associated with extensive product development and lifecycle management.

The innovation-facilitating capabilities of PLM systems stem from their integration of people, processes, business systems, and information across the entire product lifecycle and throughout the enterprise. Importantly, they serve to mitigate the impact of functional silos, commonly known as the "silo effect" [4]. The vertical approach to organizational processes, treating the organization as a collection of isolated functions within distinct divisions or departments, imposes significant complications on its functioning. It is not uncommon for employees in individual functional departments, focused on their specific tasks, to lack awareness of the broader organizational goals and fail to fully comprehend the intricacies of other functional departments, as well as their contributions to achieving the company's objectives. This approach not only hinders the optimization of activities within individual departments but also poses considerable challenges in resolving issues involving employees from diverse functional units. PLM systems address and eliminate this challenge by establishing horizontal connections within the organization, fostering improved information exchange, effective change management, and the utilization of existing knowledge resources [4].

3 Requirements that Manufacturing Companies Must Meet in the Era of Industry 4.0

The intricacies of the contemporary business landscape in the era of Industry 4.0, characterized by rapid development, global collaboration, and fierce competition for customers, necessitate enterprises to establish mechanisms for close and effective cooperation. Concurrently, continuous endeavors to develop and implement innovative products into production are imperative. To attain these objectives effectively, the integration of various business and IT systems utilized daily by the company is essential. Alongside longstanding solutions like CAx, PDM, or ERP, emerging technologies such as the Industrial Internet of Things (IoT), digital twins, augmented reality (AR), virtual reality (VR), artificial intelligence, and others are increasingly becoming integral [5].

Hence, innovation and the creation of new products emerge as pivotal concerns for most enterprises, representing decisive factors influencing future revenue growth. Present-day customers anticipate a more frequent introduction of new products to the market, tailored to their individual needs and delivered at shorter intervals. With each product generation, heightened expectations include visually appealing design, enhanced performance, superior quality, lower costs, and easy accessibility. To meet these expectations, companies must foster close collaboration within their organizational structures, as well as with partners and suppliers situated in diverse regions globally. Concurrently, enterprises grapple with the escalating complexity of both products and production processes, driven by the increasing number of environmental requirements and regulations.

The Product Lifecycle Management environment, beyond ensuring seamless integration, facilitates the linkage of ongoing programs and innovation projects with the product portfolio. It also establishes connections with detailed activities related to product implementation, parallel engineering, and production processes.

4 The Process of Implementing PLM Systems in a Manufacturing Company

Due to the fact that the PLM environment is – apart from the ERP system – the most important and complex system in the enterprise, the purpose of implementing a PLM system is always related to the implementation of the company's strategic goals. For this reason, planning an implementation project is preceded by thorough analyses and preparatory work. Moreover, the list of requirements regarding the selection of the target system solution and the implementation plan is the result of numerous factors. Most often, these requirements stem from the current situation in the company, related to the existing approach to product development processes, and factors that hinder or even obstruct the effective implementation of specific strategic goals. Common implementation goals include:

- Significant reduction of the time needed to develop and implement new products into production.
- Shortening the lead time for introducing changes to existing products.
- Reducing the total costs of product implementation.
- Improved integration of companies within the organization and its branches, especially when one of the strategic goals is development through acquisitions.
- Implementation of global working standards across the organization, applicable to all branches, regardless of their location.
- Dissemination of product knowledge throughout the organization.
- Streamlining processes related to monitoring and supervision of innovative projects.
- Implementation of the strategy – one of the pillars of the Industry 4.0 concept – defined as ubiquitous production, based on the philosophy: “design anywhere, produce anywhere, sell anywhere, service anywhere.”

Each PLM system implementation project in an organization is carried out in a slightly different way. Just as there are no two identical organizations with the same needs, strategy, and method of operation, there is also no single, established, and proven way to implement a PLM system in every organization. Selected activities are common to each project and appear in some form in most projects, but detailed activities and the scope of the project must be determined each time in relation to the needs of a given enterprise.

An example of the PLM system implementation process in a manufacturing company consists of the following stages [6]:

1. In the first stage, the needs and overall requirements for PLM solutions correlated with the company's strategic goals are identified.

2. Then, initial market research is carried out in terms of available solutions and suppliers of the PLM system – the course and duration of this stage largely depend on the company’s current level of knowledge on this subject.
3. After collecting preliminary information, talks are held with initially selected suppliers, and general presentations of the solutions they offer are given.
4. At the next stage, the initial scope of the PLM system implementation is defined, and the list of required functionalities is compiled. Often, as part of these activities, presentations of individual functionalities of selected PLM systems are given by suppliers. The number of users, categorized by system functionalities criteria, is also estimated (e.g., number of CAD users, number of product managers, project managers, etc.). At this stage, workshops are also most often organized with a selected group of users, during which the participants get to know the system and evaluate its capabilities.
5. After initially defining the scope, learning about the capabilities of PLM systems, and establishing cooperation with potential suppliers of these solutions, the final decision is made. Both the target solution and the supplier who will be responsible for its implementation are selected. Making this decision may be preceded by the implementation of a Proof of Concept¹ (PoC) or a pilot project. The duration of such a project may range from 1–3 months (in the case of PoC) to 6 or even 12 months – in the case of pilot projects preceding very large implementations.
6. Once the exact scope of implementation, detailed requirements, and a preliminary plan are determined, and the supplier provides a project time and cost estimate for the work based on these, a contract is concluded between the ordering party and the supplier. This contract often includes elements such as a timetable for the purchase of licenses, estimated launch dates, and an initial training plan.
7. In the next step, a project charter is developed, a project plan including detailed work is laid out, a project team is formed, and the project is formally opened.
8. If the on-premise model is chosen, the first activities in the implementation project are:
 - a. Purchase and commissioning of the required server infrastructure;
 - b. Purchase of the first batch of PLM licenses;
 - c. Installation of the basic PLM system components required at the first stage of the project.

If a cloud computing environment is chosen, the installation and commissioning of the required PLM system components are carried out, and they are made available to the client’s selected users.

9. Once the PLM environment is up and running, implementation activities can begin. At this stage, the first training is planned in detail and delivered. Most often, a group of key users participates in the training first. At the beginning of the project, they play the role (together with the formal project leaders) of setting the rules of working in the new system and giving their opinion on the solutions presented by

¹ A Proof of Concept (PoC) implementation is a design or prototype crafted to validate the technical feasibility of an idea or solution. The primary purpose of a PoC is to assess a concept, evaluating its suitability, efficiency, and verifying its effectiveness.

the supplier. In addition to the key users, it is also necessary to identify and establish the first roles in the PLM system² (e.g., business administrator, design standards administrator, leader, etc.). One of the important elements of implementation work carried out at each stage of the project is the establishment and implementation of work methodologies in the new system. Only full understanding and acceptance of the principles of working in a PLM environment by the company's employees will ensure full and comprehensive use of its capabilities.

10. After completing the initial implementation work, training, and testing the functionality in the test environment, the start-up of the production environment can begin. The first production projects in the new environment are generally carried out by key users. It is common practice to select projects of low complexity executed according to a well-defined scenario. If a project phase is completed, acceptance testing of the functionalities implemented as part of that phase and formal acceptance are usually carried out.
11. In the next steps, the remaining stages of the project are followed in a similar way, and implementation work is carried out. When the processes involved in the development of a new product are analyzed and transferred to a new environment, most often a decision to streamline them is made. One effective method of doing this is 'Business Process Reengineering' (BPR) [7, 8].
12. In the final stages of implementation, the most complex tasks are carried out. They require both a good knowledge of the system to be implemented and the prevailing rules (this knowledge is gained during the project work). It is also important that the system is already largely implemented and operating stably. Examples of complex tasks carried out in the final phases of implementation are:
 - a. Development of integration with existing systems in the company (such as ERP, CRM, production or sales systems);
 - b. Implementation of options and variants management;
 - c. Integration with the company's existing product configurator.
13. The final stage of the implementation project is the acceptance testing of the entire system and its final approval. A common practice as part of acceptance is the implementation of system-wide test scenarios.

After final approval, further steps are usually planned related to the development of the system, its further improvement, launching new functionalities that have not been taken into account so far, or updating the system to a new version. The described process is presented in Fig. 1.

² The names and meanings of specific roles within the PLM system are contingent upon the chosen system solution and the preferences of the company commissioning the system. These roles can be extensively configured within the system.

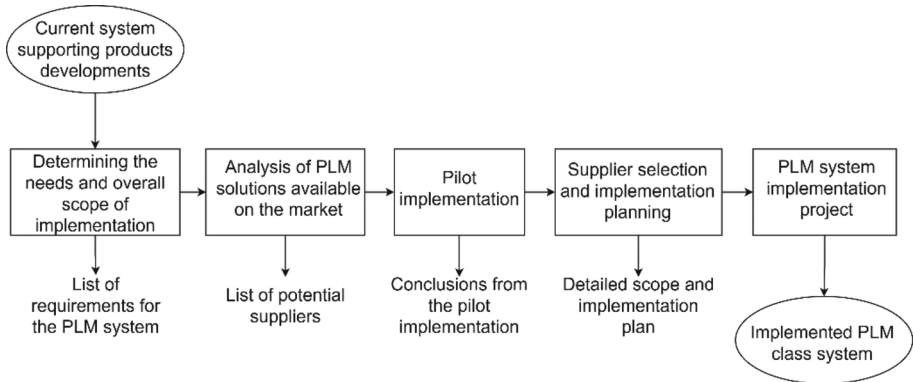


Fig. 1. The process of implementing the PLM system in a manufacturing company. Source: own elaboration based on [9].

5 Effects of Implementing PLM Systems

Important issues related to PLM systems encompass the effects arising from their utilization. Given the wide-ranging applications of PLM systems across various areas within a company, their complexity, and the level of integration with other systems, identifying the benefits organizations derive from their use is an intricate task [10]. It's noteworthy that the literature lacks reliable, specific information, including figures, regarding the effects of implementing PLM systems. This deficiency applies to both PLM system users, who are often reluctant to share detailed information, and the producers (suppliers) of these systems. The sensitivity of PLM systems in the business sphere contributes to this situation. Scientific literature typically delves into theoretical and methodological aspects of PLM system evaluation, with research results focusing on individual cases of PLM system implementation, making it challenging to draw generalizing conclusions.

According to the assumptions guiding the development of PLM class systems, they deliver benefits throughout the product lifecycle, falling into four groups:

- Economic
- Social
- Environmental
- Technical and Organizational

These benefits extend to different stakeholder groups, including producers (enterprises and their employees, owners, etc.), users (product purchasers), and society and the environment at large. The mentioned benefits target producers during design, production, product operation, and the post-use phase; product users during the product operation phase; society during the product operation and post-use phase; and the environment, predominantly during the production, operation, and end-of-life phase. This approach facilitates calculating total costs over the entire product lifecycle.

The most significant benefits of using PLM systems in each phase of the product lifecycle, in a broad sense, include [6]:

- In the product development (design) phase, there is primarily a reduction in the time needed to develop a product, from concept to market launch (time to market), as well as a reduction in the costs of developing a new product. A faster time to market provides advantages in gaining a larger market share, achieving a higher selling price, and reaping benefits related to the production learning effect.
- In the production phase, the main beneficiaries are businesses and the environment. Enterprise benefits include faster introduction (launching) of new products into production and lower production costs due to the use of Design for X tools, target costing, etc. Environmental benefits primarily involve the reduction of pollution and waste generated during production due to the use of green product manufacturing technologies.
- At the stage of product exploitation, the PLM system serves as a source of information for processes related to service and product maintenance. Additionally, PLM systems encompass processes for changing and modifying the product, enabling the faster and easier introduction of its new, improved version to the market. Beneficiaries of PLM systems include companies, users (product buyers), society, and the environment.
- In the end-of-life phase, PLM systems provide information facilitating easier product end-of-life, recycling, and disposal. Beneficiaries encompass all the stakeholders mentioned earlier and the environment.

Literature identifies four areas in which companies realize benefits from using PLM systems [11]:

- **Financial performance:** Increased revenue directly results from earlier product market introduction, along with possible additional benefits related to lower costs for purchasing materials, warranty and complaint repairs, physical prototypes, research, and tests. Savings are also associated with reduced demand for human resources due to increased automation in the PLM environment, especially in business process execution, and the reduction or elimination of redundant processing through better use and reuse of data existing in the PLM system.
- **Time reduction:** Achieved through faster and more efficient execution of product implementation projects, reduction of project time overruns, decreased time required for key business processes (especially technical change execution time), and quicker resolution of problems, complaints, and warranty claims.
- **Quality improvement:** Attained by enhancing the degree of meeting business requirements in products, minimizing production defects (especially repetitive ones), and limiting product returns and complaints, resulting in increased end customer satisfaction.
- **Improvement in overall business management efficiency (business improvement):** Realized through increased innovation rate, easier access to data (especially evident in departments not directly related to construction and technology, primarily in supply chains), simpler access to technical documentation (including 3D data) in production departments, heightened reuse of existing components (including virtual models of product components and production equipment), increased traceability of the product and its components throughout the lifecycle. Additionally, the ability to make important business decisions more easily and quickly, respond more rapidly to inquiries and customer requests, improve communication with suppliers and collaborators,

reduce the need for product changes at late stages of the lifecycle, effectively manage the global product portfolio, and ensure product compliance with laws, internal regulations, market standards, and requirements in individual markets, ensuring more effective communication and collaboration by nullifying the functional silo effect [3].

6 Effects of PLM System Implementation in a Manufacturing Company - Case Studies

The practical examples presented in this section stem from the authors' experiences gained through personal involvement in the implementation of PLM systems in two international manufacturing enterprises - a furniture factory and an organization specializing in the production of electrical transformers.

6.1 Effects of Implementing the PLM System at the Designer's Workplace

Practical examples 6.1 and 6.2 are drawn from the implementation process in an international manufacturing company specializing in designing and manufacturing intricate furniture solutions for office spaces, as well as furnishing public spaces like healthcare facilities, cinemas, auditoriums, concert halls, or stadiums.

In a traditional design office without the use of a PLM system, a designer involved in a new product development project performs all design activities on their workstation. 3D models of individual components are developed separately and independently, and only at the end of the process they are assembled into a single assembly for verification. Errors made during modeling may require corrections, and some errors might go unnoticed until later stages of the process.

In contrast, activities performed in a PLM system occur simultaneously, considering the entire product (design assembly). Verification of correctness is ongoing during project activities. Mistakes in any component are easily detected, as the assembly is built collaboratively from the start. Additionally, other departments, such as tool designers or process engineers, can work in parallel. With access to the evolving assembly and knowledge of overall dimensions, employees from other departments can commence their activities earlier without waiting for the release of design documentation.

Working in a PLM system allows for simultaneous execution of various activities, effectively eliminating bottlenecks. Concurrent design ensures greater data consistency; changes in one component affect others, facilitating the identification and elimination of significant design errors early in the process with minimal effort.

6.2 Effects of Implementing the PLM System in the Design and Technology (Production Support) Department

In organizations without a PLM system, data exchange between units occurs through various methods, often following this scenario:

- A designer exports a 3D model and saves it in a neutral format on their workstation.
- Technical documentation is exported and saved as a PDF.
- The exported data is sent via email to another department, e.g., technology.

- An employee in the technology department imports the 3D model into their system, comparing it with the sent drawing.

This method is ineffective, introducing a heightened risk of errors or data corruption, especially during export or import stages. Working in a PLM environment allows designers and technicians to collaborate in the same workspace where complete technical documentation, including 3D models and drawing and technological documentation, is stored [7]. They work concurrently using a common Product, Process, Resource (PPR) data model integrated into the PLM system. Participants in the development process use the same version of the documentation, eliminating the need for alternative communication channels. The drawing documentation is systematically linked to the 3D model, and changes made to the 3D model are automatically reflected in the drawing. The PLM system manages versions of complete technical documentation.

6.3 Effects of Using PLM Systems on an Inter-organizational Scale (Supply Chain)

In the next example, the company offers advanced solutions for key components for power transmission and distribution. The organization includes several dozen branches and factories located all over the world, across several continents. The dynamic development of the company resulted in these factories not being satisfactorily integrated with each other and the situation related to excessive diversity of - most often incompatible with each other - systems became permanent. So far, the organization has successfully implemented many initiatives aimed at introducing standardization in the field of technical documentation, but these were not global projects and covered only selected product groups and factories. Additionally, each of these projects resulted in the creation of non-integrated databases that had to be supervised and manually updated. For this reason, the company decided to launch a global initiative - a project to implement the PLM PTC Windchill system.

The company saw benefits in many areas, but hoped mostly for the significant improvements in the supply chain area, that is, primarily in purchasing and procurement. There were many systems and databases in the organization that were not integrated with each other. What is more, there were many numbering systems in use that were incompatible, local and often incomprehensible to employees from other locations (the coding of some of these systems was in local languages and even using non-Latin characters). Until now, the way things worked was for each factory (or at most several factories) to fulfill orders individually from selected suppliers, usually local. As a result, due to the lack of standardization and numerous discrepancies in numbering systems, the same (or very similar) non-standardized components were ordered by different factories, in small quantities and from different suppliers, and therefore, at very different prices. This greatly limited the company's negotiating capabilities. Additionally, it caused very serious organizational difficulties related, for example, to the taking over of production carried out at one plant by another. This also affected the efficiency of the service, whose employees had to use non-standardized documentation containing different coding systems.

The first step in implementing the aforementioned PLM system was the creation of global procurement structures. The task of people employed in this new organizational unit was to collect orders from factories across the organization, group them, and then offer suppliers a larger number of components of a given type. As a result, a more competitive offer was created by enabling ordering larger batches and selecting the best and most competitive global rather than local suppliers. Additionally, it was assumed that it would be possible to develop analyzes based on globally collected data and prepare forecasts based on them.

However, it turned out that order requests sent from factories located in different parts of the world were often incomprehensible to those in the global procurement department. The documentation attached to the orders was prepared using local standards, and the identifiers of the ordered components differed, depending on the ordering factory. As a result, the same component ordered by several different factories could have completely different names and designations, and could be represented differently on the technical documentation attached to the order. This made the analysis of the provided documentation difficult. Moreover, grouping orders for the same components into larger batches was more complicated, and sometimes even impossible.

The solution to this problem was to make advanced functionalities of the PLM system available to employees of the global purchasing department. However, to enable them to use the data collected in the PLM system, it had to be organized and reliable.

From the beginning, the project was planned as a global one, but due to the difficulties that could arise due to the scale of the undertaking and the scope of the organizational change, it was divided into phases. The long-term program was divided into many smaller projects with a smaller scope and scale of implementation:

- in the first phase, a project involving selected, most representative factories was planned - its goal was to work in a small team on a selected sample of data and develop a working solution, which was then to be implemented in selected factories;
- after the completion of the initial project, the solution developed within it was transferred and implemented in all other factories (this type of activity is referred to in the company as rollout).

The general activities carried out in the first phase were as follows:

- obtaining data from existing databases of standards applicable in the company;
- analysis of the acquired data, removing duplicates, unifying and merging data, describing them with attributes and classifying them based on a created and globally accepted hierarchical classification structure;
- uploading data to the PLM system, assigning them unified identifiers and linking them to the classification structure; generating and assigning identifiers to standard components was performed automatically by the PLM system; this system also ensured the uniqueness of identifiers;
- implementation of the PLM system with implemented data in selected factories - at this stage, the standard technical documentation used in a given factory was compared with the documentation contained in the PLM system; if components were identified in the factory that already had their equivalents in the PLM system, they

were eliminated and from that moment the components existing in the PLM system were used;

- a global team of leaders was established in the PLM system, the team was responsible for introducing new standard components and making changes to existing ones; processes were also created according to which these activities were performed. Every employee in the company with access to the PLM system could use standard components. All users of the PLM system could also submit requests to create new components or initiate changes to existing ones, but these actions had to be accepted and were performed only by a group of authorized users.

After completing the stages of the first phase, a similar approach was implemented in the remaining factories of the organization. Local standards and locally used technical documentation were gradually eliminated. From the factories where the project had already been implemented, only standardized technical documentation and global identifiers were already attached to orders sent to the global procurement department. Moreover, procurement department employees also had access to the PLM system. Therefore, if there was such a need, they could easily obtain additional information based on the sent data by searching for individual components in the PLM system database. In addition to the standard methods available for searching system resources, a data classification module has also been implemented. Each standard component was classified and described with attributes related to its place in this structure.

The source of savings achieved after implementing the project was:

- the use of global standards, it reduced the number of new components developed - thanks to the unified coding system and new, efficient search tools in the PLM system, it was easier to search and use an existing component than to create a new one;
- a large part of the designers' work time was saved, as they no longer had to search many different databases to find an existing standard component, and if not find it, create it from scratch; thanks to the fact that procurement department employees have the ability to independently use the PLM system and search for information, designers do not have to spend additional time providing information to these employees;
- employees of the global procurement department gained the ability to easily analyze, identify and group orders by category; with these improvements, they have more options and additional arguments in the bidding and price negotiation process; in certain situations, it is possible to transfer components from existing inventories between factories, instead of ordering new ones;
- after using the PLM system for some time with the new work rules implemented, it was possible for the first time to make an analysis of completed orders on the basis of real data (rather than relying on estimates and forecasts); on the basis of the analysis made, it was possible to develop a global purchasing strategy, negotiations and a more accurate list of preferred strategic suppliers.

The completed project was a source of improvements in many other areas of the company's operations as well. One of them was service, which, once the PLM standard components database was made available, enabled easier identification of components scheduled for replacement. This enabled a significant reduction in response time to customer requests and faster and more precise execution of service. Also, service employees

do not have to contact each time the factory that was responsible for manufacturing the device being serviced, but in many cases, using the PLM system, they can obtain the data on their own.

With a unified component identification system managed in a single system based on a global database, it is possible to develop design projects intended for all factories by a global design office located in any location. It is much easier to transfer production between factories, as the developed documentation is understood and easily identifiable in all factories where the PLM system has been implemented. Design projects saved to the database in any location are almost immediately available and usable in all others. Similarly, information about a change made to a standard component and its new version are immediately available throughout the system, and thus in all locations.

7 Discussion and Conclusions

PLM systems, alongside ERP systems, serve as fundamental tools for enterprise management, having evolved from supporting the work of design and technology engineers. Gradually encompassing all phases of the product lifecycle—from conceptualization, design, manufacturing, distribution, and sale to utilization, recycling, and disposal—PLM systems play an integral role in the digital transformation of manufacturing companies, a significance often overlooked.

Undeniably, PLM systems function as both integrating tools and environments for internal company processes and the entire product lifecycle. They emerge as crucial environments for various Industry 4.0 technologies by effectively facilitating data gathering, storage, information exchange, and integration. Consequently, the prompt, reliable, and flexible implementation of PLM systems becomes of paramount importance.

However, the implementation of PLM systems encounters several challenges, including:

- **Non-Generic Nature:** Despite standardized implementation processes and procedural frameworks, the intricate nature of PLM systems, diverse functionalities, and distinct company environments hinder generic applicability to every project.
- **Limited Transferability of Experience:** While implementation companies possess numerous real industrial case studies showcasing successful PLM system implementations, the intricacies of each project prevent the seamless transfer of this experience to new endeavours.
- **Confidentiality Concerns:** Due to the sensitive nature of company information processed in PLM systems and implementing organizations' apprehension regarding the disclosure of confidential data, research results on PLM systems implementation remain largely inaccessible to the public.


This article addresses specific challenges in implementing PLM systems within the context of Industry 4.0. The key arguments presented are supported by examples drawn from the implementation of PLM systems in manufacturing companies, both in Poland and globally.

References

1. Duda, J., Oleszek, S., Santarek, K.: Product Lifecycle Management (PLM) in the context of Industry 4.0. In: *Manufacturing 2022: Advances in Manufacturing III*, pp. 171–185 (2022)
2. Stark, J.: *Product Lifecycle Management (PLM)*, vol. 1. Decision Engineering. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-28864-8_1
3. Saaksvuori, A., Immonen, A.: *Product Lifecycle Management*, 3rd edn. Springer, Cham (2008)
4. Kiritsis, D.: Product lifecycle management and embedded information devices. In: Nof, S. (eds.) *Springer Handbook of Automation*, pp. 749–765. Springer, Cham (2009). https://doi.org/10.1007/978-3-540-78831-7_43
5. Bojar, W., et al.: *Przemysł 4.0 w przedsiębiorstwach z branży motoryzacyjnej, stan obecny i perspektywy rozwoju, ekspertyza KIP PAN*, Warszawa (2023)
6. Santarek, K., Duda, J., Oleszek, S.: *Zarządzanie cyklem życia produktu*, Polskie Wydawnictwo Naukowe, Warszawa (2022)
7. Srinivasan, R.: *Business Process Reengineering*. Tata McGraw Hill Education Pvt. Ltd., New Delhi (2011)
8. Susanto, H., Leu, F.-Y., Kang, C.C.: *Business Process Reengineering: An ICT Approach*. Apple Academic Press, Palm Bay (2019)
9. Myung, S.: Implementation process of enterprise PLM system. In: *International Conference on Product Lifecycle Management* (2008)
10. Alemanni, M., Alessia, G., Tornincasa, S., Vezzetti, E.: Key performance indicators for PLM benefits evaluation: the Alcatel Alenia space case study. *Comput. Ind.* **59**, 833–841 (2008)
11. Stark, J.: *Global Product: Strategy, Product Lifecycle Management and the Billion Customer Question*. Springer, Cham (2007). <https://doi.org/10.1007/978-1-84628-915-6>



Using Visions Systems and Manipulators in Industry 4.0

Anna Karwasz^(✉)  and Igor Wawrzynowicz

Poznan University of Technology, Poznan, Poland
anna.karwasz@put.poznan.pl

Abstract. The free market means that companies have to be very vigilant and react quickly to changes. Growing competition can pose a threat to a company's operations, which is why companies must constantly make sure that products meet market expectations while maintaining appropriate functional and quality requirements at the right price. It is therefore very important to supervise production processes and improve them. The production capacity and economic effects of industrial enterprises depend to a large extent on the technology used, organization and management. In terms of means of production, broadly understood automation comes to the rescue, in which robotization is becoming more and more important. The article presents the results of research on the use of vision systems and manipulators in industry 4.0. A robotic system consisting of a robot, a vision system and a feeder was selected and tested to pick up delicate products and put them into appropriate containers. Adding the robot to the production line will allow, in addition to automatic packaging of products, to monitor the number of manufactured product packages per a given unit of work shift time on an ongoing basis. The robot program additionally allows you to view statistics about the takt.

Keywords: Vision Systems · Industrial Robots · Sensors

1 Introduction

Industry 4.0 has introduced, among other things, robotization, automation and computerization so that modeling and simulation of production processes in real time or near real time will allow for the most efficient and cost-effective methods of testing, selecting and using technologically advanced materials as part of modern production processes [1]. In the first place, robots were used to replace dangerous and non-ergonomic operations. Currently, the area of their application is expanding to include precise, repetitive operations and often requiring high occupational hygiene. These are very versatile and flexible means of production that allow to replace manual work to a large extent.

1.1 Industrial Robots

Since the introduction of robots into industrial work, there has been an increased interest in scientists in achieving possible automation. One way is to randomly put things in

a box, stack them in a box, or place them in different places and positions, which is called box picking. This task is challenging because it involves 3D object recognition, perception strategies, and path planning. In many industrial processes, such as assembly or kitting, most parts are shipped in boxes or containers, and parts that may be damaged are only distributed. A common operation is the manual or automatic unloading of parts using feeders such as long conveyor belts. However, manual collection of parts has many disadvantages, such as health problems due to the weight of the components, and the practice is limited [2]. On the other hand, the use of feeding units is often expensive, inflexible and takes up a lot of space. For this reason, several research groups have addressed the problem of enabling robots to perform container picking tasks controlled by machine vision and other sensors [3–5]. Automating the process of collecting parts is difficult because it involves manipulating and estimating 3D objects, scheduling picks, planning routes, and avoiding collisions. Despite technological advances in all these areas, robotic hands have not surpassed human hands in terms of speed, adaptability, and flexibility [6]. As a result, it is difficult to implement automated bin removal applications without standardization. However, there are a few general-purpose tools on the market that can only be used for container picking, especially for containers that contain a simple type of components. On the other hand, managing containers that contain different components and complex shapes or are unknown is an open and challenging task.

Industrial robots can be grouped according to their numerous functions, which is not easy due to their versatility. The criteria for the division can therefore be very different. Among the most common ones, the following are divided according to [7, 8]:

- kinematic structure, i.e. stationary or mobile,
- construction of the kinematic unit - monolithic, modular and pseudo-modular,
- type of control - sequential, task-based, adaptive and teleoperators,
- the type of drive used, i.e. pneumatic, hydraulic, electric and mixed.

Nowadays, there are mainly electrical robots available on the market. Over the past decades, they have become so refined that they have been used where they used to be: pneumatic machines (e.g. explosive environments) or hydraulic machines (the need for high lifting capacities). In addition, cylindrical and spherical robots can be removed from the classification of robots due to their kinematic structure. They have not been on the market for many years [9].

Because humans and robots are able to perform tasks, robots and humans can work closely together, increasing the efficiency of parts collection, increasing the flexibility and productivity of the system, and improving operator efficiency when using humans and robots. In fact, robots can perform selective tasks and task positioning without fatigue, but the cognitive abilities and processing abilities of humans are good in non-human environments. Collaborative robot capabilities can help solve bin picking problems by leveraging capabilities such as manual guidance, collision detection, and human-robot interaction. Research indicates that a remotely located human can assist the robot in critical situations, solving any self-perception issues encountered during container retrieval [10–12]. In addition, it has been proposed to use a laser sensor to determine the distance between the operator and the robot, which allows the speed of the robot to be adjusted accordingly [13]. In addition, collaborative robots can hand over the picked

up objects to the operator or pick them up again in a dedicated container lifting chamber [14]. The use of these functions can significantly improve the process of picking containers and increase the efficiency of human-robot cooperation in this area.

The design of end effectors plays a crucial role in the success of container picking, as the items in the container may be disoriented, blocked, interfering with each other, or have varied shapes, textures, and materials. Gripper designs for container picking range from two-finger and multi-finger grippers to suction or magnetic grippers [15] and soft grippers [16]. Suction grippers typically have an advantage over parallel jaws or multi-finger gripping, as they can reach narrow spaces and capture objects at a single point of contact [17]. The optimal end effector design depends on the geometry of the items in the container and the state of the container, which changes as objects are picked [18]. Tool loaders allow robots to experiment with different gripper types, and a strategy for switching between multiple grippers based on object rarity has been proposed [19]. End effectors used in container recovery applications include force sensors to detect collisions, control force to avoid damage, and ensure proper object capture.

1.2 Manipulators

Manipulative movements are auxiliary activities, and their number and type depend on the form of the materials administered. In automated technological systems, handling systems are responsible for this area. The feeding processes are carried out by means of appropriate mechanisms. Handling systems can be divided into those in which parts are delivered in an orderly and disorderly manner, and these in turn into rigid and flexible systems (Fig. 1) [20, 21].

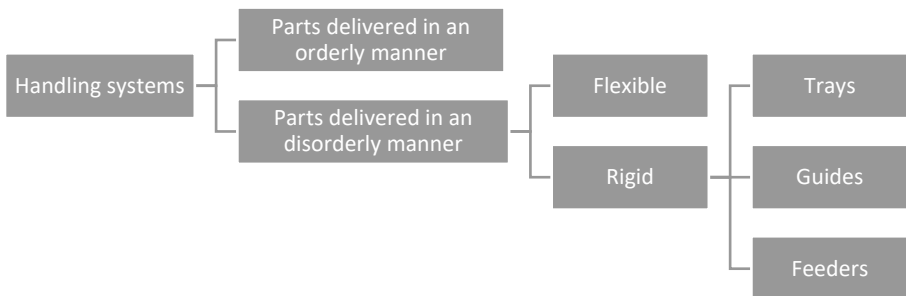


Fig. 1. Diagram of the division of handling systems [20, 21].

The review of the equipment for feeding delicate products depended on the requirements of chaotic delivery of products and their frequent variability. Rigid systems are usually dedicated to only one type of feeding part, which means that they are not used in the case of high variability of the assortment of parts. In addition, the characteristics of fragile parts such as shape, packaging and the possibility of damage disqualify this type of system. The only chance to automate the feeding of sensitive parts is therefore

provided by flexible systems. These systems are based on an industrial robot and the necessary instrumentation, which is why such solutions were looked at in further analysis of the literature and online sources.

1.3 Vision Systems

Machine vision systems are assemblies of integrated electronic components, computer hardware, and software algorithms that process and analyze the images they take. Using a vision system as the “eyes” of an industrial robot can significantly improve the accuracy and efficiency of advanced picking operations. The vision system detects the position of the product in the robot’s coordinate system and transmits these measurements directly to the robot controller. The data obtained from the vision system is used to control and automate the process or product inspection. Many manufacturing industries are adapting vision systems to perform tasks that can be mundane, repetitive, tiring, and time-consuming for workers, resulting in increased productivity and reduced operating costs.

Machine vision systems typically consist of five components (or components) that work together to play their distinct roles to create a vision system capable of advanced functions. These include [22–24]:

- Lighting and vision systems - responsible for illuminating the object and highlighting its distinct features that can be seen by the camera.
- Vision Lenses - The lens captures the image and transmits it to the image sensor inside the camera in the form of light.
- Properties such as field of view, depth of field and depth of field.
- An image sensor that converts the light captured by a lens into a digital image composed of pixels.
- A vision processing unit that analyzes an image to locate specific features that need to be observed and measured.
- Programmed specifications and criteria.
- A communication system that quickly transmits the decision made by the vision processing unit to specific machine components.

There are three types of vision systems used in industry:

- Vision sensors.
- Smart cameras.
- Camera-computer systems.

In the last decade, many applications requiring advanced machine vision (such as shape-based inspection, object digitization, visual inspection, object detection, service vision, robot optimization, mobile navigation) have developed rapidly in research and industry [25, 26]. Given the complexity of visualization tasks and systems, automation of such applications is essential to provide effective and efficient solutions [27]. Over the past decade, robotic vision systems (RVS) equipped with range sensors have proven useful in automating these tasks. However, implementing RVS to perform these tasks is considered a difficult and complex challenge. Creators face a common challenge: calculating the necessary views and important views to achieve the desired visual performance. This challenge is called the View (Point) Planning Problem (VPP).

Computer vision is a useful element of innovative solutions in the design of robotic cells. The solution presented below focuses on object detection and data collection techniques for object detection. Data collection and processing is an important stage of the machine learning process, with an average of more than 80% of time spent collecting and processing data [28]. Data-driven machine learning techniques are important for robots because robots can predict events in advance and prepare for dynamic and unexpected situations. Data collection methods vary depending on the use case [29]. In smart manufacturing, there is a lot of product variability, and when setting up systems for new products, accuracy is not lost, the ability to use existing data sets is limited. Manual labeling methods are time-consuming, expensive, require specialized knowledge, and are prone to human error [30]. The presented solution uses synthetic data generation, thus reducing the burden of manual tagging and data collection as it is generated.

The aim of this publication was to select and test a robotic system for automatic picking of fragile products and placing them in appropriate containers. The scope of work included the preparation of a test stand which is a robotic system consisting of a robot, a vision system and a feeder. The initial task was to design a station consisting of the above-mentioned components and assemble it. The system created in this way was used to check the possibility of automatic picking of delicate products.

The study took into account delicate products that differ in size, shape, weight and type of packaging, which can be aluminum, foil or cardboard. A delicate product can be a Christmas tree decoration (bauble), a glass product (a light bulb, a glass), a confectionery product (a box of chocolates). Therefore, it was necessary to individually select the appropriate parameters of the vision system. During the test, grip reliability was analyzed, understood as checking whether the robot will not drop the delicate product during movement, whether it will not crush it, whether the packaging will not tear, and what speed of the robot arm will be the best in terms of both efficiency and safety. The next stage of the research was to check the possibility of automatic insertion of the delicate product into the socket provided for it in the stamping. The test provided data that allowed the future to plan the assembly of the packaging on the production line in accordance with the predicted tact, i.e. how many products the robot will be able to insert into the extrusion in a given time. This made it possible to decide how many such robotic stations would be needed to completely eliminate manual work from this area of production. An additional aspect investigated was the possibility of computerization of production with the use of the created station, i.e. checking what data can be provided by the robot and which of them can be useful.

2 Streamlining the Packaging Process by Partially Robotizing the Production Line

The subject of the research is the packaging of delicate or soft products of various shapes, sizes and weights. The packaging includes several dozen products of various shapes, including spherical, cuboid, flat and cylindrical.

The packaging process is one of many processes carried out on a semi-automatic line. The processes of manufacturing complete orders also include: lining the cardboard

packaging, applying glue, applying the protective spacer, inserting the molding into the cardboard packaging, closing the cardboard packaging, applying labels, foiling.

The possibility of improving the packaging of fragile parts was investigated by using a robotic system using Omron equipment consisting of an RS4 robot, a camera, an Anyfeeder and integrated software supporting these devices (Fig. 2). It was decided to test such equipment due to the integrated control system for all devices of the above configuration. The offer of other companies was not complete, i.e. individual components would have to be obtained from different manufacturers and the whole thing would have to be integrated on their own.

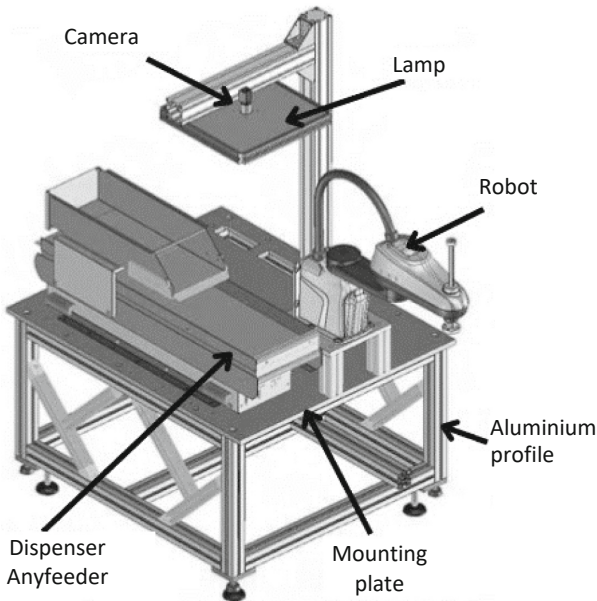


Fig. 2. Construction of a station for packing fragile parts.

A station frame was designed to allow all components to be assembled in the right place. The supporting frame of the frame has been designed with the use of aluminum profiles. An aluminium plate is attached to the frame, which is the mounting base for all components. The Anyfeeder dispenser is mounted directly to the mounting plate, while the robot is placed on a special platform so that the movement zone of the arm coincides with the feeder pick-up zone. The camera and an additional light source in the form of a rectangular lamp are attached to a bracket also attached to an aluminum plate. In addition, due to the moving parts of the robot posing a potential threat to the employee, the danger zones can be protected with a safety guard made of polycarbonate sheets.

The designed system can replace one or more manual packing stations on the packaging line (Fig. 3).

Of the available methods of gripping objects by industrial robots, suction cup gripping was chosen. Soft suction cups were better suited for handling fragile products than

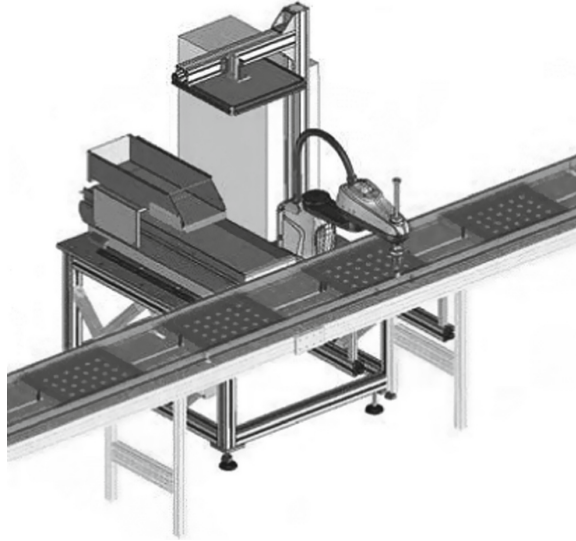


Fig. 3. Diagram of the position at the packaging line.

jaw grippers posing a risk of crushing the product. The robot is therefore equipped with a vacuum gripping system consisting of a vacuum generator from Festo with a sensor for the presence of the workpiece to be gripped and a suction cup mounted on a spring compensator with protected rotation (Fig. 4).



Fig. 4. Vacuum robot gripping system.

The final selection of the “suction cup” type was preceded by tests of grip reliability of the tested Products. 5 different types of suction cups were used for the test (Fig. 5) from four producers.

The selected nozzles differ in shape, size, hardness and fastening element.

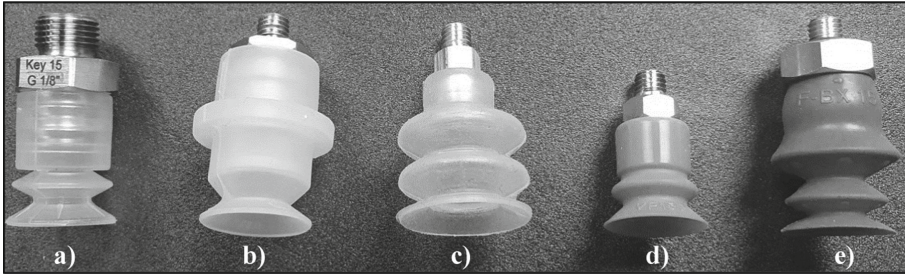


Fig. 5. Silicone suction cups analysed: a) 011626S, b) B10.016.008.S, c) 130.013, d) B10.015.007.S40, e) FBX15.

2.1 Object Detection

The use of a vision system requires adequate illumination of the area analyzed by the vision system. The image that the camera sees without an additional light source is not legible (Fig. 6). Natural light, as you can see, blurs the shape of the object and is additionally unstable - at different times of the day or year, the light shines with different intensity, affecting the stability of work.

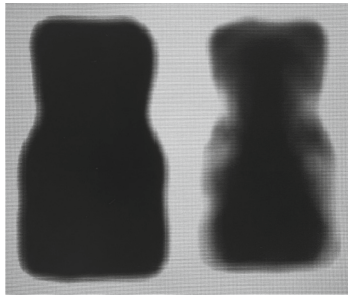


Fig. 6. A product image from a camera without an additional light source.

The created station has two sources of artificial light in the form of:

- “Backlight” with an additional IR filter that only allows infrared to pass through (the rest of the light is invisible). The source of this light is located under the Anyfeeder dispenser. This solution makes it easier to recognize the outline of the shape of the analyzed object. In the case of products that have a differently printed front and reverse, it does not allow you to tell which side the product is lying on the feeder.
- “Light” (white), in which it is also possible to illuminate the object with polarized light or without a polarizer. In the case of a product with a shape of a form, the polarization turned on allows you to see the print better, while the disabled polarization has a positive effect on the outline of the object.

In addition to providing adequate lighting, other parameters of the vision system had to be configured. Among the most important of these are the grayscale edge detection

threshold and the exposure time. The camera view of the same product is shown below with three different edge detection threshold settings: high sensitivity, normal sensitivity, low sensitivity. Changing this parameter affects the quality of the image you get. The clearest image in the case of a figure-shaped product was obtained at normal and low sensitivity settings. A photo taken at high sensitivity does not allow to identify the entire shape of the figure and most of the elements of the print. The exposure time, i.e. the time in which the sensor was exposed, is a numerical parameter set to a specific value. In Fig. 7. Three examples of images from the camera are presented using different values of this parameter (3 000, 10 000 and 30 000).

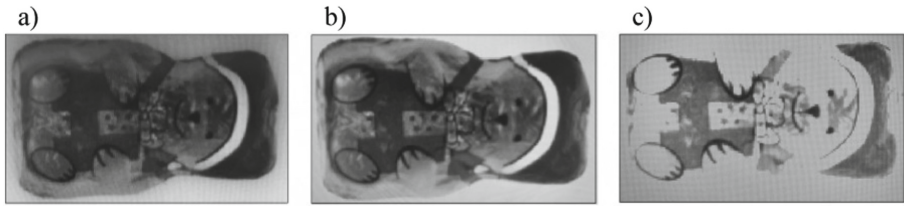


Fig. 7. Camera image of the product at different exposure times: a) 3 000; (b) 10 000; (c) 30 000.

Images obtained by changing the exposure time show that the best results for this product can be obtained at settings around 10 000. Too high a value results in an image that is too overexposed, on which it is difficult to reproduce the correct contour of the product. The selection of appropriate parameters allowed us to start teaching the vision system. After the camera has taken a photo of the product, the area of interest is marked with a rectangular frame (Fig. 8).

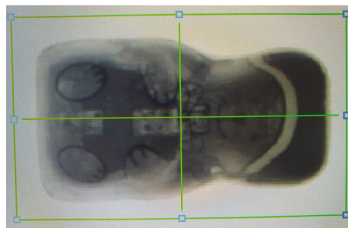


Fig. 8. A selection view of the area of the character's photo.

The vision system then analyzed the selected fragment according to a predetermined method (e.g. by shape or color). In this case, the recognition by edges was set, so the system marked all recognized lines on the overprint in green (Fig. 9a).

The image provided by the vision system is processed by removing less important features. In this case, the outline of the contour and the paws of the figurine were chosen to recognize the product - green in the view below (Fig. 9b). Blue indicates the edges that should have been selected as those that the camera does not need to detect. At this point, it was also necessary to specify the coordinate system that defines the place where the product is gripped - the yellow axes.

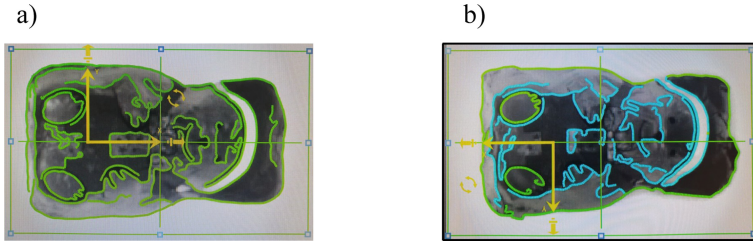


Fig. 9. Lines on the print: a) automatically marked by the vision system and; b) deselecting the less important edges from the product image.

The image prepared in this way is the basis for the vision system's product search.

3 Testing

The research on picking and inserting products began with adjusting the parameters of the vision system and the robot for each type of product. A given configuration of exposure, sensitivity and speed was adopted only when such a setting was obtained, which allowed to perform 10 successful manipulations in a row. Then the robot was started on time in the range of 30 min to 1 h to see how many pieces the robot was able to correctly place the stampings in the nest.

Table 1 presents a report of the tests performed, including the set parameters, the shape of the product and the results obtained.

Table 1. Product Picking and Insertion Test Report.

Shape	Ball A	Ball B	Figure A	Figure B	Figure C	Flat A	Flat B
Exposure	8000	5000	12000	12000	10000	10000	10000
Sensitivity	low	low	normal	Normal	normal	normal	normal
Velocity [%]	90	90	70	70	90	90	90
Tact [s]	1.8	1.8	2.2	2.2	1.8	1.7	1.8
Grip effectiveness [%]	100	100	100	100	100	100	100
Insertion efficiency [%]	100	100	100	100	100	100	100
Nozzle type	FBX15	FBX15	FBX15	FBX15	FBX15	011626S	011626S

The results of the tests allow us to observe that the robot is very effective, because one hundred percent effectiveness of both gripping and inserting products was achieved. Input parameters were crucial, as inadequate positioning resulted in deformation of the packaging or extended handling time. Figure C, Ball A and Ball B are available in only one piece, so if you want to pack them with a robot, you would have to divide the feeder

into two zones and take both products from the same device. Most of the products met the tact requirements, i.e. they were able to insert two pieces in less than 4 s. However, two pieces did not meet these requirements – Figure A and Figure B, which have a total insertion time of 4.4 s. The desire to fully automate the feeding of this product would therefore involve the use of two automated stations, whereas currently this is done by one human.

4 Summary and Conclusion

Packing products with the use of manual lines does not provide up-to-date information about the progress of work. A fast cycle time of about 4 s makes it difficult for the employees at the line to count the products passing on the conveyor, so they are counted only when they fill the entire collective package and the entire pallet. This means that information about the current production volume is transmitted at intervals ranging from a few to several minutes. Adding a robot to the production line would allow, in addition to automatic packaging of products, to monitor the number of manufactured product packaging per a given unit of shift time on an ongoing basis. In addition, the robot's program allows you to view statistics on the cycle with which it worked, which allows you to see how the efficiency of the entire packaging line changed during one shift, i.e. at what times the greatest delays or errors occurred, e.g. in the form of a lack of stamping - its detection is possible thanks to a special sensor mounted at the station. On the other hand, there is no need for the vision system to detect missing products in the stamping, as this is done by an inspection device located further down the line and is more accurate.

The invention and introduction of robots into industry makes it much easier to automate some technological operations, but it is associated with the need to equip it with appropriate tools and aids. A significant area of application for robots is handling activities related to the delivery of parts to the work zone. On the basis of the research carried out, it can be concluded that feeding delicate products is possible, but much more difficult than homogeneous parts - made of plastics produced from injection molds or metal parts from dies, which have repetitive physical characteristics. Delicate products are much more fragile, which makes them susceptible to damage. Packaging also often makes handling operations difficult. In the case of aluminum foil packaging, they differ in their micro folds, which complicate the image recognition of the shape due to their random arrangement. In addition, this type of packaging is much more susceptible to damage during handling, e.g. tearing. During the test, there were damaged products, but the robot did not detect them. Plastic foil packaging, on the other hand, is much more resistant to gripping and tearing. The products are placed in them with appropriate looseness, which results in an irregular shape of the packaging. This makes it difficult for the vision system to achieve stability in shape recognition.

Acknowledgments. The presented results are derived from a scientific statutory research project number 0613/SBAD/4770 conducted by Faculty of Mechanical Engineering, Poznan University of Technology, Poland, supported by the Polish Ministry of Science and Higher Education.

References

1. Andreadis, I.I., Gioumouxouzis, C.I., Eleftheriadis, G.K., Fatouros, D.G.: The advent of a new era in digital healthcare: a role for 3D printing technologies in drug manufacturing? *Pharmaceutics* **14**, 609 (2022)
2. Martinez, C., Chen, H., Boca, R.: Automated 3D vision guided bin picking process for randomly located industrial parts. In: Proceedings of the IEEE International Conference on Industrial Technology, Seville, Spain, 17–19 March 2015, pp. 3172–3177 (2015)
3. Rahardja, K., Kosaka, A.: Vision-based bin-picking: recognition and localization of multiple complex objects using simple visual cues. In: Proceedings of the IEEE International Conference on Intelligent Robots and Systems, Osaka, Japan, 8 November 1996, vol. 3, pp. 1448–1457 (1996)
4. Liu, M., Tuzel, O., Veeraraghavan, A., Taguchi, Y., Marks, T.K., Chellappa, R.: Fast object localization and pose estimation in heavy clutter for robotic bin picking. *Int. J. Robot. Res.* **31**, 951–973 (2012)
5. Schraft, R.D., Ledermann, T.: Intelligent picking of chaotically stored objects. *Assem. Autom.* **23**, 38–42 (2003)
6. Bencak, P., Hercog, D., Lerher, T.: Evaluating robot bin-picking performance based on Box and Blocks Test. *IFAC-PapersOnLine* **55**, 502–507 (2022)
7. Kaczmarek, W., Panasiuk, J.: *Robotization of Production Processes*. PWN Scientific Publishing House, Warsaw (2018)
8. Żabicki, D.: Robots & Manipulators. <https://automatykaonline.pl/Artykuly/Robotyka/Roboty-i-manipulatory>. Accessed 4 Nov 2023
9. <https://fabryka-robotow.pl/2017/06/klasyfikacja-robotow-przemyslowych/>. Accessed 1 Nov 2023
10. Kaipa, K.N., Thevendria-Karthic, S.S., Shriyam, S., Kabir, A.M., Langsfeld, J.D., Gupta, S.K.: Resolving automated perception system failures in bin-picking tasks using assistance from remote human operators. In: Proceedings of the IEEE International Conference on Automation Science and Engineering, Gothenburg, Sweden, 24–28 August 2015, pp. 1453–1458 (2015)
11. Kaipa, K.N., et al.: Enhancing robotic unstructured bin-picking performance by enabling remote human interventions in challenging perception scenarios. In: Proceedings of the IEEE International Conference on Automation Science and Engineering, Fort Worth, TX, USA, 21–25 August 2016, pp. 639–645 (2016)
12. Kaipa, K.N., et al.: Addressing perception uncertainty induced failure modes in robotic bin-picking. *Robot. Comput.-Integr. Manuf.* **42**, 17–38 (2016)
13. Olesen, A.S., Gergaly, B.B., Ryberg, E.A., Thomsen, M.R., Chrysostomou, D.: A collaborative robot cell for random bin-picking based on deep learning policies and a multi-gripper switching strategy. *Procedia Manuf.* **51**, 3–10 (2020)
14. Fuchs, S., Haddadin, S., Keller, M., Parusel, S., Kolb, A., Suppa, M.: Cooperative bin-picking with time-of-flight camera and impedance controlled DLR lightweight robot III. In: Proceedings of the IEEE/RSJ 2010 International Conference on Intelligent Robots and Systems, Taipei, Taiwan, 18–22 October 2010, pp. 4862–4867 (2010)
15. Roy, D.: Development of novel magnetic grippers for use in unstructured robotic workspace. *Robot. Comput.-Integr. Manuf.* **35**, 16–41 (2015)
16. Shintake, J., Cacucciolo, V., Floreano, D., Shea, H.: Soft robotic grippers. *Adv. Mater.* **30**, 1707035 (2018)
17. Mahler, J., Matl, M., Liu, X., Li, A., Gealy, D., Goldberg, K.: Dex-Net 3.0: computing robust vacuum suction grasp targets in point clouds using a new analytic model and deep learning. In: Proceedings of the 2018 IEEE International Conference on Robotics and Automation (ICRA), Brisbane, QLD, Australia, 21–25 May 2018, pp. 5620–5627 (2018)

18. Sanders, K., Danielczuk, M., Mahler, J., Tanwani, A., Goldberg, K.: Non-Markov policies to reduce sequential failures in robot bin picking. In: Proceedings of the IEEE International Conference on Automation Science and Engineering, Hong Kong, China, 20–21 August 2020, pp. 1141–1148 (2020)
19. Fujita, M., et al.: Bin-picking robot using a multi-gripper switching strategy based on object sparseness. In: Proceedings of the IEEE International Conference on Automation Science and Engineering, Vancouver, BC, Canada, 22–26 August 2019, pp. 1540–1547 (2019)
20. Domińczuk, J., Kost, G., Łebkowski, P.: Automation and Robotization of Production Processes. Polish Economic Publishing House, Warsaw (2021)
21. Barczyk, J., Igielski, J., Łunarski, J.: Feeding Systems in Automatic Assembly Systems. Warsaw University of Technology Publishing House, Warsaw (1996)
22. https://unitem.pl/baza_wiedzy/systemy-wizyjne/. Accessed 6 Nov 2023
23. <https://www.iqsdirectory.com/articles/machine-vision-system.html>. Accessed 6 Nov 2023
24. <https://www.keyence.com/products/vision/vision-sys/>. Accessed 6 Nov 2023
25. Müller, C., Kutzbach, N.: World Robotics 2019—Industrial Robots; IFR Statistical Department, VDMA Services GmbH: Frankfurt am Main, Germany (2019)
26. Peuzin-Jubert, M., Polette, A., Nozais, D., Mari, J.L., Pernot, J.P.: Survey on the view planning problem for reverse engineering and automated control applications. *Comput.-Aided Des.* **141**, 103094 (2021)
27. Gospodnetić, P., Mosbach, D., Rauhut, M., Hagen, H.: Viewpoint placement for inspection planning. *Mach. Vis. Appl.* **33**, 1–21 (2022)
28. Cognilytica. Data Engineering, Preparation, and Labeling for AI (2019). <https://www.cloudfactory.com/reports/data-engineering-preparation-labeling-for-ai>. Accessed 28 Aug 2023
29. Roh, Y., Heo, G., Whang, S.: A survey on data collection for machine learning: a big data-AI integration perspective. *IEEE Trans. Knowl. Data Eng.* **33**, 1328–1347 (2019)
30. Bertolini, M., Mezzogori, D., Neroni, M., Zammori, F.: Machine learning for industrial applications: a comprehensive literature review. *Expert Syst. Appl.* **175**, 114820 (2021)



Geometric Complexity Evaluation Method for Adoption of Additive Manufacturing

Ankur Krishna^(✉)  and Rajesh Duraisamy

Tata Consultancy Services, Pune, India
ankur.krishna@tcs.com

Abstract. The rapid evolution of additive manufacturing, commonly known as 3D printing, has spurred the need to determine when this technology should be favored over conventional or subtractive manufacturing techniques. Selecting additive manufacturing for a given part hinges on its complexity, as it must offer an economic advantage over traditional manufacturing methods.

This paper introduces a method for assessing the geometric complexity of parts intended for additive manufacturing. While the prevalent approach in most industries relies on surface area to volume ratio as an indicator of complexity, our study highlights its limitations and potential for misleading manufacturers. In response, we propose a novel method that leverages machining surface generation and scrap ratio to evaluate part complexity. The effectiveness of this method is demonstrated through validation with real-world industrial parts and virtual manufacturing assessments, proving its superiority to the traditional surface area to volume ratio.

One of the key advantages of our proposed method is its potential for automation, with the capability to analyze stereolithography (STL) files and estimate part complexity features. This automation has the potential to significantly reduce the cognitive load on additive manufacturing experts, making the technology more accessible and efficient. Overall, our research contributes to the critical decision-making process for selecting the most suitable manufacturing method, ensuring that additive manufacturing is chosen when it offers a distinct economic advantage driven by part complexity.

Keywords: Algorithm · STL · Geometric Complexity · CAD model

1 Introduction

3D printing, or additive manufacturing, is the construction of a three-dimensional object from a CAD model or a digital model [1]. Additive manufacturing is a process in which components are made by adding material layer by layer. Additive manufacturing overcomes the limitations of traditional manufacturing methods to create highly complex parts with improved functionality [2–5]. But the additive manufacturing technology is costlier than the traditional manufacturing process [6]. So, a decision is required whether to produce the part using traditional or additive manufacturing. Even today these decisions are taken by the manufacturing experts or by producing the part in both techniques

and then analyzing the cost and time [7]. Since there are millions of parts manufactured in industries it is nearly impossible to evaluate each part in this way. So, there is a need for a system and method which automatically evaluates the CAD model of the part for complexity and recommends which manufacturing technology is suitable for the part.

Shape complexity evaluation methods offer various approaches for analysis. The most preferred technique involves assessing shape complexity through the lens of prior manufacturing experiences [8, 9]. Nevertheless, this estimation approach is inherently subjective and heavily reliant on the individual performing the assessment. For highly experienced individuals, this estimation process is notably swift and accurate. Conversely, inexperienced individuals may produce assessments that are entirely erroneous, resulting in suboptimal and costly solutions being adopted.

Several attempts have been made [10, 11] to evaluate geometric complexity of part using STL [12] files. However, the authors have used final shape surface area and volume to do the analysis and combine it with property of STL such as number of triangles and size of triangles in STL file. This approach is not only computation extensive but also prone to error in case of triangulation error. The proposed method presented uses fundamental of machine surface generation and machining volume to compute complexity indicator.

2 Geometric Complexity Evaluation Method

2.1 Existing Way of Calculating Complexity

Complexity score is calculated [13] based on Surface Area (SA) to Volume (V) ratio of part.

$$\text{Complexity score} = \frac{\text{Surface Area (SA)}}{\text{Volume (V)}} \quad (1)$$

A complex part will be having a high complexity score. The Major disadvantage of this approach is that different parts with different shapes and sizes can't be compared together in terms of complexity score.

Since the formula is not dimensionally normalized. Hence a generic complexity range cannot be made. The proposed method for complexity estimation gives a dimensional neutralized index through which a different set of parts can be compared for complexity simultaneously.

2.2 The Proposed Method of Evaluating Complexity of Parts

Conventional machining on parts generates surface area and removes material from the raw material to achieve the final shape. The developed Part Complexity Indicator (PCI) takes both into consideration how much material is removed, and a new surface area is generated with respect to raw material to evaluate the part complexity. The part complexity indicator of CAD model is calculated based on the part surface area, volume, bounding box or cylinder surface area, and volume. The part complexity indicator indicates the manufacturing complexity of part using a conventional machining process.

Since the geometric or shape complexity increases machining time due to additional setups, number of tool changes and amount of material removal required to achieve final shape. Based on part PCI (part complexity indicator) a decision is taken using additive manufacturing adoption matrix. The additive manufacturing adoption matrix is prepared with the help of part manufacturers who are manufacturing parts using conventional manufacturing techniques. The scale is prepared for decision making using a PCI score. This method and system are automated using a programming language that takes part CAD model as input and suggests manufacturing techniques based on part complexity.

The steps to evaluate complexity of parts are explained below.

- I. Calculation of the part surface area, volume, bounding box or cylinder surface area, and volume. These parameters will be used further for the calculation of Part Complexity Indicator (PCI). These geometric parameters can be calculated directly from CAD file i.e., STL File format or other CAD File format or manually using the part drawing.
- II. Once part surface area, volume, bounding box or cylinder surface area, and volume are calculated, the next step is to calculate Machining Surface Generation Ratio (MSGR) and Machining Scrap Ratio (MSR) using the expressions 2 and 3 as given below. The first formula gives the ratio of newly generated surface area with respect to raw material surface area i.e., the bounding box or cylinder surface area. While the second formula indicates how much material has been removed from raw or input material to achieve the final finished shape. Since now we have two indicators Machining Surface Generation Ratio (MSGR) and Machining Scrap Rate (MSR). The composite Part Complexity Index (PCI) is given of multiplication of MSGR and MSR as shown in equation.

$$MSGR = \left(\frac{\text{Part surface area}}{\text{Surface area of bounding box or cylinder}} \right) \quad (2)$$

$$MSR = 1 - \left(\frac{\text{Part Volume}}{\text{Volume of bounding box or cylinder}} \right) \quad (3)$$

$$PCI = MSGR \times MSR \quad (4)$$

- III. Based on the Part Complexity Index (PCI) decision is made using an additive manufacturing adoption matrix. The ranges and corresponding decisions are shown in Table 1. The table is made with the help of a part manufacturer using a conventional machining technique. The manufacturers are asked to rate part complexity in terms of time and setups to manufacture the parts. The Part Complexity Index (PCI) of part is mapped against the complexity rating provided by the manufacturer in increasing order as shown in Table [4]. Now, once a new part comes with a Part Complexity Index (PCI), the part complexity can be decided and the decision for additive manufacturability can be made using additive manufacturing adoption matrix.

Table 1. Additive Manufacturing/3 DP adoption matrix

PCI	<0.1	0.1–0.3	0.3–0.5	0.5–0.9	>0.9
Complexity	Very Low	Low	Medium	High	Very High
Decision	Conventional Machining (AM Not recommended at all)	Conventional Machining (Not Recommended)	Additive Manufacturing (Redesign the part for more complexity if possible)	Additive Manufacturing (Recommended)	Additive Manufacturing (Highly Recommended for 3DP)

2.3 Workflow for Part Complexity Evaluation (Fig. 1)

Modelling Tool is a software where part CAD models are built. The part model can also be built on drawing paper with the help of required drafting tools. But in current industry practices, CAD software is used to build a part model instead of hand drawing.

Part CAD model is the output of CAD software in which part geometric information, GD&T, and manufacturing information are stored in different formats as shown in Fig 2. The part CAD model could be a surface model such as a STL file format (an abbreviation of “stereolithography”). It is a file format native to the stereolithography CAD software created by 3D Systems or a .3DXML file format which is a proprietary 3D file format developed by Dassault Systems. These are well known industry standard CAD surface model file formats which are being used across industries. The part CAD model could also be a solid model file format such as a .IGES file format. Initial Graphics Exchange Specification (IGES) is a neutral file format designed to transfer 2D and 3D drawing data between dissimilar CAD systems or a .PRT file format. PRT is a part or model file format developed by PTC Pro/Engineer or a .STEP file format. STEP file is a CAD file format, usually used to share 3D models between users with different CAD systems. Graphics Exchange Specification (IGES) is a neutral file format designed to transfer 2D and 3D drawing data between dissimilar CAD systems or a .PRT file format. PRT is a part or model file format developed by PTC Pro/Engineer or a .STEP file format. STEP file is a CAD file format, usually used to share 3D models between users with different CAD systems.

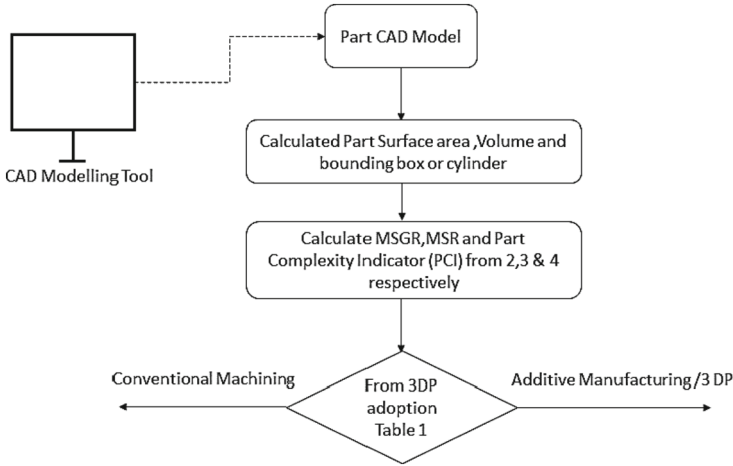


Fig. 1. Part Complexity Evaluation Workflow for Computer Program

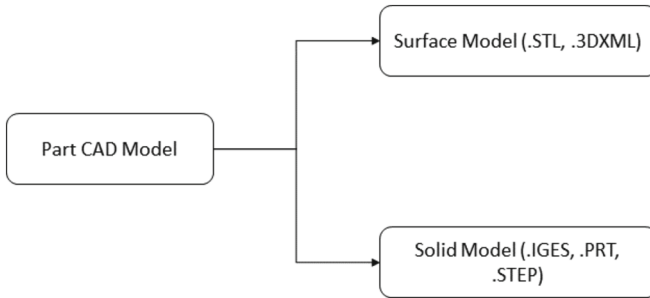


Fig. 2. Input Part CAD Model Details

Calculation of Part Geometric Properties. From Part CAD model file format geometric properties such as part surface area, Part Volume, bounding box or cylinder are fetched. There are various automated ways of fetching these details from the CAD model. Here Python stl open-source library was used to fetch these details from STL file format. The user can also calculate these parameters manually if part drawings are available instead of CAD file format.

Calculation of Part Complexity Index (PCI). Once the geometric parameters are calculated the next step is to calculate Machining Surface Generation Ratio (MSGR), Machining Scrap Ratio (MSR) from the Eqs. 2 and 3 respectively. With the help of MSGR and MSR, Part Complexity Index (PCI) is calculated using Eq. 4.

Decision Making Part Complexity Index (PCI) is used for decision making using an additive manufacturing adoption matrix as shown in Table 1. If $PCI < 0.1$, the system does not recommend at all for additive manufacturing based on complexity of the part. Similarly, if $PCI > 0.9$, the system highly recommends parts for additive manufacturing. The intermediate index is interpolated accordingly as shown in Table 1.

3 Results and Discussion

The proposed novel methodology is tested against the industrial parts. The surface area to volume ratio is calculated using STL file of respective parts. The python package numpy-stl is used to compute STL surface area and volume of the parts. The STL file approximates part shapes using triangles. The surface area of parts can be calculated using adding surface area of approximating circle. Similarly, the volume of the parts can be calculated using enclosed volume by the approximating circle. The calculated surface area and volume ratio of the parts are shown in Table 2. According to surface area to volume ratio complexity determination the car body is least, and concept brick is most complicated geometry to manufacture.

Table 2. The calculated surface area and volume ratio of the parts

Part Name	Surface Area/Volume
Car body	0.11
Stiffener	0.30
Hop Top	0.415
Bearing Bracket	0.474
Bracket	0.54
Pump Casing	0.86
Steering Mount	0.86
Wing Panel	1.037
Sphere Lattice	1.30
Concept Brick	1.91

Figure 3 shows the parts in ascending order of its geometric complexity of part according to surface area to volume method. The sphere lattice, which is most geometrically complex, ranks below the concept brick.

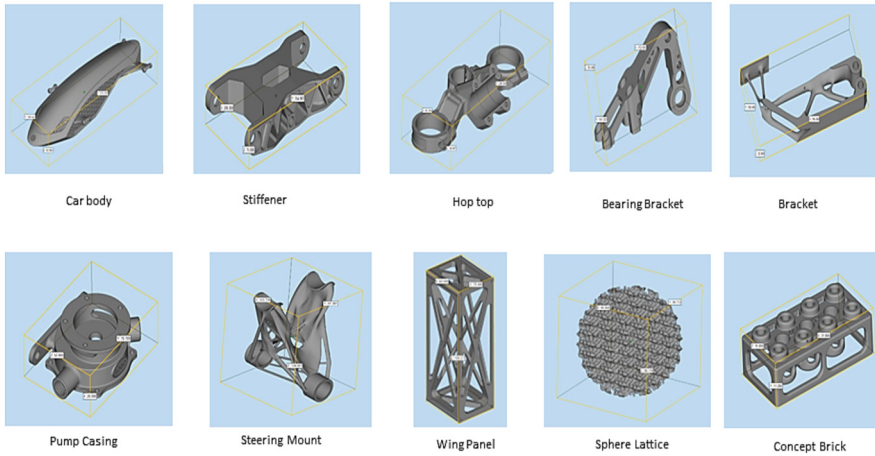


Fig. 3. Parts in ascending order of its geometric complexity of part according to surface area to volume method

The part complexity indicator of same parts is calculated by first estimating the surface area and volume of bounding box or cylinder. The numpy-stl python package is used to mesh the STL part geometric and maximum and minimum dimension in each x, y and z direction are estimated. The bounding box dimensions are estimated by subtracting maximum and minimum dimensions in x, y and z directions. Once bounding box dimensions are known the surface area and volume of bounding box can be calculated as below expression 5 and 6. The PCI can be automatically computed using part STL file and python program using proposed method. This reduces manual dependency to review each part.

$$\text{Bounding box surface area} = 2 * (x * y + y * z + z * x) \quad (5)$$

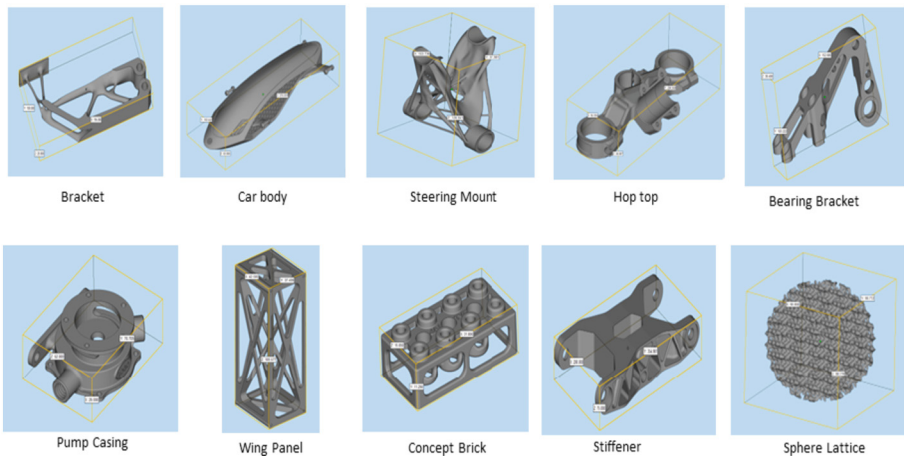
$$\text{Bounding box volume} = x * y * z \quad (6)$$

The expressions (2), (3) and (4) are used to calculate part complexity indicator. The Table 3 shows the part complexity indicator and additive manufacturing feasibility as per Table 1 of the parts. According to part complexity indicator (PCI) the bracket is least complex and sphere lattice is the most geometrically complex part.

Table 3. The calculated PCI and 3D manufacturing feasibility

Part Name	Part Complexity Indicator (PCI)	3D manufacturing feasibility
Bracket	0.11	No
Car body	0.30	No
Steering mount	0.415	Low
Hop top	0.474	Low
Bearing Bracket	0.54	High
Pump Casing	0.86	High
Wing Panel	0.86	High
Concept Brick	1.037	Very High
Stiffener	1.30	Very High
Sphere Lattice	1.91	Very High

Figure 4 shows the parts in ascending order of its geometric complexity of part according to novel PCI method. The sphere lattice, which is most geometrically complex, is ranked highest. The bracket is ranked least.

**Fig. 4.** Parts in ascending order of its geometric complexity of part according to novel PCI method

The comparison of two methods is done using number of setups required, number of axes required and complexity of CNC part program using Creo CNC part program generator. Table 4 shows the comparison of two methods against actual manufacturing complexity. The higher the rank part is more complex to produce using conventional manufacturing methods such as CNC.

Table 4. Comparison of two methods against actual manufacturing complexity

Part Name	Rank (SA/Vol)	Rank (PCI)	Rank-Actual
Bracket	5	1	1
Car body	1	2	2
Steering mount	7	3	9
Hop top	3	4	4
Bearing Bracket	4	5	5
Pump Casing	6	6	6
Wing Panel	8	7	7
Concept Brick	10	8	8
Stiffener	2	9	6
Sphere Lattice	9	10	10

Figure 5 shows the graphical representation of comparison of rank of industrial parts. Out of 10 parts the surface area to volume method can predict only one part accurately i.e., pump casing hence accuracy of this method is 10% while the proposed method is able to predict 8 parts accurately out of 10, hence its accuracy is 80%.

The two methods predict the same complexity ranks as actual ones for pump casing. The maximum deviation in rank using surface area to volume ratio method is of 4 and it is 3 for using part complexity indicator method. The instance of deviation is limited to one in PCI while it is 9 for SA/Vol method.

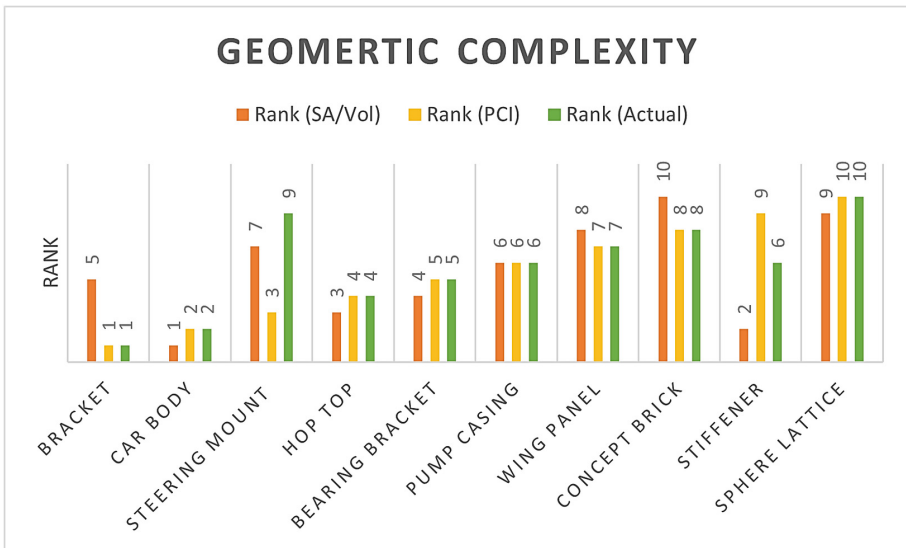


Fig. 5. Graphical representation of comparison of rank of industrial parts

4 Conclusion

This paper has presented a novel approach for evaluating the geometric complexity of parts with the aim of determining their suitability for additive manufacturing. While the conventional approach relies on the surface area to volume ratio as a measure of complexity, this study has pointed out its limitations and potential for misleading manufacturers. In response, a new method, the Part Complexity Indicator (PCI), has been introduced, which considers both the generation of new surface area and the amount of material removal in the context of conventional machining. This method offers a more robust and dimensionally normalized index for comparing the complexity of various parts.

The proposed method has been successfully applied to real-world industrial parts, demonstrating its superiority over the traditional surface area to volume ratio method in accurately assessing complexity. The automated nature of this approach, which can analyze CAD models, particularly STL files, offers significant advantages, reducing the cognitive burden on additive manufacturing experts and making the technology more accessible and efficient.

The results of this research provide valuable insights for manufacturers, enabling them to make informed decisions on when to opt for additive manufacturing over conventional methods based on part complexity. This not only improves the efficiency of manufacturing but also contributes to cost savings and overall competitiveness in the industry.

By introducing the Part Complexity Indicator and the additive manufacturing adoption matrix, this paper paves the way for a more data-driven approach to manufacturing decisions, ensuring that additive manufacturing is chosen when it offers a distinct economic advantage driven by part complexity. This work aligns with the evolving landscape of additive manufacturing, offering a reliable tool to navigate the decision-making process and promote its wider adoption.

References

1. Tofail, S.A.M., Koumoulos, E.P., Bandyopadhyay, A., Bose, S., O'Donoghue, L., Charitidis, C.: Additive manufacturing: scientific and technological challenges, market uptake and opportunities. *Mater. Today* **21**(1), 22–37 (2018)
2. Gibson, I.: *Additive Manufacturing Technologies. Rapid Prototyping to Direct Digital Manufacturing*. Springer, Cham (2010). <https://doi.org/10.1007/978-1-4419-1120-9>
3. Alaluss, K., Matthes, K.-J.: Minimal deformation and internal stress in the production of geometrically complex components using contour-building powder layer pulse plasma welding (IPTA). *Int. J. Join. Mater.* **13**, 102–106 (2001)
4. Bambach, M.D., Bambach, M., Sviridov, A., Weiss, S.: New process chains involving additive manufacturing and metal forming—a chance for saving energy? *Procedia Eng.* **207**, 1176–1181 (2017)
5. Shi, X., et al.: Selective laser melting-wire arc additive manufacturing hybrid fabrication of Ti-6Al-4V alloy: microstructure and mechanical properties. *Mater. Sci. Eng.* **684**, 196–204 (2017)
6. Pereira, T., Kennedy, J.V., Potgieter, J.: A comparison of traditional manufacturing vs additive manufacturing, the best method for the job. *Procedia Manuf.* **30**, 11–18 (2019)

7. Siller, N., Werner, S., Molina, V., Göhlich, D.: Method for potential assessment and adaptation for additive manufacturing of conventionally manufactured components. *Res. Eng. Des.* **35**, 73–96 (2023)
8. Weck, M., Nottebaum, T.: Optimization of large composite structures. *CIRP Ann.* **40**(1), 411–414 (1991)
9. Boër, C.R., El-Chaar, J., Imperio, E., Aval, A.: Criteria for optimum layout design of assembly systems. *CIRP Ann.* **40**(1), 415–418 (1991)
10. Valentan, B., Brajlilih, T., Drstvensek, I., Balic, J.: Evaluation of shape complexity based on STL data. *J. Achiev. Mater. Manuf. Eng.* **17**, 293–296 (2006)
11. Valentan, B., Brajlilih, T., Balic, J.: Basic solutions on shape complexity evaluation of STL data. *J. Achiev. Mater. Manuf. Eng.* **17**(1–2), 73–80 (2008)
12. Wah, W.H.: Introduction to STL format, June 1999. http://rpdrc.ic.polyu.edu.hk/content/stl/stl_introduction.htm. Retrieved 4 May 2006
13. Merkt, S., Hinke, C., Voswinckel, H., Schleifenbaum, H.: Geometric complexity analysis in an integrative technology evaluation model (ITEM) for selective laser melting (SLM). *S. Afr. J. Ind. Eng.* **23**(2), 97–105 (2012)



Using AI Tools to Enhance the Risk Management Process in the Automotive Industry

Diana Dragomir¹ , Florin Popișter¹ , and Kamil Erkan Kabak² 

¹ Technical University of Cluj-Napoca, Cluj-Napoca, Romania
diana.dragomir@muri.utcluj.ro

² Izmir University of Economics, Izmir, Turkey

Abstract. The paper presents an exploratory investigation concerning the usage of AI tools in automotive companies in order to streamline their risk management processes. A risk identification procedure is performed at organizational and process levels, and a comparative analysis is undertaken between the classical approach for developing proper mitigation measures and the AI-supported manner of doing the same. Some of the most popular tools in this field are employed and studied, such as large language models, data analytics and knowledge representation. The differences and changes are analyzed from the point of view of their effectiveness, efficiency and adaptability within the existing manufacturing frameworks in the automotive industry.

Keywords: artificial intelligence · risk management · automotive industry

1 Introduction

In the context of the present, where the twin transition becomes a necessity [1], as well as an opportunity, the use of advanced digital technologies in risk management can prove to be a challenging task for manufacturing companies. Out of the traditional sectors of manufacturing, automotive production is considered to be at the forefront of the confluence between technology and customer trends, therefore it is conceivable that production managers are searching for ways to help their firms navigate the complexities of today's market.

The current work proposes an exploration of the possibilities to quickly and efficiently use the most common techniques encountered in the field of AI, which have gained a large popularity in the past year. It examines characteristic features of the modern risk management process that is distinguished by the addressing of uncertainty and employing partial information. As key staff become overburdened by tasks, their involvement could be supplanted by employing proper tools coming from the digital sector. These tools are natively designed to work with large amounts of data and process business and manufacturing intelligence in heuristic approaches for developing innovative solutions and timely decisions. The investigation exploits a generic risk management approach that is tailored to the needs of automotive component manufacturers and explores its resolution between a classical approach and an AI-powered one in parallel. The discussion of results is undertaken based on a guided compare & contrast map using predefined axes.

2 Literature Review on Automotive Risk Management

Risk management in the automotive industry, especially for SMEs that manufacture components [2], is a complex undertaking that has been covered in literature from different perspectives [3]. As the management activities related to an automotive supplier's business model are inevitably connected to a supply chain, in various positions, there are many contributions that deal with improving the performance of risk evaluation and mitigation along the relations established within the chain using multicriterial analysis [4]. From delays to quality issues having more intricate dealings such as shared know-how and common product development, these aspects are difficult to deal with and have the potential to severely affect the survivability and competitiveness of the companies leading to challenging and complex decision-making processes [5]. Other organizational [6] and industry level situations that have the potential to generate risk and require reduction strategies include the greening of production [7], the digital transformation and the relationship with the workforce.

In many cases, the most visible aspect of risk management in the automotive industry and the costliest one is related to organization of the production system and the configuration of the production processes it employs [8]. The variability of production is a constant threat to the bottom line of the company as it generates nonconformities and complaints, which can reach up to the market level. Many of the mandatory risk instruments required in the industry standard are related to the following areas: predictive maintenance [9], statistical process control, measurement system analysis, failure modes and effects analysis, etc.

One of the most sensitive aspects of risk management on the production floor is worker safety particularly while the operators are interacting with the manufacturing equipment and other specific hardware [10]. The regulatory framework and the applicable standards supplemented by the requirements of unions and worker representative organizations drive considerable interest in this area. This is also expanding nowadays with new threats such as coworking with robots and AI-based decisions that are not calibrated for human safety. As an extension of these issues, the increasingly important and ubiquitous digital system are exposed to a large array of cybersecurity risks [11] and they require a special consideration.

Product risks fall mostly within the realm of reliability issues and product lifecycle management approaches. Automotive components are expected to perform at high standards of reliability for a precise duration, which determines different approaches in their design and manufacturing as opposed to regular consumer goods. Environmental risks [12], affecting both products and processes, are also well covered in literature with various proposed solutions.

Finally, the literature has methodological studies that seek to adapt existing instruments or create new ones to be able to perform risk analysis and the subsequent interventions in line with the requirements of the industry such as the House of Risk [13], Threat Agent Risk Assessment & STRIDE [14] or SAHARA [15]. However, there is still a long way from academic or professional proposal until factory validation and an even longer way until widespread industry acceptance and use.

3 Methodology and Materials

The AI implementation and parallel analysis has been conducted using a generic model of the risk management process (Fig. 1). This serves as a qualitative prototype to enable the generation of the compare and contrast map later in the paper.



Fig. 1. Generic model of the risk management process in automotive companies.

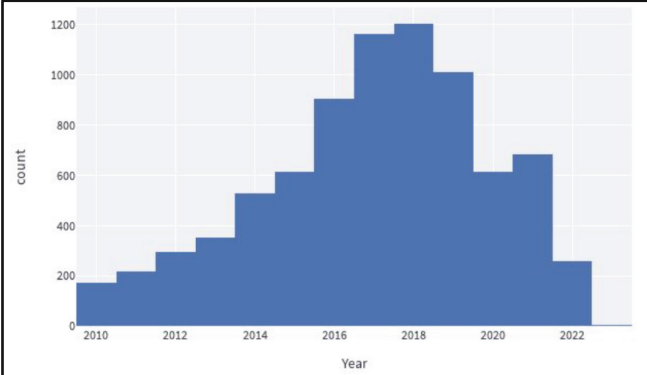
4 Results of the Parallel Implementation

In the following, we present in parallel the main characteristics and results of performing classical risk management (RM) and AI-supported RM, using some of the currently available tools for each stage described previously (see Fig. 1) in order. It is noted that all the AI instruments exemplified below have been identified using the website “There’s an AI for that” (TAAFT) available here <https://theresanaiforthat.com/> [16] (Tables 1, 2, 3, 4, 5 and 6).

Table 1. Environmental scanning (external) performed with ChatGPT 3.5 free version [17]

RM Stage	Environmental Scanning
Classical approach RM	Use of tools like: SWOT, PEST, Balanced Scorecard, Hoshin Kanri X Matrix, etc. Use own personnel from: legal, marketing, sales, procurement, HR Use external consultants for: strategic management, integrated management, HR, financial management
AI-supported RM (example)	AI tool to use: ChatGPT by OpenAI - https://chat.openai.com/ (LLM) <div style="border: 1px solid black; padding: 5px; margin: 5px 0;"> <p>You Can you list 5 main risks to an automotive manufacturer in Romania in a short form?</p> <p>ChatGPT</p> <ol style="list-style-type: none"> Market Demand Fluctuations: Dependency on external factors such as economic conditions and consumer preferences can lead to fluctuations in market demand, impacting sales and production volumes. Supply Chain Disruptions: Vulnerability to disruptions in the global supply chain, including shortages of critical components, transportation challenges, or geopolitical events, may affect manufacturing operations. Regulatory Changes: Changes in local or international regulations related to emissions standards, safety requirements, or trade policies can pose challenges for compliance and may necessitate costly adjustments to manufacturing processes. Technological Shifts: Rapid advancements in automotive technologies, such as electric vehicles and autonomous driving, can pose a risk if manufacturers fail to adapt quickly, invest in research and development, or retrain their workforce. Labor Market Challenges: Issues related to the availability and skill level of the workforce, as well as potential labor strikes or disputes, can impact production efficiency and increase operational costs for automotive manufacturers in Romania. <p>Message ChatGPT...</p> <p><small>ChatGPT can make mistakes. Consider checking important information.</small></p> </div> <div style="border: 1px solid black; padding: 5px; margin: 5px 0;"> <p>You Can you propose a solution for each of these risks?</p> <p>ChatGPT Certainly, here are proposed solutions for each of the identified risks:</p> <ol style="list-style-type: none"> Market Demand Fluctuations: <ul style="list-style-type: none"> Diversification of Product Portfolio: Offer a diverse range of vehicles that caters to various consumer segments and preferences. Market Research and Forecasting: Invest in robust market research and forecasting tools to anticipate changes in demand, allowing for proactive adjustments to production levels. Supply Chain Disruptions: <ul style="list-style-type: none"> Supplier Relationship Management: Establish strong relationships with key suppliers and consider dual-sourcing strategies to mitigate risks associated with a single supplier. Risk Assessment and Contingency Planning: Regularly assess potential risks in the supply chain and develop contingency plans to address disruptions promptly. Regulatory Changes: <ul style="list-style-type: none"> Continuous Monitoring: Stay vigilant about changes in regulations through regular monitoring of industry updates and maintain a dedicated regulatory compliance team. <p>Message ChatGPT...</p> <p><small>ChatGPT can make mistakes. Consider checking important information.</small></p> </div>

Table 2. Process variability related analysis with hal9 trial version using the included publicly available Kaggle USA cars' database [18]

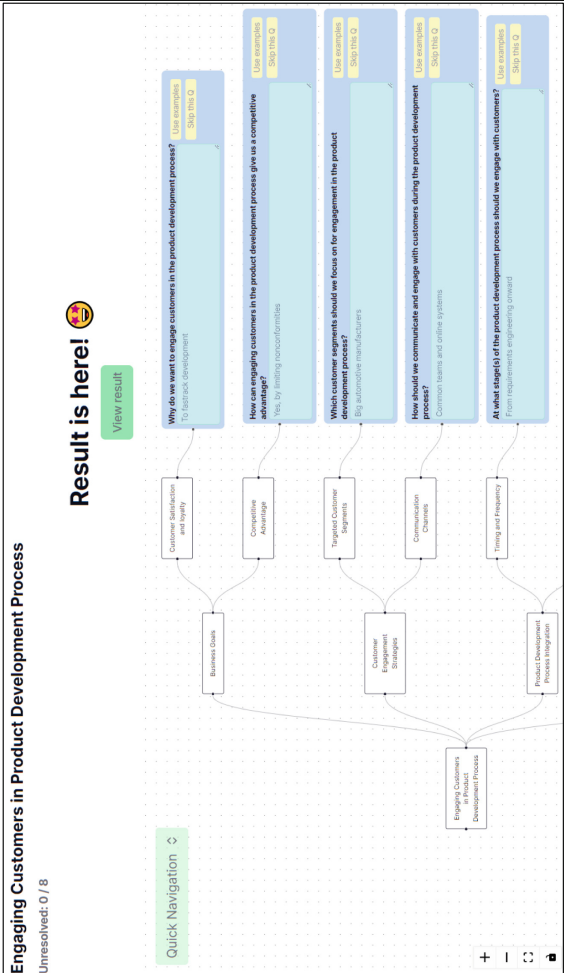
RM Stage	Process variability sources
Classical approach RM	Use of tools like: Statistical Process Control, Capability studies, Gage R&R, Measurement System Analysis, FMEA etc. Use own personnel from: design, production, maintenance Use sensors, monitoring equipment, internal and external laboratories, perform simulations
AI-supported RM (example)	AI tool: hal9 by hal9 Inc. - https://hal9.com/ (Data analytics) <div style="border: 1px solid black; padding: 10px; margin: 10px 0;">  <p style="text-align: center; font-weight: bold; font-size: 1.2em;">how often cars break down?</p> </div> <ul style="list-style-type: none"> <li>• The question can be applied to the manufacturer's own data to gather insights regarding production related issues that lead to trends and patterns in product faults <li>• Similarly, the question can be applied within the production system to determine production equipment failures in relation to design model, maintenance interventions, supplier delivered components, etc.

5 Discussion and Comparison

After completing the previous analysis, a series of aspects becomes apparent related to the benefits and challenges of both methods (see Fig. 2).

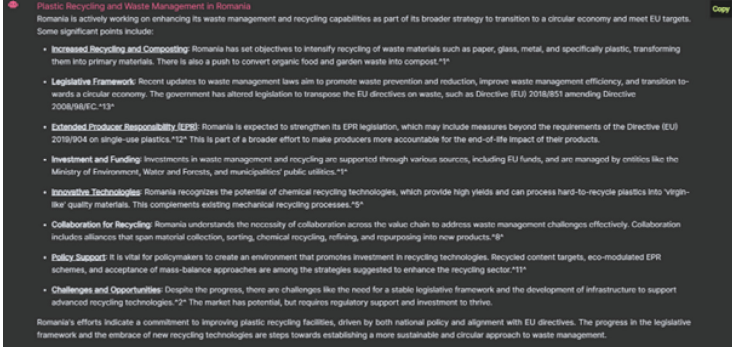
The classical approach has the advantages of accuracy and flexibility on its side, while the AI-supported risk management method can be considerably faster, albeit only mildly skilled. This is on the one hand due to the lack of dedicated tools at the moment and on the other hand to the inherent limitations of technology. However, they both

Table 3. Product failure reduction project with Clarify AI [19]

RM Stage	Product failure sources
Classical approach RM	Use of tools like: FMEA, FTA, Tree diagram, TRIZ, Ansoff Matrix, Quality Function Deployment, Kano model, Morphological Chart, DMADV from Six Sigma, etc. Use own personnel from: marketing, design, quality assurance Use product sensors, market intelligence, distributor data, service and replacement data
AI-supported RM (example)	AI tool: Clarify AI by Clarify AI - https://www.clarify-ai.com/ (Generative AI)
	 <p>The screenshot displays the Clarify AI interface for the 'Engaging Customers in Product Development Process'. It features a central flowchart with five main nodes, each linked to a strategic area and a specific question:</p> <ul style="list-style-type: none"> Business Goals: Customer Satisfaction and Loyalty. Question: 'Why do we want to engage customers in the product development process?' (Feedback Development). Example: 'Step 1: 100%'. Customer Engagement Strategies: Competitive Advantage. Question: 'How can engaging customers in the product development process give us a competitive advantage?' (Yes, by setting conformities). Example: 'Step 1: 100%'. Customer Engagement Strategies: Targeted Customer Segments. Question: 'Which customer segments should we focus on for engagement in the product development process?' (Big automotive manufacturers). Example: 'Step 1: 100%'. Customer Engagement Strategies: Communication Channels. Question: 'How should we communicate and engage with customers during the product development process?' (Common teams and online systems). Example: 'Step 1: 100%'. Product Development Process Integration: Timing and Frequency. Question: 'At what stage(s) of the product development process should we engage with customers?' (From requirements engineering onward). Example: 'Step 1: 100%'. <p>The interface includes a 'Quick Navigation' button, a 'View result' button, and a 'Result is here!' notification. The bottom status bar shows 'Unresolved: 0 / 8' and navigation icons.</p>

need to provide their results to the decision makers in the company in order to initiate a complete improvement cycle.

Table 4. End-of-Life-cycle ideas generated by Telborg free version [20]

RM Stage	Life-cycle reliability
Classical approach RM	Use of tools like: Life-cycle assessment, Sustainability scores, Design for X, UML diagrams, etc. Use own personnel from: design, production, customer support Use sensors, monitoring equipment, consultants, perform simulations
AI-supported RM	AI tool: Telborg by Telborg, Inc. - https://www.telborg.com/ (LLM)
(example)	 <p>Plastic Recycling and Waste Management in Romania Romania is actively working on enhancing its waste management and recycling capabilities as part of its broader strategy to transition to a circular economy and meet EU targets. Some significant points include:</p> <ul style="list-style-type: none"> Increased Recycling and Compositing: Romania has set objectives to intensify recycling of waste materials such as paper, glass, metal, and specifically plastic, transforming them into primary materials. There is also a push to convert organic food and garden waste into compost.¹¹ Legislative Framework: Recent updates to waste management laws aim to promote waste prevention and reduction, improve waste management efficiency, and transition to a circular economy. The government has altered legislation to transpose the EU directives on waste, such as Directive (EU) 2018/851 amending Directive 2008/98/EC.¹² Extended Producer Responsibility (EPR): Romania is expected to strengthen its EPR legislation, which may include measures beyond the requirements of the Directive (EU) 2018/904 on single-use plastics.¹³ This is part of a broader effort to make producers more accountable for the end-of-life impact of their products. Investment and Funding: Investments in waste management and recycling are supported through various sources, including EU funds, and are managed by entities like the Ministry of Environment, Water and Forests, and municipal public utilities.¹⁴ Innovative Technologies: Romania recognizes the potential of chemical recycling technologies, which provide high yields and can process hard-to-recycle plastics into 'virgin-like' quality materials. This complements existing mechanical recycling processes.¹⁵ Collaboration for Recycling: Romania understands the necessity of collaboration across the value chain to address waste management challenges effectively. Collaboration includes alliances that span material collection, sorting, chemical recycling, refining, and repurposing into new products.¹⁶ Policy Support: It is vital for policymakers to create an environment that promotes investment in recycling technologies. Recycled content targets, eco-modulated EPR schemes, and acceptance of mass-balance approaches are among the strategies suggested to enhance the recycling sector.¹⁷ Challenges and Opportunities: Despite the progress, there are challenges like the need for a stable legislative framework and the development of infrastructure to support advanced recycling technologies.¹⁸ The market has potential, but requires regulatory support and investment to thrive. <p>Romania's efforts indicate a commitment to improving plastic recycling facilities, driven by both national policy and alignment with EU directives. The progress in the legislative framework and the embrace of new recycling technologies are steps towards establishing a more sustainable and circular approach to waste management.</p>

6 Conclusions

Both methodologies can prove to be useful for an automotive company looking to improve its results. However, one of the most important lessons learned during the study is to tailor the modus operandi to the task at hand, either favoring speed or specificity. Eventually, as more instruments develop and the datasets become more complex, it is possible to conceive of an RM process that seamlessly combines human insight and the AI strength of trend discovery. The intricacy of the analyzed industry is a key factor in recommending only limited adoption of AI RM at this moment, but simpler industrial context might benefit from the approach on a larger scale.

Table 5. Customer/buyer personas generated by Wepost trial version [21]














RM Stage	Customer acceptance
Classical approach RM	Use of tools like: Business Model Canvas, Marketing mix, CRM Use own personnel from: design, marketing, top management Use external marketing consultants and service providers
AI-supported RM (example)	AI tool: Wepost by Sem Sælends (Wepost) - https://www.wepost.ai/ (Generative AI) <div style="background-color: #1a202c; color: white; padding: 10px; margin-top: 10px;"> <div style="display: flex; justify-content: space-between;"> <div style="width: 30%;">  </div> <div style="width: 65%;"> <h3 style="margin: 0;">Event-Engineer Evan</h3> <p style="font-size: 0.8em; margin: 0;"> 39 years Male Financial Growth Engineer Engineering Masters </p> <p style="font-size: 0.7em; margin: 0;"> Event-Engineer Evan is a seasoned professional in the engineering field, highly regarded for his technical expertise and innovative approach. At 39, he juggles demanding project timelines with a desire to expand his professional network through industry events. He values quality and uniqueness in services and strives to achieve financial success, reflecting a drive for efficiency and an appreciation for value in both his professional and personal life. </p> <div style="display: flex; justify-content: space-between; align-items: center; margin-top: 10px;"> <div style="text-align: center;"> <p style="font-size: 0.7em; margin: 0;">powered by</p>  </div> <div style="text-align: center;">     <p style="font-size: 0.7em; margin: 0;"> LinkedIn Webinar Analytical Innovative </p> </div> </div> </div> </div> <div style="display: flex; justify-content: space-between; margin-top: 10px;"> <div style="width: 30%;">  </div> <div style="width: 65%;"> <h3 style="margin: 0;">Blueprint Becky</h3> <p style="font-size: 0.8em; margin: 0;"> 42 years Female Financial Security Engineer Engineering Masters </p> <p style="font-size: 0.7em; margin: 0;"> Blueprint Becky represents the meticulous nature of an engineer in the engineering industry, with a focus on precision and efficiency. At 42, she is driven by a career that thrives on innovation and quality. Her daily routine is packed with project management and she relies on dependable partners to organize successful industry events. Aspiring to achieve financial security, she is drawn to services that promise operational excellence without compromising on budget or quality. </p> <div style="display: flex; justify-content: space-between; align-items: center; margin-top: 10px;"> <div style="text-align: center;"> <p style="font-size: 0.7em; margin: 0;">powered by</p>  </div> <div style="text-align: center;">      <p style="font-size: 0.7em; margin: 0;"> LinkedIn Webinar Detail-Quality-Conscious </p> </div> </div> </div> </div> </div>

Table 6. Searching for unknown risk causes performed with ChatGPT 3.5 free version [17]

RM Stage	Unknowledgeable causes
Classical approach RM	Use of tools like: Brainstorming, Mind-Mapping, etc. Use own personnel from: top management Use external consultants for forecasting and foresight
AI-supported RM (example)	<p>AI tool to use: ChatGPT by OpenAI - https://chat.openai.com/ (LLM)</p> <div style="border: 1px solid black; padding: 10px;"> <p>You What are three main sources of unknown risks for automotive manufacturing?</p> <p>ChatGPT Identifying unknown or unexpected risks can be challenging, but some potential sources include:</p> <ol style="list-style-type: none"> Emerging Technologies: <ul style="list-style-type: none"> <i>Rapid Technological Advancements:</i> The automotive industry is undergoing significant technological transformations, including the development of electric and autonomous vehicles, connectivity, and artificial intelligence. Unknown risks may arise from the pace of technological advancements, such as unexpected technical issues, cybersecurity threats, or disruptions caused by new entrants to the market. Global Economic and Geopolitical Factors: <ul style="list-style-type: none"> <i>International Trade Relations:</i> Shifts in global economic conditions, trade policies, or geopolitical events can introduce uncertainties. Changes in tariffs, trade agreements, or political instability in key regions may impact the supply chain, production costs, and market demand for automotive manufacturers. Environmental and Climate Change Factors: <ul style="list-style-type: none"> <i>Regulatory Changes and Environmental Impact:</i> Heightened awareness of environmental issues may lead to stricter regulations related to emissions, recycling, and sustainable manufacturing practices. Unforeseen regulatory changes or an increased emphasis on environmentally friendly practices could pose challenges for manufacturers not adequately prepared for such shifts. <p>Message ChatGPT_</p> <p style="font-size: small; text-align: center;">ChatGPT can make mistakes. Consider checking important information.</p> </div>

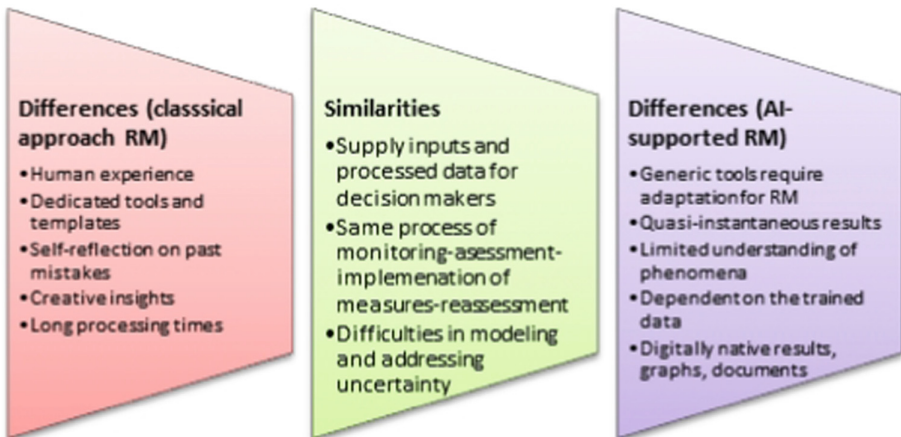


Fig. 2. Compare and contrast map of classic vs. AI-supported risk management.

References

1. Joint Research Center: Towards a Green & Digital Future. Publications Office of the European Union 2022, Luxembourg (2022)
2. de Araújo Lima, P.F., Crema, M., Verbano, C.: Risk management in SMEs: a systematic literature review and future directions. *Eur. Manag. J.* **38**, 78–94 (2020)
3. Kapitonov, M.V.: Evaluation and analysis of risks in automotive industry. *Transp. Res. Procedia* **61**, 556–560 (2022)
4. Mzougui, I., Carpitella, S., Certa, A., El Felsoufi, Z., Izquierdo, J.: Assessing supply chain risks in the automotive industry through a modified MCDM-based FMECA. *Processes* **8**, 579 (2020)
5. Häntsch, M., Huchzermeier, A.: Transparency of risk for global and complex network decisions in the automotive industry. *Int. J. Prod. Econ.* **175**, 81–95 (2016)
6. Surange, V.G., Bokade, S.U., Singh, A.K.: Integrated entropy-VIKOR approach for ranking risks in Indian automotive manufacturing industries. *Mater. Today Proc.* **52**, 1143–1146 (2022)
7. Prochatzki, G., et al.: A critical review of the current state of circular economy in the automotive sector. *J. Clean. Prod.* **425**, 138787 (2023)
8. Pacana, A., Czerwińska, K., Zwolenik, P.: Risk management elements in the production of a selected automotive product. *Sci. Pap. Silesian Univ. Technol. Organ. Manag. Ser.* **151**, 539–551 (2021)
9. Einabadi, B., Mahmoodjanloo, M., Baboli, A., Rother, E.: Dynamic predictive and preventive maintenance planning with failure risk and opportunistic grouping considerations: a case study in the automotive industry. *J. Manuf. Syst.* **69**, 292–310 (2023)
10. Yousefi, S., Alizadeh, A., Hayati, J., Baghery, M.: HSE risk prioritization using robust DEA-FMEA approach with undesirable outputs: a study of automotive parts industry in Iran. *Saf. Sci.* **102**, 144–158 (2018)
11. Schmittner, C., Dobaj, J., Macher, G., Brenner, E.: A preliminary view on automotive cyber security management systems. In: *Design, Automation and Test in Europe (DATE 2020)* (2020)
12. Richert, M., Dudek, M.: Selected problems of the automotive industry—material and economic risk. *J. Risk Financ. Manage.* **16**, 368 (2023)
13. Partiwī, S.G., Islami, V.N., Firmanto, H.: House of Risk (HOR) approach to manage risk involving multi-stakeholders: the case of automotive industry cluster of Multifunctional Rural Mechanized Tool (MRMT). *Oper. Supply Chain Manag.* **16**(1), 133–139 (2023)
14. Karahasanovic, A., Kleberger, P., Almgren, M.: Adapting threat modeling methods for the automotive industry. In: *15th ESCAR Conference, Berlin* (2017)
15. Macher, G., Armengaud, E., Brenner, E., Kreiner, C.: Threat and risk assessment methodologies in the automotive domain. *Procedia Comput. Sci.* **83**, 1288–1294 (2016)
16. Nedelcu, A. (founder): There’s An AI For That (TAAFT), 2 December 2022. <https://theresanaiforthat.com/>. Accessed 10 Dec 2023
17. OpenAI: ChatGPT (2022). <https://chat.openai.com/>. Accessed 10 Dec 2023
18. hal9 Inc.: hal9 (2023). <https://hal9.com/>. Accessed 12 Dec 2023
19. Clarify AI: Clarify AI (2023). <https://www.clarify-ai.com/>. Accessed 16 Dec 2023
20. Telborg, Inc.: Telborg (2023). <https://www.telborg.com/>. Accessed 14 Dec 2023
21. Sem Sælands (Wepost): Wepost (2023). <https://www.wepost.ai/>. Accessed 16 Dec 2023

Optimization of Production Processes



Innovations - Changes in the Environment of the Production Planning Process in Enterprises

Marek Fertsch , Agnieszka Stachowiak , and Joanna Oleśków-Szłapka 

Poznan University of Technology, Poznan, Poland
joanna.oleskow-szlapka@put.poznan.pl

Abstract. Planning in dynamic and changing environment is not easy. Requires considering both external (market) factors and internal (technological) factors, recognizing synergies and trade-offs between them and exploiting their potential. The article contains an attempt to describe the impact of changes taking place in the environment of the production planning process and in the enterprise, i.e. factors such as innovations, technical progress, producers' strategies, on the development of the enterprise. Components of the production planning process determinants such as market research, introduction of new products to the market or use of new technologies were taken into account and characterized based on review of the literature. References to innovations, their types and importance were presented as well, showing innovations as results of market research and reason for technological changes and product development. The conclusions from the analysis were used to prepare a summary of the article and conclusions were presented in the context of contemporary concepts such as Sustainable Development, Industry 4.0, and Industry 5.0.

Keywords: production planning · innovation · production management · Industry 5.0

1 Introduction

The importance of planning in management was appreciated very quickly. It was at the top of the list of managerial functions [1]. The appreciation of the theoretical role of planning in theory also led to the appreciation of its practical importance. This occurred as a result of empirical research conducted in the American industry in the 1950s and 1960s [2–5]. The following paper is set in the area of production management and deals with production planning. This area is dynamically changing due to changes in production referred to as Industry 4.0 and challenges resulting from Sustainable Development requirements.

We are trying to address the changes benefiting from the available and well-developed literature in the area and the expertise and practical experience. The paper is structured as follows: The first section presents research problem, briefly describing production planning issues and presenting research questions. The second section covers answers

to research questions, the third offers discussion on research results and the last section gives conclusions referred to the new management paradigms such as Industry 4.0 and Industry 5.0.

2 Research Problem

There are many definitions of planning in the literature. The authors of this article refrained from analyzing and comparing them. For the purposes of this article, they selected the most up-to-date definition, which, in their opinion, well reflects the essence of this complex process and takes into account various techniques of its implementation. According to the selected definition, “planning is the rational part of action. It is an abstract process in which activities are considered and organized according to the criterion of their future results. The task of planning is to find the best way, considering the adopted criteria, to achieve previously set goals” [6]. The result of the planning process is a developed plan. It is used to continuously develop and improve the competitive potential of the enterprise and to identify changes necessary in the enterprise’s operations in response to changes in demand occurring on the market in order to ensure their compliance with the enterprise’s permanent goals (maintaining financial liquidity and generating profit) and the enterprise’s development intentions.

The production planning process in enterprises takes place at various management levels and concerns different time periods (planning horizons). There are usually three planning horizons: long-term planning regarding a long planning horizon. The task of long-term planning is usually the responsibility of the owners (proprietor) of the enterprise and the highest levels of management of the enterprise. In carrying out this task, they often use the help of external specialists from outside the company; medium-term planning regarding the medium planning horizon. The planning horizon in medium-term planning is usually one year. This results from the obligations imposed on enterprises by economic law. Every company is obliged to settle the results of its activities once a year. Commercial law companies have an additional obligation to make public the results of their activities. The task of developing medium-term plans is usually the responsibility of individual company functions such as finance, sales, and production; short-term planning concerns a short planning horizon. It is often called ongoing control or operational management. The task of developing short-term (operational) plans is the responsibility of individual organizational units.

Launching long-term (strategic) planning in an enterprise requires a number of preparatory activities. These activities begin with market research, which can be followed by innovation implementation.

Considering the nature and structure of production planning there are two questions addressed in the paper:

To what extent does the market research impact production planning?

and

To what extent do innovations impact production planning?

The answers to these questions are discussed to identify various approaches to production planning and conclude them in the context of contemporary management

paradigms such as Sustainability, Industry 4.0 and Industry 5.0. The methods used to answer the questions include literature review and experts insight based on discussions during regular Board of International Foundations for Production Research meetings focused on state-of-the art and future of production research.

3 Research Results

3.1 Market Research

Market research is used to estimate the volume of future sales of current, new or modified products that the company currently offers to its customers or intends to introduce to its sales range. Market research involves using statistical methods to collect and analyze data regarding consumer needs and requirements regarding products that the company currently offers on the market and intends to introduce to the market. Market research allows us to estimate the future volume of demand and customer expectations regarding product quality, packaging standard and buyer behavior (frequency of purchase, brand attachment, accepted price level). It allows you to estimate the future sales volume, turnover and profit that may be achieved. Market research results can also be used to identify features of new products desired by customers. These features should be taken into account in the process of designing new products. Customer preferences may concern colors, dimensions, method of operation and other functional features of products. On their basis, you can also determine the approximate sales price and its potential variability due to additional features included in the design. Market research is conducted in several stages [7]. It begins with an analysis of the company's current situation, identification of its strengths and weaknesses, and the company's position relative to the competition. Based on the results of the analysis of the company's current situation, research planning begins. The information that needs to be obtained, the methods of collecting it, and the organization of research are determined. Then the data is collected and analyzed using static methods. When collecting data and analyzing it, attention should be paid to identifying additional factors that may affect sales. Market research ends with the development of a final report and presentation of the report to the company's management. In conditions of high market volatility or instability of the environment in which the company operates, market research must be conducted continuously.

Based on the results of market research, the company's top management bodies set the company's goals. These goals concern: sales value and profit, sales range and, in the case of a manufacturing company, also production range. In some cases, the goals are supplemented with investment goals (creation of new production capacity, merger or acquisition of another company).

If the goals formulated by the company's management include introducing new products to the market or using new technologies, achieving them requires the company to undertake work in the areas of research and development and implementation of innovations. According to the opinion of H.-J. Bullinger [8] innovations are today the best way to build competitive advantage. They enable higher prices and faster market share expansion. Their introduction makes it possible to offer new products or services. It improves product quality and speeds up product development processes. The most effective form of innovation is the development and use of new technologies, especially

technologies that can be used in many areas (cross-sectional technologies), such as information technologies or nanotechnology.

3.2 Implementation of Innovations, New Products and Technologies

The examination of innovation facets indicates that since the inception of initial innovation definitions, the discourse surrounding innovation aspects has significantly advanced. Innovation is recognized not solely as a process of alteration or a tangible entity but also as a tool for change and a prerequisite for such transformation. Aspects of innovation are presented in the Table 1.

Table 1. Six aspects of innovation by Ahmed and Shepherd [9]

Aspect of innovation	Focus of definition
Creation (invention)	Utilizing resources (human, temporal, and financial) for the creation or advancement of a novel product, service, alternative approach to tasks, or a fresh perspective on concepts
Diffusion and learning	In obtaining, endorsing, or employing a product or concepts
Event	Discrete event, such as the development of a single product, service, idea or decision
Change (incremental or radical)	Implementing change. Some innovations involve minor modifications, while others are characterized by radical or discontinuous shifts in nature
Process (firm level)	Innovation is not a solitary act but rather a sequence of activities undertaken by a company to result in the creation of an outcome, specifically, the innovation itself
Context (region, nature, etc.) level processes	Engaging beyond the boundaries of an individual or firm involves an emphasis on institutional frameworks, socio-political networks, and proximal factor endowments as crucial elements in the process of innovation

Examining various approaches to classifying innovation reveals the following representation of innovation types:

- 1) Classic types such as process innovation, product innovation, service innovation, etc., are incorporated in numerous studies on innovation typologies. (Block A in the Table 2).
- 2) The second cluster encompasses the so-called “new” forms of innovation. These emerged 5–10 years ago and haven’t attained the status of “classic” ones. They involve

innovation types like frugal innovation, red ocean innovation, organic innovation, and numerous others—some of which may be considered “very exotic” in strict terminology. (block B in Table 2). These innovation types are primarily employed in models designed for innovation management and in business models for new products or services. Consequently, these categories tend to be more “appealing” and attention-grabbing than strictly scientific and precise in their definitions.

- 3) The third category consists of types of innovation categorized based on the level of innovation. Hence, innovations characterized as radical, breakthrough, or revolutionary are classified as “strong innovation,” whereas those that are less drastic or minor in nature are categorized as “weak innovation.” (Block C, Table 2).
- 4) In conclusion, innovations can be classified in a dichotomous manner. In this scenario, distinct pairs of innovation types can be recognized, such as open/closed innovation, radical/incremental, and product/process, among others. (Block D, Table 2).

Table 2. Summary of innovation types [10]

Types	Example
Block A “Classical” types	Product innovation, process innovation, service innovation, marketing innovation, organizational innovation, design innovation, supply chain innovation
Block B “New” types	Frugal innovation, red ocean innovation, blue ocean innovation, experience innovation, value-migration innovation, business model innovation, organic innovation etc.
Block C “Innovativeness degree” types	Weak innovation (incremental, routine, minor, regular, non-drastric basic innovation); medium strength (architectural, niche creation, modular/fusion/evolutionary/sustaining innovation
Block D “Dichotomical” types	User-driven supply-side innovation, open/closed innovation, product/process innovation, incremental innovation (and other examples of “strong/weak” classification of innovation, continuous/discontinuous innovation, instrumental/ultimate innovation, true/adoption innovation, original/reformulated innovation, innovation/renovations

Introducing a new product to the market is a specific challenge. The company must ensure that the product will not only compare well with the products of current competitors but also pay attention to those product features that distinguish it from competing products sold at a similar price. To ensure sales, the product must be cheaper than competitive products or have properties that they do not have.

If there are many identical products on the market, it is important to identify the number of products produced and sold by competitors in order to identify the total potential sales

volume. This data may be obtained directly from the competition or by collecting it based on the analysis of data published by the statistical office, data from the stock exchange, and annual competition reports. Analysis of sales volume data, including additional data on factors that influence sales, such as population, income level, and purchase frequency, can indicate trends in market development.

4 Discussion

Many markets are changing rapidly. In their case, not only historical sales data should be taken into account, but also the effects of the appearance of new products and new technologies. In such a situation, estimating the market size is particularly difficult. The necessary data can be collected by taking into account factors that may influence sales. They can be identified by collecting additional information.

The approach to technical progress and innovation depends on the manufacturer's attitude. Ayres [11, 12] notes that a large manufacturer may choose not to implement an important invention and instead adapt production processes, sales methods, etc. to the new technique. However, most manufacturers prefer a different approach. Within it, three attitudes can be distinguished:

- cost minimization - when the manufacturer presents this attitude, research and development work is aimed at reducing production costs. This works well in mass production settings because even small savings can lead to significant gains in profit. Prospective research in such conditions is of little interest. Nowadays, the manufacturer's attitude discussed above is usually associated with basing production organization on the concept of lean production. The producers of this group's R.U. Ayres included public services, communications, transportation, metals, glass, cement, concrete and oil industries.
- sales maximization - when the manufacturer presents this attitude, he allocates a large percentage of his income to marketing, advertising and the development of the product range. Most research and development work concerns the study of consumer reactions to innovations in the field of packaging, names and advertising slogans. In fact, this attitude contributes little to real technical progress and the spread of real innovations. Nowadays, the manufacturer's attitude discussed above is usually associated with basing production organization on the concept of lean production. The producers of this group's R.U. Ayres included the automotive industry, cosmetics, manufacturers of cleaning products and detergents, food and clothing industries.
- maximum penetration of existing markets with existing products and emphasis on new products and/or new markets (maximization of action). When the manufacturer presents this attitude, he builds his position on the market primarily on advanced technology and therefore focuses his attention on research and development work, or even sometimes basic research. The producers of this group include R.U. Ayres' aerospace, computer, armaments, electronics, nuclear, petrochemical, scientific equipment and shipbuilding industries.

Most manufacturers will use a combination of the approaches discussed above in their operations. Behavior differentiation occurs by market or by product groups (families). Manufacturers with a "maximize market penetration" attitude were the fastest growing

and most successful in the second half of the 20th century. It should be noted, however, that the simultaneous occurrence of rapid growth and rapid technical progress does not prove the existence of a relationship between these two phenomena.

Ayres developed his taxonomy for the purpose of forecasting the behavior of producers regarding the directions of research work and expenditure on research and development.

Simmonds [13] criticized Ayres' taxonomy. He stated that it was incomplete. He proposed supplementing it with a group including the investment goods industry (construction, machinery, tools), the raw materials industry, services and the arms industry. A common feature of all producers belonging to this group is competition based on offering the customer products of a specific standard at a price lower than the competition. In terms of research and development, the behavior of producers belonging to this group is identical to that of producers representing an attitude focused on minimizing production costs. The organization of production in this group depends on the production volume. In conditions of continuity of production and mass production forced by the technology used, it is usually based on the concept of lean production. With the decline in serial production, the spectrum of solutions used in the organization of production is shifting towards the concept of agile production.

Simons also modified and expanded the model proposed by Ayres for producers focused on maximum penetration of existing markets with existing products and placing emphasis on new products and/or new markets. Simmond [13] uses the name "maximum efficiency producers" to refer to this group. Simons claims that the factors shaping the behavior of this group of producers are technical innovations, production scale and demand. He writes that "continuous technical innovations reduce the cost of a given technical potential and, as a rule, increase the range of use of a given product. Reducing production costs allows for price reductions, which allows for a significant increase in sales. Increased sales allows you to build larger production plants. A larger scale of production allows for further savings and further reductions in unit costs. So, overall, reducing the costs of introducing technical improvements and reducing costs due to increased production scale is a strong driving force behind falling prices and ever-increasing demand. A specific and characteristic model of development caused by the twin factors of innovation and production scale was therefore imposed on these producers. In the operation of producers focused on achieving maximum efficiency, the size of the production plant, other factors being equal, tends to increase with the increase in residence in a stepwise manner.

A lot of time has passed since the works of Ayres and Simons appeared. In such a situation, it is worth checking to what extent the claims of the two authors cited above remain valid.

Technical progress and increasing competition have significantly changed the situation of the group of producers, whom Ayres defines as those focused on maximum penetration of existing markets with existing products and placing emphasis on new products and/or new markets, and Simons as producers focused on achieving maximum efficiency. Currently, they produce products that are highly advanced in design and technology. The conditions of their operation differ so much from the conditions in which other producers operate that this resulted in the emergence of new interdisciplinary

knowledge (combining elements of technical sciences and management sciences) commonly referred to as “high-tech management” [14]. Manufacturers belonging to this group build their competitive position based on the features (technical parameters) of the manufactured products or technologies used. Innovations in these areas require long-term and expensive work in the field of research and development, and often even in the field of basic research. The effectiveness of this research is rather low - on average, one in seven new solutions in the field of design and technology successfully crosses the border between the prototype phase and the product that has found its place on the market. New solutions are quickly copied by competitors. A copy of the first supersonic passenger plane flew earlier than the original. However, it didn't fly very far or for very long. Nowadays, the need to safely copy competitors' designs and technologies has led to the emergence of a new field of knowledge in technical and legal sciences. It is called “reverse engineering” [15] and is taught at many technical universities around the world.

Manufacturers belonging to the discussed group, even in the case of a positive result of research and development work and successful implementation of their results into practice, have little chance of obtaining a refund of the research expenditure. They require systematic financial support from governments. The group in question currently includes producers from the aviation, space and nuclear industries, some producers from the computer industry (producers of supercomputers but not laptops) and some producers of the arms industry (producers of the most technically advanced weapons and so-called “weapon systems”, but not producers of standard rifles.) or grenades, manufacturers of scientific equipment and some producers from the pharmaceutical industry producing the most advanced drugs. It is regrettable to say that at the moment there is not a single representative of the “high-tech” group in the structure of the Polish industry. Chances of appearing in the future in the structure of the Polish industry of producers belonging to this group are difficult to estimate.

Significantly smaller changes than those described above occurred in the behavior of the second group discussed by the mentioned authors - producers focused on sales maximization. It is created by producers of consumer products. They compete with each other by satisfying consumer needs, including the efficient distribution of their products. The operation of the distribution sphere in the case of these producers must ensure quick and efficient delivery of products to their buyers at low costs. A tendency currently observed among producers of this group is to give up building their own distribution networks and entrust this task to specialized external contractors on the basis of outsourcing. This often involves using the services of not one specialized distribution company, but many companies covering many different distribution channels and ensuring reaching the largest possible group of customers. Distribution companies use a different operating model than manufacturers - cost minimization. In such a situation, distribution companies often take over some of the tasks in the field of research and development from producers (of course in the form of activities carried out by the discussed group of producers - research on consumer reactions to innovations in the field of packaging, names, advertising slogans) and combine it with the implemented for its own use, research and development work aimed at reducing the costs of current distribution activities. For the success of producers focused on maximizing sales, an efficient system that guarantees quick identification of emerging new demand (market gap) or even the ability to create

such a demand (marketing) is crucial. In the sphere of production, the most important thing is flexibility of operation, which must ensure the stability of production costs in the face of rapidly changing demand and the possibility of quickly increasing production when demand arises without long-term investment outlays. An important success factor in the considered group of producers is the durability of the delivery cycle (the period that elapses from the moment of placing the order to its implementation) and the reliability of delivery (the probability that the delivery cycle agreed with the customer will be met).

Typical representatives of the group of producers focused on sales maximization are all producers belonging to the automotive, cosmetics, household chemicals, food, clothing, furniture, toys, footwear, household appliances, consumer electronics industries, and some producers belonging to the computer, arms and pharmaceutical industries. In a broader context, this group also includes the commercial part of services, including commercial health care and commercial education.

The next group of producers are companies focused on minimizing costs. In this group, research and development work is aimed at reducing production costs. Currently, it includes producers representing the energy industry, metallurgy, raw materials industry, construction materials industry, means of transport, shipbuilding, glass industry, cement industry, part of the chemical industry (producers of fuels, plastics) and freight transport services. In a broader context, this group also includes public services (national health service and education) and passenger transport.

Simons suggested separating another group of producers. In terms of innovation, companies belonging to this group behave like companies focused on minimizing costs. They compete with each other by offering the customer products of a specific standard at a price lower than the competition. The basis of competition is a set of product features that are created by three factors: product quality, its price and image (the image of the manufacturer and/or product in the eyes of the customer). The customer makes a choice based on a comprehensive and subjective assessment of these factors. He included the investment goods industry (construction, machinery, tools), the raw materials industry, services and the arms industry in this group. Technical progress and increasing competition have caused some manufacturers to move to other groups discussed earlier. Currently, the group proposed by Simons includes producers from the construction industry and parts of the chemical industry (enterprises producing advanced chemical products for their further use as raw materials by producers of other products) and producers of measuring equipment and laboratory equipment. In a broader context, this group includes agricultural production enterprises.

Against the background of the attitude of producers towards innovation and technical progress presented above, a special place is occupied by enterprises belonging to the mechanical engineering industry, producing machine tools, robots, tools, working machines - generally means of production for the needs of other producers. The selection of production machines and equipment depends, on the one hand, on the technology used, and on the other hand, on the adopted production organization model and method of competition. Therefore, manufacturers focused on achieving maximum efficiency will look for machines and production equipment with the highest technical and operational

parameters. Manufacturers aiming to maximize sales will purchase machines and production equipment with high flexibility and efficiency and with the possibility of many versatile applications not related to the production of a specific product range. In turn, for manufacturers focused on minimizing production costs (using the lean production model), the main criterion for selecting production machines and equipment will be low acquisition and operating costs. Therefore, manufacturers of production and auxiliary machines and equipment (supporting the production process) must always adapt their behavior to the customer's needs. In the American literature, one can find considerations on the need to prepare offers for government agencies, the military, enterprises and individual clients differently [14]. This necessity places objectively the highest demands on manufacturers of production and auxiliary machines and equipment. They operate in the most difficult competitive conditions.

Let us return to the above-quoted statement by H.-J. Bullinger. He states that the most effective form of innovation is the development and use of new technologies, especially technologies that can be used in many areas (cross-sectional technologies), such as information technologies. R.U. made a similar statement. Ayres. He pointed out that "society is experiencing an 'information explosion' and the rate of information flow is increasing much faster than the population, energy consumption, gross national product or any other important socio-economic parameter." It seems that the "information explosion" and the development of information technologies will be the factors that will most strongly influence the behavior of producers in the near future and modify these behaviors.

Modern products are increasingly designed with a focus on innovation and sustainability, adhering to the principles of the 6R framework – Reduce, Reuse, Recycle, Rethink, Repair, and Refuse. This approach aims to minimize environmental impact by creating products that are not only cutting-edge but also prioritize resource efficiency and longevity [16]. By incorporating these criteria into the design process, manufacturers strive to contribute to a more sustainable and circular economy, where products are built to last, can be easily repaired or repurposed, and are mindful of the entire lifecycle, from production to disposal. This trend reflects a growing awareness of the importance of responsible and eco-friendly design in addressing global environmental challenges.

5 Conclusions

In order to facilitate a transition towards sustainable innovation, businesses are required to engage with the complexity and systemic interactions of innovation systems [17–19]. According to the sustainability systems thinking framework [20], sustainable innovation is difficult to achieve within a single organization and thus requires collaboration with other relevant organizations in order to continually create valuable products and services for customers (Anttonen, Halme, Houtbeckers, & Nurkka, 2013; Cappa, Del Sette, Hayes, & Rosso, 2016; Desouza et al., 2008).

Sustainable innovations today encompass a diverse range of practices and technologies aimed at minimizing environmental impact, fostering social responsibility, and ensuring economic viability. Contemporary sustainable innovations span various sectors, leveraging technology, responsible business practices, and a holistic approach to

address environmental and social challenges, fostering a more sustainable and resilient future.

Predicting future trends in innovation is challenging, but several themes are likely to shape the landscape of innovation in companies. There are some expected future trends such as: Digital Transformation, Sustainability and ESG Focus, Remote Technologies, Cybersecurity Innovations, Clean Energy and Green Technologies, Autonomous Systems, 5G Technology, Personalized Customer Experiences. It's essential for companies to stay agile and adaptable, fostering a culture that encourages experimentation and embraces emerging technologies to stay ahead in the ever-evolving landscape of business innovation.

Companies nowadays are facing Industry 4.0 and Industry 5.0. Industry 5.0 principles, emphasizing human-machine collaboration, are integrated into companies' strategies and product innovations through a human-centric approach to design and production, fostering customization with technologies like 3D printing, facilitating data-driven decision-making using advanced analytics, optimizing supply chains with IoT and blockchain, incorporating AR and VR for improved human-machine interaction, implementing sustainable and circular economy practices, deploying collaborative robots to enhance productivity and safety, and utilizing cyber-physical systems for seamless integration of digital and physical operations. Innovative companies aspiring to adopt Industry 5.0 are at the forefront of the latest industrial revolution, emphasizing a collaborative and human-centric approach to manufacturing. These forward-thinking organizations are driven by the idea of fostering harmonious collaboration between humans and machines, encouraging creativity, problem-solving, and increased adaptability. Industry 5.0 envisions a manufacturing landscape where advanced technologies, such as robotics and artificial intelligence, work seamlessly with human expertise, resulting in more flexible and responsive production processes. These companies prioritize customization, real-time decision-making, and sustainable practices, aligning their strategies with the principles of Industry 5.0 to create more efficient, adaptable, and socially responsible manufacturing ecosystems.




References

1. Gulick, L., Urwick, L.: Papers of the Science of Administration. Institute of Public Administration, New York (1937)
2. Koontz, H., O'Donnell, C.: Principles of Management. An Analysis of Managerial Functions. Mac Graw-Hill Book Company, Inc., New York (1955)
3. Koontz, H., O'Donnell, C.: Zasady zarządzania. Analiza funkcji kierowniczych. Państwowe Wydawnictwo Naukowe, Warszawa (1969)
4. Ackoff R.L.: Zasady planowania w korporacjach, Państwowe Wydawnictwo Ekonomiczne, Warszawa, (1973)
5. Ackoff, R.L.: A Concept on Corporate Planning. Wiley-Interscience, New York (1970)
6. Ghallab, M., Nau, D., Traverso, P.: Automated Planning Theory and Practice. Morgan Kaufmann Publishers, Amsterdam-Boston (2004)
7. Sule, D.R.: Manufacturing Facilities. Location, Planning and Design, 3rd edn. CRP Press, Taylor and Francis Group, Boca Raton (2009)

8. Bullinger, H.-J., Spath, D., Warschat, J., Slama, A., Ohlhausen, P.: Technology and innovation management in the future. In: International Foundation for Production Research: International Conference on Production Research, ICPR 2020. CD-ROM: Science and Technology to Promote Harmonized Production, 2–6 August 2009, Shanghai, China (2009)
9. Ahmed, P.K., Shepherd, C.: Innovation Management: Context, Strategies, Systems and Processes. Financial Times Prentice Hall, Harlow (2010)
10. Kotsemir, M., Abroskin, A., Meissner, D.: Innovation concepts and typology—an evolutionary discussion. Higher School of Economics Research Paper No. WP BRP, 5 (2013)
11. Ayres, R.U.: Technological Forecasting and Long – Range Planning. McGraw-Hill, New York (1969)
12. Ayres, R.U.: Prognozowanie rozwoju techniki i planowanie długookresowe. Państwowe Wydawnictwo Ekonomiczne, Warszawa (1973)
13. Simmonds, W.H.C.: Analiza przemysłu i jej zastosowanie w prognozowaniu. In: Bright, J.R., Schoeman, M.E.F. (eds.) Prognozowanie w technice, Wydawnictwo Naukowo – Techniczne, Warszawa (1978)
14. Cohen, W.A.: High-Tech Management, A Revised Edition of “Principles of Technical Management” (Originally Published in 1980). American Management Association, New York (1986)
15. Eilam, E.: Reversing: Secrets of Reverse Engineering. Wiley Publishing Inc., Indianapolis (2005)
16. Gupta, A.R., Deshmukh, S.K.: Sustainable Construction Engineering & Management, Self-published (2020)
17. Foxon, T.J., Pearson, P.J.G.: Overcoming barriers to innovation and diffusion of cleaner technologies: some features of a sustainable innovation policy regime. *J. Clean. Prod.* **16**(1), 148–161 (2008)
18. Malone, T.F., Yohe, G.W.: Knowledge partnerships for a sustainable, equitable and stable society. *J. Knowl. Manag.* **6**(4), 368–378 (2002)
19. van Geenhuizen, M., Ye, Q.: Responsible innovators: open networks on the way to sustainability transitions. *Technol. Forecast. Soc. Change* **87**, 28–40 (2014)
20. Williams, A., Philipp, F., Kennedy, S., Whiteman, G.: Systems thinking: a review of sustainability management research. *J. Clean. Prod.* **148**, 866–881 (2017)
21. Anttonen, M., Halme, M., Houtbeckers, E., Nurkka, J.: The other side of sustainable innovation: Is there a demand for innovative services. *J. Clean. Prod.* **45**, 89–103 (2013)
22. Cappa, F., Del Sette, F., Hayes, D., Rosso, F.: How to deliver open sustainable innovation: an integrated approach for a sustainable marketable product. *Sustainability* **8**(12), 1341 (2016)
23. Desouza, K.C., et al.: Customer-driven innovation. *Res.-Technol. Manage.* **51**(3), 35–44 (2008)



Heuristic-Based Algorithm for Suboptimal Scheduling Realized in Hybrid Production Environment

Wojciech Danilczuk¹ , Arkadiusz Gola² , and Jakub Pizon² 

¹ XPLOREXIT sp. z o.o., Warsaw, Poland

² Lublin University of Technology, Lublin, Poland
a.gola@pollub.pl

Abstract. The article presents the developed heuristic-based scheduling algorithm dedicated for MTO-MTS hybrid production. The developed algorithm allows to maximize the machines load by production tasks taking into account economic and organizational conditions such as the materials availability, costs of storage, the value of frozen funds and the probability of selling or using a given part in the production process while meeting deadlines for the implementation of production tasks resulting from customer orders. In order to verify the proposed solution, a number of experiments were carried out, both using real data from a manufacturing company from the automotive industry as well as simulation data. The obtained results confirmed the thesis, and based on the experiments, conclusions were drawn about the effectiveness of the proposed method.

Keywords: hybrid production · make-to-order · make to-stock · production · scheduling

1 Introduction

For an increasing number of manufacturing companies, the ability to clearly define their production model becomes difficult or even impossible [1, 2]. Both the consumer and industrial markets define new needs that require meeting newer solutions and products [3]. The market expects that these needs will be met in the shortest possible time [4, 5]. Moreover, the development of manufacturing technologies means that production companies do not have to feel permanently tied to the same technological solutions [6, 7]. The life cycle of manufacturing technologies in manufacturing enterprises is becoming shorter and shorter, and manufacturing processes are changing much more frequently than even several dozen years ago [8].

All these factors make it difficult for modern manufacturing companies to clearly determine whether their production model is based on MTS (Make to Stock) or MTO (Make to Order). It is becoming less and less obvious - in practice, production is carried out in a mixed (hybrid) model [9, 10]. Regardless of whether the company implements a production strategy to stock, to order or a hybrid of both models, there are still a

number of problems and difficulties related to production planning and scheduling [11–13]. In the case of MTS production, methods are known and described, e.g. for balancing production lines (line balancing problem), economic order quantity (EOQ) or reorder point [14, 15] In the MTO model, e.g., task scheduling theories or mass customization strategies can be used [16]. For enterprises producing in a hybrid model, identifying clear methods or theories of production planning is not an obvious task - it requires the achievement of goals within a given time horizon - both the part of production that will be allocated to the warehouse and the part produced to customer orders (especially that these goals may be different and contradictory) [17]. Moreover, the complexity of the problem of production planning and scheduling means that taking appropriate actions by manufacturing companies is not an easy decision [18].

Due to the lack of appropriate solutions, a decision was made on initiating work on developing a method for suboptimal production scheduling implemented in the MTO-MTS hybrid model. As part of the research work performed, various production models were characterized. Then, a general hybrid production scheduling algorithm with production task selection functions was proposed. Next, the results of simulation of production planning processes using the proposed algorithm are presented and the results achieved using the proposed algorithm are compared against the background of known task scheduling rules. Finally, conclusions are presented from the work carried out and further work on the problem was proposed.

2 Task Scheduling Algorithm for MTO-MTS Hybrid Production

When developing the scheduling method for production in the hybrid model, assumptions similar to the considerations presented in the works of Morowik, Adan and others [19, 20] were made. The initial production model is production to order. Some of the semi-finished products can be produced in stock and used later as components of machines manufactured to order. Components produced in this way (in advance) can also be used as spare parts in the event of failure of machines already manufactured. The launch of warehouse production is intended to create a buffer for made-to-order production. Production to stock is launched when free production capacity appears. Parts produced in the MTS model do not have to result from sales plans for made-to-order production.

The motivation for launching MTS production is to maximize the use of existing production capacity. Parts produced in this model result from demand forecasts and are not related to current orders or current sales plans.

The aim of the algorithm is (based on the adopted nominal schedule (known, determined and resulting from the MTO production part) and the database of parts produced in the MTS model) to determine:

1. which tasks (semi-finished products, machine elements) from MTS production parts can be performed at all within the adopted nominal schedule (stage I of the algorithm),
2. which of the possible tasks should be added to the schedule and placing the selected task in the nominal schedule - creating a supplemented schedule (stage II of the algorithm).

The general flowchart of the algorithm is shown in Fig. 1.

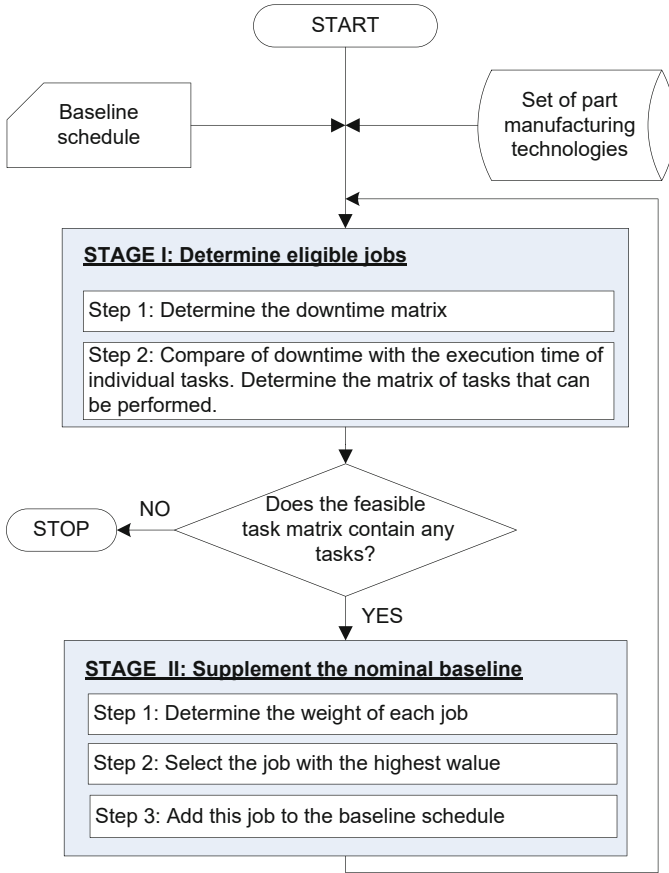


Fig. 1. A general job scheduling algorithm for hybrid MTO-MTS production

The input data to the task scheduling algorithm are the nominal schedule and the set of MTS tasks. The nominal schedule is a schedule prepared for part of the production carried out in the made-to-order model. This schedule, written in matrix form, consists of the following data sets:

- set M (machines), which is a set of m machines included in the production system:

$$M = \{M_1, M_2, \dots, M_m\}, \tag{1}$$

- set J (jobs), containing n tasks to be performed:

$$J = \{J_1, J_2, \dots, J_n\}, \tag{2}$$

- operation set (OS) matrix - containing information whether a given task J requires passing (performing actions) on individual machines from set M . The matrix elements take the values 1 or 0. The value 1 means that a given operation of task J requires

performing an operation on a machine M. The value 0 means that a given operation of task J does not require the execution of an operation on machine M.

$$OS = \begin{matrix} & M_1 & M_2 & \dots & M_m \\ \begin{matrix} J_1 \\ J_2 \\ \dots \\ J_n \end{matrix} & \begin{bmatrix} o_{11} & o_{12} & \dots & o_{1m} \\ o_{21} & o_{22} & \dots & o_{2m} \\ \dots & \dots & o_{ij} & \dots \\ o_{n1} & o_{n2} & \dots & o_{nm} \end{bmatrix} \end{matrix}, \tag{3}$$

$$OS = [o_{ij}], \tag{4}$$

where: o_{ij} – a number specifying the necessity to perform an operation j task on a given machine and taking the values:

$$o_{ij} = \begin{cases} 0, & \text{when the operation is not performed} \\ & \text{on the machine } m, \\ 1, & \text{when the operation is performed} \\ & \text{on the machine } m, \end{cases}$$

- machine order (MO) matrix containing information on the order of performing activities within a specific task from set J on individual machines M

$$MO = \begin{matrix} & M_1 & M_2 & \dots & M_m \\ \begin{matrix} J_1 \\ J_2 \\ \dots \\ J_n \end{matrix} & \begin{bmatrix} o_{11} & o_{12} & \dots & o_{1m} \\ o_{21} & o_{22} & \dots & o_{2m} \\ \dots & \dots & o_{ij} & \dots \\ o_{n1} & o_{n2} & \dots & o_{nm} \end{bmatrix} \end{matrix}, \tag{5}$$

$$O = [o_i], \tag{6}$$

where: o_{ij} – a number specifying the order of execution of the j task’s operations and taking the values:

$$o_{ij} = \begin{cases} 0, & \text{when the operation is not performed} \\ & \text{on the machine } m, \\ \{1, \dots, m\}, & \text{when the operation is performed} \\ & \text{on machine number } m, \end{cases}$$

m – number of machines carrying out technological processes,

- processing times (PT) matrix containing information on the times of individual technological operations:

$$PT = \begin{matrix} & M_1 & M_2 & \dots & M_m \\ \begin{matrix} J_1 \\ J_2 \\ \dots \\ J_n \end{matrix} & \begin{bmatrix} pt_{11} & pt_{12} & \dots & pt_{1m} \\ pt_{21} & pt_{22} & \dots & pt_{2m} \\ \dots & \dots & pt_{ij} & \dots \\ pt_{n1} & pt_{n2} & \dots & pt_{nm} \end{bmatrix} \end{matrix}, \tag{7}$$

$$PT = [pt_{ij}], \tag{8}$$

where: pt_{ij} – a number specifying the total j operation time on i task; wherein:

$$\begin{aligned} \wedge pt_{ij} &= 0 \\ o_{ij} &= 0 \end{aligned}$$

- *completion times* (CT) matrix, containing information on the completion times of individual technological operations:

$$CT = \begin{matrix} & M_1 & M_2 & \dots & M_m \\ \begin{matrix} J_1 \\ J_2 \\ \dots \\ J_n \end{matrix} & \begin{bmatrix} ct_{11} & ct_{12} & \dots & ct_{1m} \\ ct_{21} & ct_{22} & \dots & ct_{2m} \\ \dots & \dots & ct_{ij} & \dots \\ ct_{n1} & ct_{n2} & \dots & ct_{nm} \end{bmatrix} \end{matrix}, \quad (9)$$

$$CT = [ct_{ij}], \quad (10)$$

where: ct_{ij} - a number specifying the total j operation time of i task; wherein

$$\begin{aligned} \wedge ct_{ij} &= 0 \\ o_{ij} &= 0 \end{aligned}$$

The second set of data necessary to initiate the algorithm is the set of MTS tasks. These are tasks describing the production of all machine components and subassemblies that the company can and wants to produce in the warehouse model. The MTS task set is described by two groups of parameters. The first one contains information about technological routes and execution times of individual tasks from the MTS task set, i.e.:

- operation set (*OS*) matrix (with parameters analogous to the matrix OS nominal schedule),
- machine order (*MO*) matrix (with parameters analogous to the MO matrix of the nominal schedule),
- processing times (*PT*) matrix (with parameters analogous to the PT matrix of the nominal schedule).

The second group of parameters will be used to determine which tasks should be placed in the Nominal Schedule in the selected iteration of the algorithm (procedure for determining the weight matrix). These parameters are presented in the form:

- *material availability* (F_{mat}) matrix containing information on how many pieces of a given task J the manufacturing company has material stock in the warehouse:

$$F_{mat} = \begin{bmatrix} f_{mat\ 1} \\ f_{mat\ 2} \\ \dots \\ f_{mat\ n} \end{bmatrix} = [f_{mat\ i}], \quad (11)$$

where: f_{mati} – a number specifying how many pieces of the i task and material inventory the company has, taking natural numbers as values,

- *frozen capital* F_{zk} matrix containing information on the cost of frozen capital in the event of producing a given component (as part of J task) and allocating it to the warehouse

$$F_{zk} = \begin{bmatrix} f_{zk\ 1} \\ f_{zk\ 2} \\ \dots \\ f_{zk\ n} \end{bmatrix}, \quad (12)$$

$$F_{zk} = [f_{zk\ i}], \quad (13)$$

where: f_{zki} – a number specifying the value of frozen capital for the task J ,

- *storage costs* (F_{km}) matrix containing information on the cost of storing the product implemented under J task

$$F_{km} = \begin{bmatrix} f_{km\ 1} \\ f_{km\ 2} \\ \dots \\ f_{km\ n} \end{bmatrix}, \quad (14)$$

$$F_{km} = [f_{km\ i}], \quad (15)$$

where: f_{kmi} – a number defining the value of the storage cost for J task

- *number of MTS tasks already added to the schedule* (IZ_{MTS}) matrix, containing information on how many pieces of parts from the MTS set have already been added to the schedule (both as a result of the operation of the hybrid production task scheduling algorithm and MTS parts that were placed in the nominal schedule before the algorithm ran):

$$IZ_{MTS} = \begin{bmatrix} iz_{mts\ 1} \\ iz_{mts\ 2} \\ \dots \\ iz_{mts\ n} \end{bmatrix}, \quad (16)$$

$$IZ_{MTS} = [iz_{mts\ i}], \quad (17)$$

where: iz_{msi} – a number specifying how many pieces of parts for J task have already been added to the schedule.

- *historical data* containing information on the sale of parts from the MTS sentence collection in previous planning periods. This information is used as part of the weight calculation algorithm.
- *amplification factors* w_1, w_2, w_3, w_4 . These coefficients are defined individually by the enterprise and result from existing organizational and economic conditions. These coefficients are used as part of the weight calculation algorithm.

The operation of the algorithm is iterative, which means that after completing one loop of the task scheduling algorithm for hybrid production, a supplemented schedule is generated, which is a nominal schedule with one task added from the MTS task set. This does not mean, however, that all downtime has been used and that no further tasks can be added to the schedule. Therefore, after one iteration of the algorithm, the nominal schedule is overwritten by the supplemented schedule (the supplemented schedule becomes the “new” nominal schedule). After determining the downtime matrix, the matrix of tasks that can be performed is calculated. If this matrix is non-empty (there are tasks that can be added to the nominal schedule), then the weight matrix is calculated, the task with the highest weight is selected and this task is added to the nominal schedule. In the weight calculation procedure, the number of pieces (number of tasks) that have already been added to the nominal schedule in previous iterations of the algorithm is taken as an argument of the function. For example, if in the previous iteration the J1_MTS task was added to the schedule, and the availability of materials for the production of the J1_MTS element was 1, then in the next iteration the weighting algorithm for the component responsible for the material availability function will assign a weight equal to zero to this task.

The algorithm will perform subsequent iterations until the calculated matrix of possible tasks is empty. This means that it is unable to place any additional tasks from the MTS task set into the schedule. This does not mean that all downtimes have been fulfilled. It may happen that there is free processing capacity in the schedule, but the downtime is too short to be supplemented with subsequent tasks, or the order in which downtime occurs on individual machines is not consistent with the technological route of any task from the MTS task set.

After reaching this state (the matrix of tasks that can be performed is empty), the algorithm ends its operation and the completed schedule is returned, which is the original nominal schedule supplemented with the number of tasks from the MTS task set equal to the number of iterations of the algorithm.

3 Experimental Verification of the Developed Algorithm

The key stage of the presented work was the verification of the developed task scheduling method for production carried out in the MTO-MTS hybrid model according to adopted assumptions regarding the production system and production model. The experiments carried out were aimed at examining the possibility of using the proposed algorithm for scheduling tasks in hybrid production and assessing the effectiveness of the proposed scheduling method.

The experiment was conducted on real data from a manufacturing company in the machinery industry. Based on historical data, a set of MTS tasks was determined and a production schedule was selected, which was treated as a nominal schedule. For the tasks from the MTS task set, the parameters necessary to determine the weight matrix were determined. The aim of the experiment was to create a supplemented schedule in accordance with the developed algorithm and to compare the schedule quality indicators C_{max} , \bar{F} , \bar{I} , LE between the nominal and supplemented schedules. The research compared the difference in individual quality indicators between the optimal schedule and other

schedules. The aim of the first experiment was to verify the scientific theses of the work using data from a real enterprise.

A classroom computer was used to carry out the experiments PC equipped with an Intel Core i5 1035G1 processor, 16 GB RAM, Windows 10 Pro operating system (64-bit version). The software used to conduct the experiment is LiSA Software and Matlab.

The data used in the verification process of the developed hybrid production scheduling method comes from a production company producing dedicated machines and devices that are part of production lines in the automotive industry. The company carries out production according to the MTO model using production stations such as: a laser plotter, a bending machine, a CNC machining center, an endless saw, a locksmith and welding station, a pickling shop, an electrical assembly station and a mechanical assembly station. The acquired historical data concerned:

- the production schedule which was used as the nominal schedule (Fig. 2),
- technology and standard production times of parts and semi-finished products, which from the enterprise's perspective may constitute a set of MTS tasks,
- information about historical warehouse stocks of materials necessary to produce tasks from the MTS collection,
- information on storage costs and the value of frozen capital of tasks from the MTS set,
- historical sales data for each part from the MTS task set,
- historical data on the sales volume of individual assortment items from the MTS collection, on the basis of which the forecast number of products for sale in the next planning period was determined.

In addition to historical data, the company determined the value of the amplification factors w_1, w_2, w_3, w_4 used in the weight calculation procedure. The data was obtained from the enterprise's ERP system database and was saved in a matrix form supported by the developed algorithm and readable by the MATLAB program.

The next step after reading the nominal schedule was to determine the set of parts and semi-finished products that could be produced in the warehouse model in the company in question (defining the set of MTS tasks). MTS tasks were characterized by relatively short production times (the time of performing a single operation did not exceed 5 h). The set of MTS tasks was limited to 15 parts (from this group) with the highest sales volume. The set of MTS tasks was saved in the form of OS, PT and MO matrices in the m-file (Fig. 3).

The next stage of obtaining and preparing input data was to determine the parameters used by the weighting algorithm. Since the schedule that was drawn as a nominal schedule came from a specific moment, the warehouse status at the beginning of the planning period adopted for analysis was read from the ERP system module database. On this basis, for each task from the set of MTS tasks, the availability of materials to produce a given quantity of an element was determined (the F_{mat} matrix of the algorithm determining the weights of individual MTS tasks, corresponding to the number of individual parts that can be produced from the current inventory).

Then, for each part from the set of MTS tasks, the value of frozen capital and the cost of storage were assigned (based on data from the company's ERP system) (F_{zk} and F_{km} matrices).

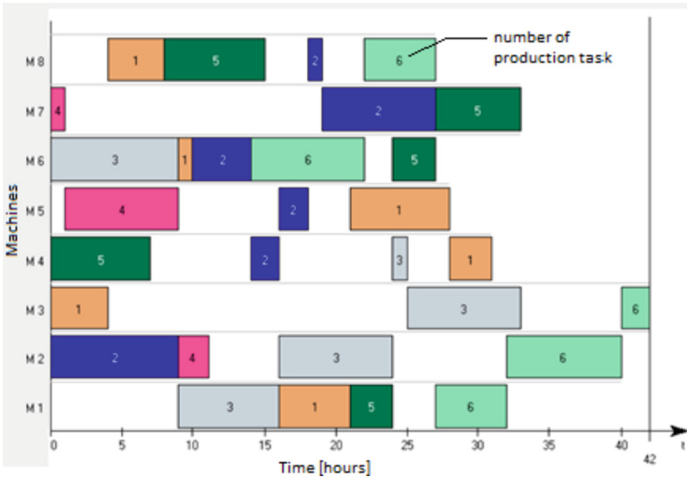


Fig. 2. The base (nominal) schedule used in the process of scheduling production tasks.

Based on historical data from the ERP system, the algorithm prepared a sales forecast in the next planning period for tasks from the MTS task set. The forecast was prepared according to a model that takes into account trend and seasonality. The value of the forecast number of products for sale in the next planning period was written as the p matrix.

For the analyzed nominal schedule, no task from the MTS task set was included in the nominal schedule. The IZ_{MTS} matrix was a zero matrix.

The last step that needed to be performed was to assign amplification factors for each of the component parameters of the weighting algorithm. Based on its organizational and economic conditions and limitations, the company determined the following strengthening factors:

- For the material availability parameter, the amplification index $w_1 = 1$ was adopted - the company had a significant stock of raw materials that could be used for production;
- For the value of frozen capital, the amplification index $w_2 = 0.75$ was assumed - the company was in good financial condition and the frozen capital was not a problem for the company;
- For the cost of storage, the amplification index $w_3 = 3$ was adopted - due to the limited space in the warehouse, the company used rented warehouse space and consequently strived to be as low as possible storage costs;
- For the value of the sales opportunity, the amplification index $w_3 = 2$ was assumed - the company wanted to use the parts produced in stock as quickly as possible.

As a result, the elements of the weight matrix were calculated according to the formula (18).

$$WG = 1 * P_{mat} + 0,75 * P_{zk} + 3 * P_{km} + 2 * P_{sz} \tag{18}$$

Having the data prepared in this way and saved in the form of files supported by the MATLAB environment, the main part of the experiment began - determining the

```
1. processing_times MTS = [
2. 0 1 3 0 0 5 5 0
3. 0 0 0 4 4 2 3 0
4. 4 5 0 0 0 4 1 0
5. 0 2 0 0 3 0 4 0
6. 5 2 0 1 2 2 0 3
7. 0 2 0 0 2 0 0 3
8. 0 1 0 0 5 0 2 0
9. 0 0 0 0 3 0 0 5
10. 4 0 5 0 0 5 3 0
11. 2 0 0 0 2 0 5 0
12. 4 0 0 5 0 0 0 3
13. 0 0 1 0 0 4 5 4
14. 3 5 1 0 0 0 2 0
15. 3 1 2 0 0 4 0 1
16. 0 0 0 0 4 3 5 0 ];
17. operation_set_MTS = [
18. 0 1 1 0 0 1 1 0
19. 0 0 0 1 1 1 1 0
20. 1 1 0 0 0 1 1 0
21. 0 1 0 0 1 0 1 0
22. 1 1 0 1 1 1 0 1
23. 0 1 0 0 1 0 0 1
24. 0 1 0 0 1 0 1 0
25. 0 0 0 0 1 0 0 1
26. 1 0 1 0 0 1 1 0
27. 1 0 0 0 1 0 1 0
28. 1 0 0 1 0 0 0 1
29. 0 0 1 0 0 1 1 1
30. 1 1 1 0 0 0 1 0
31. 1 1 1 0 0 1 0 1
32. 0 0 0 0 1 1 1 0 ];
33. machine_order_MTS = [
34. 0 4 3 0 0 1 2 0
35. 0 0 0 2 1 3 4 0
36. 2 4 0 0 0 1 3 0
37. 0 1 0 0 2 0 3 0
38. 6 1 0 2 4 5 0 3
39. 0 3 0 0 1 0 0 2
40. 0 2 0 0 1 0 3 0
41. 0 0 0 0 2 0 0 1
42. 3 0 4 0 0 1 2 0
43. 3 0 0 0 2 0 1 0
44. 3 0 0 1 0 0 0 2
45. 0 0 2 0 0 3 4 1
46. 2 3 4 0 0 0 1 0
47. 5 1 4 0 0 2 0 3
48. 0 0 0 0 1 2 3 0 ];
```

Fig. 3. A collection of MTS tasks in matrix form, saved as an m-file.

schedule supplemented by placing selected tasks from the set of MTS tasks in the nominal schedule (schedule for hybrid production).

Figure 4 presents the nominal schedule and the schedule supplemented in the form of a Gantt chart, after passing the first iteration of the task scheduling algorithm for hybrid production.

After passing the first iteration of the algorithm, the quality measures LE and \bar{I} were improved (Table 1). The average flow time \bar{F} has slightly deteriorated. The total implementation time (C_{max}) has not been extended.

After passing the first iteration of the algorithm, subsequent iterations are performed. The completed schedule overwrites the nominal schedule and in the second iteration (and in each subsequent one) the task scheduling procedure for hybrid production is repeated.

Because a new task was added to the schedule, the time available for completion on individual machines (MP matrix) changed. Therefore, the algorithm recalculates the

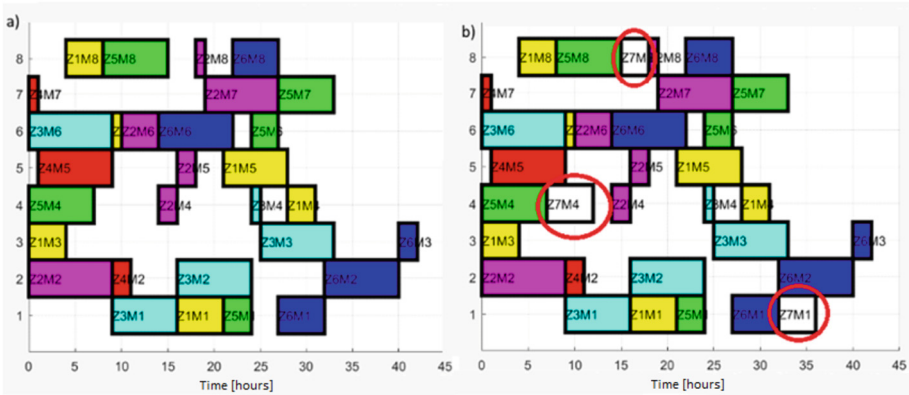


Fig. 4. The nominal schedule (a) and the completed schedule (b) after passing the first loop of the algorithm

Table 1. Schedule quality metrics after the first iteration of the algorithm

Schedule quality index	Value for nominal schedule	Value for the completed schedule
C_{max}	42	42
LE	44%	47%
\bar{F}	27.16	27.43
\bar{I}	23.50	22

MP, DC, ZG matrices and determines a new set of tasks that can be performed ZM. If the matrix of possible tasks includes at least one task that can be included in the schedule, the WG weight matrix is recalculated, the task with the highest weight is selected and placed in the schedule. The procedure is repeated until the ZM matrix is not a zero matrix. If in a given iteration the ZM matrix turns out to be a zero matrix (it is not possible to add more tasks to the schedule), then the algorithm stops its operation and returns a completed schedule (containing tasks from the nominal schedule and all tasks from the set of MTS tasks added by all previous iterations).

It is also worth noting that in each subsequent iteration of the algorithm, different tasks may be available to be performed - with subsequent iterations, less and less downtime is available in the schedule and a smaller and smaller fragment of the set of MTS tasks can be included in the schedule.

Moreover, in each subsequent iteration the WG weight matrices may assume different values. For example, if one task from the set of MTS tasks has already been placed in the nominal schedule and can also be placed in the next loop, it may not receive the highest importance among the tasks that can be performed (e.g. due to a decrease in the value of the sales opportunity parameter P_{sz}).

In the case of the analyzed nominal schedule, the algorithm performed 8 iterations (added 8 sentences from the set of MTS tasks to the nominal schedule). As part of

subsequent iterations, the following tasks were added to the nominal schedule: J11_MTS, J11_MTS, J2_MTS, J10_MTS, J10_MTS, J6_MTS, J4_MTS. Table 2 compares the quality measures and the LE efficiency coefficient of the nominal schedule and the schedule completed after the algorithm has been completed. Figure 5 shows the nominal schedule and the supplemented schedule for the tested schedule.

Table 2. Schedule quality metrics after the first iteration of the algorithm

Schedule quality index	Value for nominal schedule	Value for the completed schedule	Difference
C_{max}	42	42	0
LE	44%	67%	23%
\bar{F}	27.16	25.43	1.73
\bar{I}	23.50	13.63	9.87

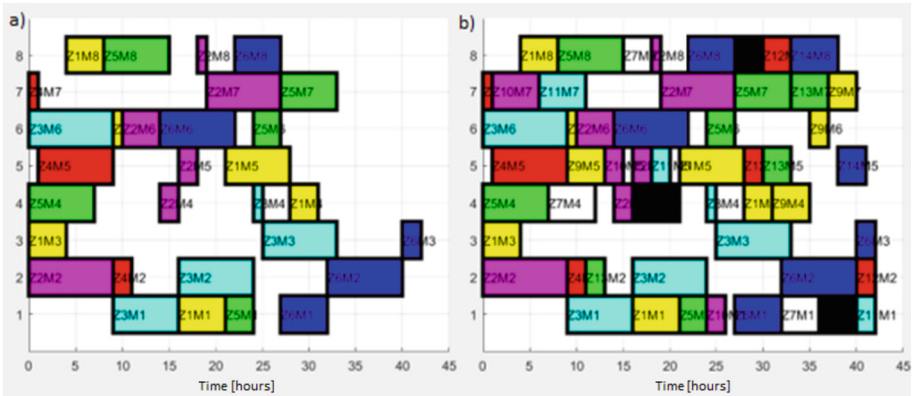


Fig. 5. The nominal schedule and the schedule completed after the algorithm finishes

The developed algorithm significantly improved the use of the company’s production capacity. LE’s capacity utilization rate increased by 23%. The average flow time was reduced by approximately 6%, while the average machine idle time was reduced by 42%. The total completion time of all scheduled tasks has not changed.

4 Summary and Conclusions

The result of the research work carried out is the task scheduling method for MTO-MTS hybrid production. The developed one enables the hybrid production scheduling procedure to be carried out taking into account the limitations and economic and organizational conditions occurring in real production enterprises. The schedules generated by the developed algorithm are characterized by a higher degree of production capacity utilization compared to the nominal schedules, while maintaining the completion date of all tasks included in the nominal schedule.

The individual procedures included in the algorithm have been developed in such a way that it is possible to later implement them using typical high-level programming languages and, as a consequence, to build a tool in the form of a computer program implementing the task scheduling process for hybrid production.

The implementation of the developed algorithm may not only enable the hybrid production planning process, but also has a positive impact on increasing the use of the company's production capacity and may enable an increase in the supply of products while maintaining the deadlines resulting from customer orders. Moreover, the developed algorithm does not require a time-consuming schedule optimization procedure.

The developed method is a new approach to the problem of scheduling MTO-MTS hybrid production in relation to the solutions previously presented in the literature. The developed algorithm is characterized by a high degree of universality and can be a starting point for further research on the problem of task scheduling for hybrid production.

References

1. Jasiulewicz-Kaczmarek, M., Antosz, K., Chao, Z., Waszkowski, R.: Assessing the barriers to industry 4.0 implementation from a maintenance management perspective - pilot study results. *IFAC-PapersOnLine* **55**(2), 222–228 (2022)
2. Urban, W.: TOC implementation in a medium-scale manufacturing system with diverse product routing. *Prod. Manuf. Res.* **7**(1), 178–194 (2019)
3. Kujawińska, A., Diering, M.: The impact of the organization of the visual inspection process on its effectiveness. *Int. J. Adv. Manuf. Technol.* **112**, 1295–1306 (2021)
4. Relich, M., Nielsen, I., Gola, A.: Reducing the total cost at the product design stage. *Appl. Sci.* **12**(4), 1921 (2022)
5. Bocewicz, G., Wójcik, R., Sitek, P., Banaszak, Z.: Towards digital twin-driven performance evaluation methodology of FMS. *Appl. Comput. Sci.* **18**(3), 5–18 (2022)
6. Adamczak, M., Kolinski, A., Trojanowska, J., Husar, J.: Digitalization trend and its influence on the development of the operational process in production companies. *Appl. Sci.* **13**(3), 1939 (2023)
7. Świć, A., Gola, A.: Economic analysis of casing parts production in a flexible manufacturing system. *Actual Probl. Econ.* **141**(3), 526–533 (2013)
8. Kolny, D., Kaczmar-Kolny, E., Dulina, L.: Modeling and simulation of the furniture manufacturing and assembly process in the arena simulation software. *Technologia I Automatyzacja Montażu (Assembl. Tech. Technol.)* **119**(1), 13–22 (2023)
9. Danilczuk, W., Gola, A., Grzmar, P.: Job scheduling algorithm for a hybrid MTO-MTS production process. *IFAC-PapersOnLine* **55**(2), 451–456 (2022)
10. Sato, Y., Maeda, H., Toshima, R., Nagasawa, K., Morikawa, K., Takahashi, K.: Switching decisions in a hybrid MTS/MTO production system comprising multiple machines considering setup. *Int. J. Prod. Econ.* **263**, 108877 (2023)
11. Plinta, D., Radwan, K.: Improving material flow in a modified production system. *Appl. Comput. Sci.* **19**(1), 95–106 (2023)
12. Kočańska, J., Burduk, A.: A method of assessing the effectiveness of the use of available resources when implementing production processes. *Appl. Sci.* **13**(13), 7764 (2023)
13. Wittbrodt, P., Łapuńska, I., Baytikenova, G., Gola, A., Zakimova, A.: Identification of the impact of the availability factor on the efficiency of production processes using the AHP and fuzzy AHP methods. *Appl. Comput. Sci.* **18**(4), 116–129 (2022)

14. Ming-Huang Chiang, D., Wei-Di Wu, A.: Discrete-order admission ATP model with joint effect of margin and order size in a MTO environment. *Int. J. Prod. Econ.* **133**(2), 761–775 (2011)
15. Wikarek, J., Sitek, P.: A new approach to the allocation of multidimensional resources in production processes. *Appl. Sci.* **12**(14), 6933 (2022)
16. Sahar, H., Herrou, B., Sekkat, S.: Optimization of job shop scheduling problem by genetic algorithms: case study. *Manage. Prod. Eng. Rev.* **14**(3), 44–56 (2023)
17. Yetis, H., Karakose, M., Baygin, N.: Blockchain-based mass customization framework using optimized production management for industry 4.0 applications. *Eng. Sci. Technol. Int. J.* **36**, 101151 (2022)
18. Liang, Z., et al.: A genetic algorithm-based approach for flexible job shop rescheduling problem with machine failure interference. *Eksplotacja i Niezawodność – Maint. Reliab.* **25**(4), 171784 (2023)
19. Morikawa, K., Takahashi, K., Hirotani, D.: Make-to-stock policies for a multistage serial system under a make-to-order production environment. *Int. J. Prod. Econ.* **147**, 30–37 (2014)
20. Adan, I.J.B.F., van der Wal, J.: Combining make to order and make to stock. *OR Spektrum* **20**, 73–81 (1998)



Minimum Job Completion Time in Petri Nets

Reggie Davidrajuh¹(✉) , Damian Krenczyk² , and Bozena Skolud² 

¹ University of Stavanger, Stavanger, Norway
reggie.davidrajuh@uis.no

² Silesian University of Technology, Gliwice, Poland

Abstract. Petri Nets are well known as a tool to model discrete systems. Petri Nets possess arc weights that represent the number of tokens consumed by a transition from its input place (input arc weight) or deposited into its output place (output arc weight). The arc weights are fundamental during the simulation run ('dynamic analysis') of the Petri Net. Petri Net theory also offers static analyses (*aka* 'structural analysis,' or invariants), which are quicker and do not change with the dynamics (e.g., initial tokens or firing times of the transitions). This paper attempts to distribute 'firing times' as arc weights on Petri Nets so that more structural analyses can be performed - a so-called quasi-dynamic approach; for example, this quasi-dynamic analysis can find a faster route from a source to a destination (minimum job completion time). Otherwise, finding the minimum job completion time using simulations is slow and may not provide the correct answer. The approach presented in this paper for finding the minimum job completion time can be used in many branches of engineering, such as manufacturing.

Keywords: Petri Nets · Timed Petri Nets · Time as arc weights · Structural analysis · quasi-dynamic analysis · GPenSIM

1 Introduction

Researchers use Petri Nets for modeling and analysis of discrete systems. The analysis of Petri Nets falls into two categories: 1) Static analysis (*aka* structural analysis or invariants) and 2) Dynamic analysis (e.g., simulation runs, reachability trees, matrix-based linear algebraic computations) [1].

Dynamic analyses are based on parameters for the simulation (such as initial tokens and the number of available resources), time (e.g., firing time of the transitions and starting time of the simulation), and cost (e.g., firing costs of the transitions and usage costs the resources). The dynamic analyses make the core of the analysis as they find the bottlenecks, dominating cycles, throughput, total costs, etc. In the literature, several Petri Net models with time have been defined, time and timed, where enabled transitions may fire within given time intervals or as soon as given time delays have elapsed, thus differing timing structure and firing rules [2].

However, dynamic analyses are time-consuming, especially considering Petri Net models of large systems; Petri Net models of large systems are usually huge. In these

cases, it is necessary to deal with the problems of state explosion and an increase in computational costs, requiring in general case exponential computational time and memory. Although applications of continuous or hybrid Petri Nets are proposed to address these problems, which allow the use of many techniques developed for the discrete structure, the continuous Petri Nets do not preserve all behavioral properties of their discrete counterpart [2, 3].

Static analyses (structural analyses) are based on a static Petri Net graph, considering only the nodes (places and transitions) in a Petri Net and how they are connected (network topology) and do not depend on the initial markings. Typical examples of the use of structural analysis in the design of flexible and automated manufacturing systems include, among others, the calculation of siphons and traps in the problems of detection and prevention of deadlocks [3–6]. Static analyses are faster and do not change with time unless changes are made to the topology (changes in the nodes and their connection).

The structure of this paper is as follow: Sect. 2 presents some basic definitions of Petri Net. Section 3 three different ways of mapping (distributing) time onto the arcs weights. Section 4 presents the approach for finding the minimum job completion time in a Petri Net. Section 5 presents an application example. Section 6 is devoted to discussion and conclusion.

2 Static and Dynamic Petri Nets

To emphasize the difference between static and dynamic analyses, we present two definitions of Petri Nets, followed by a definition of Timed Petri Nets. Also, GPenSIM is introduced as a tool for realizing Petri net models.

2.1 Static Petri Net

A static Petri Net is also called a Petri Net graph, as the focus is on the network topology and not on the dynamics. Also, we limit ourselves to the simplest type of Petri Nets, namely Ordinary Petri Nets.

Definition: A **Static Petri Net** (SPN, for short) is defined as a four-tuple [1, 7]:

$$SPN = (P, T, A, K), \quad (1)$$

where:

P is a set of places, $P = \{p_1, p_2, \dots, p_{n_p}\}$.

$\forall p_i \in P, K(p_i) \rightarrow N^+ \cup \{\infty\}$, is the maximum capacity of the place p_i .

T is a set of transitions, $T = \{t_1, t_2, \dots, t_{n_t}\}$.

$$P \cap T = \emptyset.$$

A is the set of arcs (from places to transitions and from transitions to places).

$A \subseteq (P \times T) \cup (T \times P)$. The arc weight $w(a_{ij})$ is one, $\forall a_{ij} \in A$.

2.2 Dynamic Petri Net

Adding markings to a Static Petri Net makes it a dynamic Petri Net (*aka* Marked Petri Nets).

Definition: A Dynamic Petri Net (MPN, for short) is defined as a five-tuple [1, 7]:

$$MPN = (P, T, A, K, M), \quad (2)$$

where:

P, T, A, K are the same as defined for Static Petri Net.

M is the row vector of markings (tokens) on the set of places.

$\forall t \in T, FT \in \mathbb{R}^+, FT(t) > 0$.

$M = [M(p_1), M(p_2), \dots, M(p_{n_p})] \in N^{n_p}$, M_0 is the initial marking.

2.3 Timed Petri Net

Ordinary Petri nets do not involve time. Hence, Ordinary Petri nets are insufficient to model engineering systems as these systems usually involve time. **Timed Petri net** (TPN) is an extension to Ordinary Petri net to incorporate time.

There are many definitions of Timed Petri Nets exist. The following definition for Timed Petri Nets is the one that is implemented in the tool GPenSIM [8–10].

Definition: A Timed Petri net (TPN, for short) is defined as a six-tuple:

$$TPN = (P, T, A, K, M, FT), \quad (3)$$

where:

(P, T, A, K, M) is a Dynamic Petri Net,

FT is a mapping of T into \mathbb{R}^+ :

$\forall t \in T, FT \in \mathbb{R}^+, FT(t) > 0$.

$FT(t)$ is known as the **firing times** of the transitions and is defined to be greater than zero.

2.4 GPenSIM

General-purpose Petri Net Simulation (GPenSIM) is a new tool for modeling and simulation of discrete systems as Petri Net models. The first author of this paper developed GPenSIM. The design goals of GPenSIM are [8, 9]:

- Easy to learn.
- Easy to use.
- Flexible (extensible) to model various problems in different domains.
- Capable of modeling large discrete systems.

GPenSIM can be freely downloaded [11], and it is well-documented [8–10].

3 Mapping Firing Times as Arc Weights

First, we will look into the role of time in Petri nets. Then, we will use this concept to map the firing times of transition as arc weights.

3.1 The Role of Time in Petri Nets

There are three different ways to include time in Petri nets:

- Add time to transitions [12].
- Add time to places [13].
- Add time to places and transitions [14].

In GPenSIM, time is only attached to transitions [15]. For realizing discrete systems as Petri Net models, GPenSIM's approach is to focus on transitions because transitions are the active elements, and places are, in essence, carried along by the transitions.

3.2 Firing Times as Arc Weights

Let us say the firing time of a transition t_j is ΔT_j . There are three ways the firing time of a transition can be distributed to arc weights:

1. *a priori* to a transition: the firing time (ΔT_j) is imposed as weights on the input arcs (input arcs are the ones that are from the input places to a transition). See Fig. 1(a).
2. *a posteriori*: the firing time (ΔT_j) is imposed as weights on the output arcs (output arcs are the ones that are from a transition to its output places). See Fig. 1(b).
3. Hybrid: The firing time is divided by two ($\Delta T_j/2$) and is imposed as weights on the input and output arcs of the transition. See Fig. 1(c).

A priori method: This method will face a problem if the Petri Net possesses generator transitions (*aka* 'cold' transition, a transition without any input places; see Fig. 2(a)). In this case, there is no way we can map the firing time of this cold transition to the input arcs, as this transition does not have any input arcs.

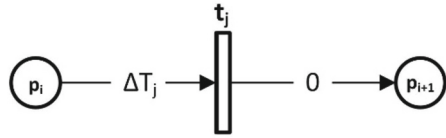
A posteriori method: This method will face a problem if the Petri Net possesses 'sink' transitions (a transition without any output places; Fig. 2(b)). In this case, there is no way we can map the firing time of this sink transition to the output arcs, as this transition does not have any output arcs.

Hybrid method: This method will face problems if the Petri Net possesses generator transitions and or sink transitions.

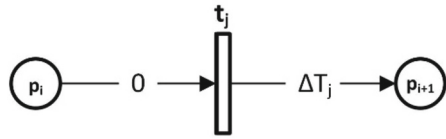
Note that GPenSIM also allows a special transition known as a 'supervisor' transition, which does not possess any input places or output places (Fig. 2(c)). In essence, a supervisor is both a generator and a sink at the same time. The role of this supervisor transition is to monitor all the activities during the simulation runs.

To eliminate the problems caused by generator transitions, sink transitions, and supervisors, the approach described in this paper has the following assumption:

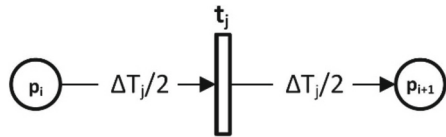
A Petri Net does not possess any generator, sink, or supervisor transitions; if there are any generator transitions, a 'dummy' place will be put as the input place to each generator transition; see Fig. 3(a). If there are any sink transitions, a 'dummy' place will



(a) A priori approach

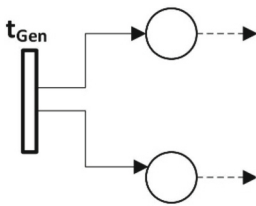


(b) A posteriori approach

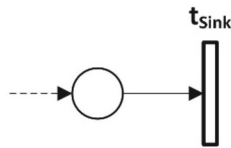


(c) Hybrid approach

Fig. 1. The three approaches.



(a) Generator transition t_{Gen}



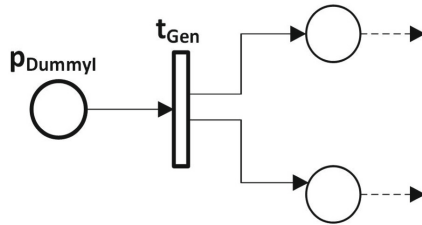
(b) Sink transition t_{Sink}



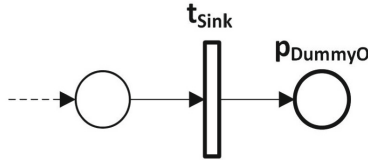
(c) Supervisor t_{Supv}

Fig. 2. Generator transition and sink transition.

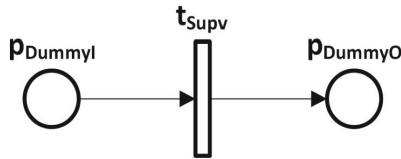
be added as the output place after each sink transition; see Fig. 3(b). A supervisor will either be eliminated from the model or will be added a dummy input place and a dummy output place (Fig. 3(c)).



(a) t_{Gen} with a dummy input place



(b) t_{Sink} with a dummy output place



(c) t_{Supv} with dummy input and output places

Fig. 3. Fixing the generator transition and sink transition.

4 Finding the Minimum Job Completion Time

The approach for finding the minimum job completion time with Petri Nets consists of three simple steps:

1. Model the discrete system as a Petri Net model. The model should have source places to hold the initial tokens so that the execution of the model can be started. The model should also have sink places to stop the simulation once all the tokens end up in these sink places.
2. Distribute the firing times of the transitions using one of the three methods discussed in Sect. 3.2; in the following, we use the hybrid method.
3. Run “Single-source Shortest Paths (SSSP)” algorithm from each of the source places.
4. The pair (source place, sink place) with the shortest path: the distance represents the minimum job completion time.

Single-source Shortest Paths (SSSP) algorithm is a basic graph algorithm. Bellman-Ford and Dijkstra are two well-known algorithms that takes polynomial running time $O(V \times E)$, where V is the total number of nodes (places and transitions) and time E is the total number of arcs [3].

5 Application Example

Let us consider a manufacturing grid that is composed of some machines. This manufacturing grid possesses multiple entry points (IPs) through which raw materials (or semi-products) enter the manufacturing system. Also, the manufacturing grid has multiple exit points (OPs) where the final products are output, as shown in Fig. 4. Between these multiple entry points and exit points, materials flow through diverse production machines. Also, let us assume that the facility produces only one type of product, and these multiple production lines are to scale up the throughput.

Let us assume that the machines in this manufacturing grid are not uniform, as their manufacturing speeds vary. Since various machines with varying production speeds are used in the production lines, one may want to know which path would take the minimum time from an entry point to an exit point (*aka*, “Minimum Job Completion Time”). This knowledge of Minimum Job Completion Time will be useful when the manufacturing enterprise plans to speed up manufacturing due to market requirements.

Figure 5 shows the Petri net model of the manufacturing grid in which some details are omitted (e.g., machines M13 to M45).

In the Petri net model shown in Fig. 5:

- **The entry points and exit points:** Places **pIP1–pIP4** represent the entry points, and **pOP1–pOP4**, the exit points.
- **The Machines:** Machines M_{xx} is represented by an input place (pI_{xx}), a transition (tM_{xx}), and an output place (pO_{xx}). pI_{xx} represents the input buffer of machine M_{xx} , and pO_{xx} represents the output buffer.
- **The switches:** The Petri net model consists of many intermediate transitions. These transitions represent switches (*aka* routers) that route materials to an available machine. The first column of switches between the entry points IPs and the first column of machines M11–M41 are named **ti0–ti9**. The successive column of switches between any two machines, from $M_{X_i}Y$ to $M_{X_{i+1}}Y_{i-1}$, $M_{X_{i+1}}Y_i$, and $M_{X_{i+1}}Y_{i+1}$, are named tX_iY_{i-1} , tX_iY_i , and tX_iY_{i+1} . Finally, the last column of switches between the machines M15–M45 and the exit points OPs are named from **to0** to **to9**.

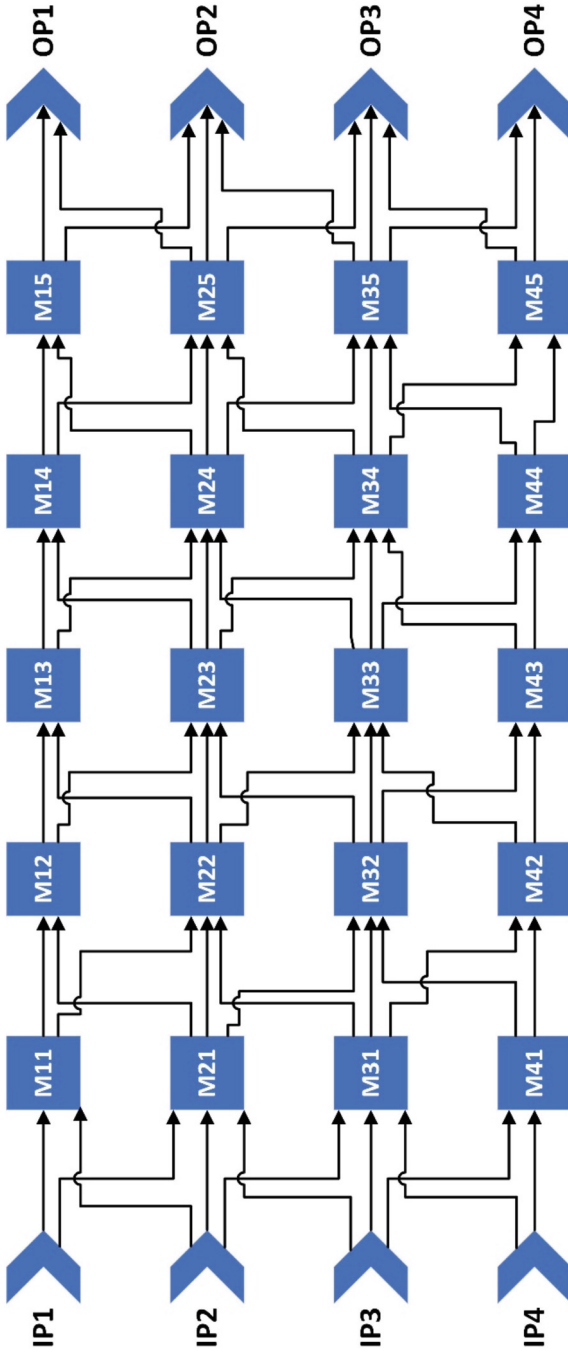


Fig. 4. A manufacturing grid.

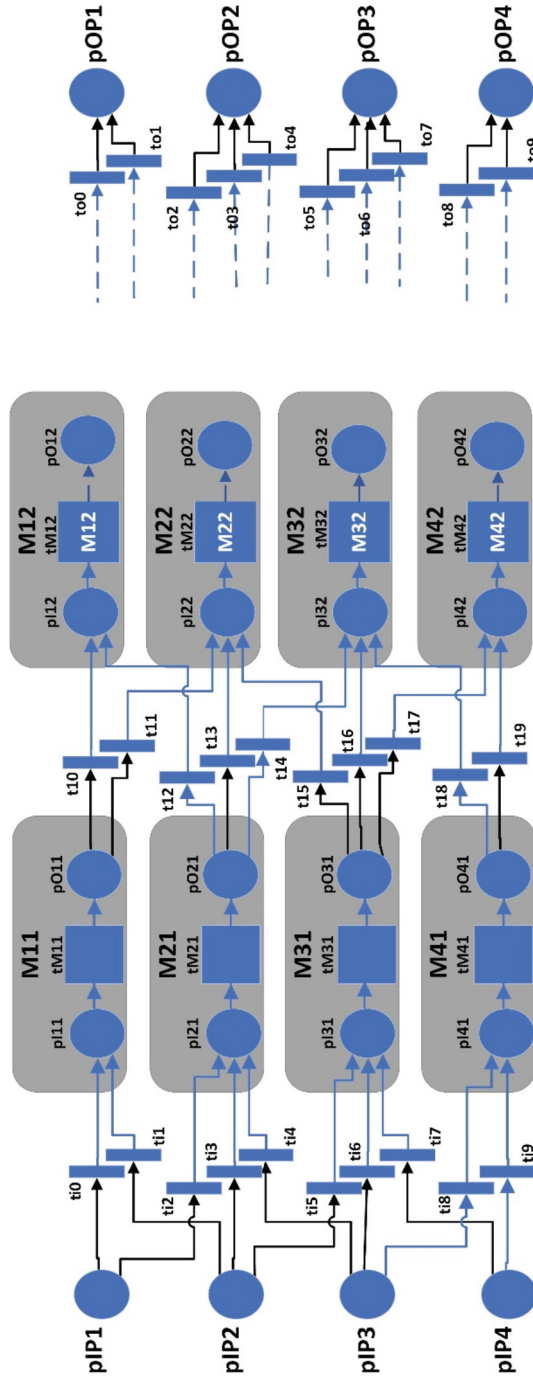


Fig. 5. Petri net model of the manufacturing grid.

5.1 Implementation of the Model

The model is developed as a modular system with the following modules:

- **Entry module:** this module is composed of the places (**pIP1–pIP4**) representing the entry points and the transitions **ti0–ti9** representing the first column of switches.
- **Exit module:** this module is composed of the places (**pOP1–pOP4**) representing the exit points and the transitions **to0–to9** representing the final column of switches.
- Five **machine modules:** The twenty machines are grouped into five machine modules. For example, the first column of machines, from M11 to M41, is grouped into module M11M41 and the second column of machines (M12 to M42) is grouped into module M12M42.
- Four **Inter-modular connectors:** Four inter-modular connectors (IMCs) connect two machine modules. For example, IMC M11M41_M12M42 connects the machine module M11M41 to the machine module M12M42.

Timing: the following hypothetical firing times are assigned to the transitions so that it will be easy to reproduce and verify the simulation results.

- Machine MXY will take XY units of machining time. For example, machines M24 and M35 will take 24 and 35 time units, respectively.
- The switches (**ti0–ti9**, **t10–t49**, and **to0–to9**) take one (singleton ‘1’) time unit.

Due to brevity, the GPenSIM code for the implementation is not shown in this paper. However, the complete code is available for the interested reader in [16].

5.2 Simulation Results

Due to the hypothetical firing times assigned to the machines and the switches, it is easy to see the minimum job completion times between the entry points and the exit points:

- IP1 - OP1: minimum time is 65 time units (path: M11, M12, M13, M14, M15)
- IP2 - OP2: minimum time is 65 time units (path: M11, M12, M13, M14, M15)
- IP3 - OP3: minimum time is 85 time units (path: M21, M12, M13, M14, M25)
- IP4 - OP4: minimum time is 125 time units (path: M31, M22, M13, M24, M35)

Please note that the findings can be extended to any pair (IP_i , OP_j). However, even after simulations of 10000 iterations using the Petri net, the results revealed only two minimum job completion times, IP2 - OP2 and IP3 - OP3. Also, the absolute minimum job completion time (65 time units, from IP1 to OP1, through the machines M11, M12, M13, M14, and M15) was not found. However, using the approach mentioned in Sect. 4, all the paths for the minimum job completion times were found.

6 Discussion and Conclusion

The novelty of this paper is that it proposes a simple yet effective approach for mapping the firing times of transitions as arc weights. This approach can be very useful for analyses of Petri nets, e.g., finding minimum job completion time using a Petri net

model. Usually, using Petri nets, the minimum time for completion of jobs can be found only by simulations, which can take a huge amount of time. For large Petri net models, simulations may never find the absolute minimum time. Hence, the approach proposed in this paper can be very useful.

Though simulations take a lot of time, a Petri net's statical properties (structural properties) can usually be found in polynomial time. However, time is a dynamic property; thus, the structural analysis cannot be used to find the minimum job completion time. Hence, this paper proposes an approach with which the time ('firing time' of transitions) can be distributed as arc weights so that a structural analysis - single source shortest paths - can be performed on the Petri net model itself to find the minimum job completion time also in polynomial time.

Hence, the novelty of the approach presented in this paper is that the same Petri net - e.g., the Petri net model of a manufacturing system - can be used for dynamic analysis (e.g., finding the throughput, bottlenecks, and deadlocks), structural analysis (e.g., finding the siphons, traps, and cycles), and also for finding minimum job completion time.

References

1. Peterson, J.L.: Petri Net Theory and The Modeling of Systems. Prentice Hall PTR (1981)
2. Seatzu, C.: Modeling, analysis, and control of automated manufacturing systems using petri nets. In: 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), pp. 27–30 (2019). <https://doi.org/10.1109/ETFA.2019.8869012>
3. Karatkevich, A.: Dynamic Analysis of Petri Net-Based Discrete Systems, vol. 356. Springer, Heidelberg (2007). <https://doi.org/10.1007/978-3-540-71560-3>
4. Duan, W., Zhong, C., Wang, X., Rehman, A.U., Umer, U., Wu, N.: A deadlock prevention policy for flexible manufacturing systems modeled with petri nets using structural analysis. *IEEE Access* **7**, 49362–49376 (2019). <https://doi.org/10.1109/ACCESS.2019.2906324>
5. Wang, F., Xing, K.-Y., Zhou, M.-C., Xu, X.P., Han, L.-B.: A robust deadlock prevention control for automated manufacturing systems with unreliable resources. *Inf. Sci.* **345**, 243–256 (2016). <https://doi.org/10.1016/j.ins.2016.01.057>
6. Barkaoui, K., Ben Abdallah, I.: A deadlock prevention method for a class of FMS. In: 1995 IEEE International Conference on Systems, Man and Cybernetics. Intelligent Systems for the 21st Century, vol. 5, pp. 4119–4124 (1995). <https://doi.org/10.1109/ICSMC.1995.538436>
7. Murata, T.: Petri nets: properties, analysis and applications. *Proc. IEEE* **77**(4), 541–580 (1989)
8. Davidrajuh, R.: Modeling Discrete-Event Systems with GPenSIM. Springer, Cham (2018). <https://doi.org/10.1007/978-3-319-73102-5>
9. Davidrajuh, R.: Petri Nets for Modeling of Large Discrete Systems. Springer, Singapore (2021). <https://doi.org/10.1007/978-981-16-5203-5>
10. Davidrajuh, R.: Colored Petri Nets for Modeling of Discrete Systems: A Practical Approach With GPenSIM. Springer, Singapore (2023). <https://doi.org/10.1007/978-981-99-6859-6>
11. GPenSIM: General-purpose Petri net simulator. Technical report (2019). <http://www.davidrajuh.net/gpensim>. Accessed 20 Jul 2020
12. Zuberek, W.M.: Timed petri nets definitions, properties, and applications. *Microelectron. Reliab.* **31**(4), 627–644 (1991)
13. Lee, D.Y., DiCesare, F.: Scheduling flexible manufacturing systems using petri nets and heuristic search. *IEEE Trans. Robot. Autom.* **10**(2), 123–132 (1994)

14. Sifakis, J., Yovine, S.: Compositional specification of timed systems. In: Puech, C., Reischuk, R. (eds.) STACS 1996. LNCS, vol. 1046, pp. 345–359. Springer, Heidelberg (1996). https://doi.org/10.1007/3-540-60922-9_29
15. Cormen, T.H., Leiserson, C.E., Rivest, R.L., Stein, C.: Introduction to Algorithms. MIT Press (2022)
16. Complete-Code: Minimum job completion time in Petri Nets. Technical report (2023). <http://davidrajuh.net/gpensim/Pub/2023/minimum-job.htm>



Optimization and Evaluation of Storage Processes Based on a Selected Example

Anna Borucka^(✉) , Krzysztof Patrejko , Łukasz Patrejko ,
and Konrad Polakowski

Military University of Technology, Warsaw, Poland
anna.borucka@wat.edu.pl

Abstract. Technological advancements and market changes force the pursuit of continuous improvement of processes implemented in the enterprise. This is largely due to the increasing demands of customers regarding the price of products, their quality, durability, and delivery time. Society's changes, including the ongoing Industrial Revolution 4.0 and 5.0, also have an impact on this, affecting the development of logistics. Logistics is one of the essential elements in the functioning of companies, crucial for maintaining their competitiveness, responsible for the fluidity and efficiency of goods delivery. Thanks to technological advancements and changes in international trade, logistics is becoming increasingly complex, while its execution capabilities are growing. However, the mere existence of a logistics department does not automatically guarantee better financial results. To assess the effectiveness of logistics in a company, it is necessary to systematically conduct detailed analyses of related processes. Only such an examination allows answering the question of whether logistics fulfills its role in the company's structures, which is the aim of this article. In it, an analysis and evaluation of the impact of implementing selected technology on the development of the internal supply chain processes are presented, in this case, concerning the warehousing process. The obtained results are presented using a manufacturing company as an example. A research hypothesis was adopted, assuming that the application of selected Industry 4.0 technological solutions will increase the efficiency of the analyzed supply chain.

Keywords: logistics · storage process · Industry 4.0 · RFID

1 Introduction – Industrial Revolutions

We refer to a revolution when new technologies and innovative ways of perceiving the world lead to a profound change in economic systems and social structures [1, 2]. All previous industrial revolutions can be precisely characterized in this way. The development of industry can be divided into four stages, each initiated by significant achievements. The first industrial revolution, which lasted from around 1760 to around 1840, was triggered by the construction of railways and the invention of the steam engine, initiating the mechanization of production. The second industrial revolution,

which began in the late 19th century and lasted until the early 20th century, enabled mass production through the use of electric power and the creation of the first assembly lines. The third industrial revolution, often referred to as the computer or digital revolution, began in the 1960s. During this time, there was significant progress in the automation and digitization of processes in enterprises [3]. The fourth industrial revolution, using information and communication technologies [4], is called Industry 4.0. This is another step, following the automation of production, towards its autonomy. Through networked connections of all elements, cyber-physical production systems and smart factories are emerging. Currently, the term Industry 5.0 is beginning to appear, as a complement to the philosophy of Industry 4.0, where, in addition to the innovative expansion of industry and economic growth, emphasis is placed on its sustainable development in harmony with the natural environment [5–7], as well as the resilience of the supply chain to potential threats and crises [8].

Inherent in Industry 4.0 are smart technologies [9], which are also a pillar of development of Industry 5.0 [10]. The main elements are [11, 12]:

- Spatial production,
- Augmented reality,
- Autonomous robots,
- Big data and machine learning,
- Cloud connectivity,
- Cybersecurity,
- Horizontal and vertical system integration,
- Internet of Things (IoT),
- Digital Twin.

Modern technologies support the execution of logistics processes and significantly enhance their performance [13–16]. However, the optimization of logistic operations involves continuous coordination of all process elements [17], including the used equipment [18]. Therefore, the key is to identify processes within the company and recognize which ones are the most critical for the proper and optimal functioning of the given company [19–21]. Only then is it possible to implement improvements. An example of such a procedure is presented in this article. Its goal was to verify, using a selected company as an example, whether logistics fulfills its role, as well as to analyze and assess the impact of the chosen implementation on the development of internal supply chain processes. In the article, only one element of internal logistics, the warehousing process, was analyzed. The main research question adopted was as follows: How can a company be analyzed in terms of its proper functioning and how to indicate the possibility of improving processes within its internal supply chain?

To achieve this goal, a variety of research methods, techniques, and tools were used, such as literature analysis, process mapping, comparative analysis, and reasoning. The article consists of an introduction, a company description, and an assessment of the production process using selected indicators. Subsequently, the implementation of a chosen improvement was proposed, and the impact of this change on the company's functioning was assessed. Finally, a comparison was made, and concluding remarks were presented.

2 Characteristics of the Studied Company

The analysis was conducted on a company engaged in the production of high-quality solid wood and laminate furniture. The company sells its products throughout Europe and is based in Poland (hence the calculations presented in the Polish currency – PLN). It operates its logistics center, including a warehouse with a storage area of over 35,000 m². This warehouse has 10,000 running meters of shelving with over 15,000 pallet slots [22]. The company has implemented an information system that supports the rapid flow of key information in the processes of direct planning and organizing the flow of the entire supply chain of the company.

The storage zone is the most critical element of the company's logistics infrastructure, ensuring the flow of materials, raw materials, and finished products from the supplier to the end customer. Therefore, the organization of efficient warehouse management is incredibly important. In the warehousing process, the warehouse plays a vital role as a separate system that combines the company's key resources, including human resources, financial resources, and material resources.

The aim of the warehousing process is to store cargoes, monitor the status of cargoes across the warehouse's usable area, and maintain records of the stored cargo. The warehouse consists of a storage zone, unloading zone, and the appropriate area where delivery trucks perform unloading activities. The warehouse space is equipped with shelves to optimize the utilization of the warehouse hall. Strategic placement of shelves in the warehouse increases the number of stored cargoes within its premises [22].

The warehousing process in the examined company starts outside the storage area with a request to the office for specific goods and the creation of a shipping list containing all the necessary details. Warehouse staff and the company's chief logistician then verify the consistency of the delivered goods and address any shortages or surpluses (discrepancies). Once the verification process is complete, the goods are accepted into the warehouse, and information about them is entered into the company's information system. Details of unloading are communicated to operators of internal transport equipment. Forklift operators handle unloading the vehicle and placing the cargo according to predefined destinations, where each item is meant to be transferred. The warehouse is divided into storage zones depending on the location to which the finished products, produced in the production department, will be transported within a specified time frame. Goods are placed in their assigned storage areas, making it significantly easier to identify and locate items within the warehouse. After unloading is completed, the driver adjusts based on the recommendations of the company's chief logistician and parks the empty vehicle in the designated area. Following the allocation of the cargo within the warehouse, the warehousing process commences, which involves storing goods until they are needed by the recipient. The warehousing process ends when information about the demand for goods is received from the recipient. The chief logistician creates a loading list in this process, containing details of the transported goods. The aim is to arrange the loading in a manner that, depending on the vehicle's technical specifications, it can be fully loaded without overloading. Additionally, it should allow the driver to deliver the goods to the recipient as quickly as possible and using the optimal route. The forklift operator, referring to the prepared loading list, loads the goods into the designated vehicle located in the appropriate loading zone. Warehouse staff then verifies the consistency

of the loaded goods with the loading list. Depending on whether any discrepancies are found, adjustments are made to align the loading with the loading list, and permission is granted for the driver to leave the warehouse and commence the journey.

After permission to leave the warehouse is given, changes in the quantity of goods stored in the warehouse space are recorded in the company’s information system. A map of the entire enterprise process is shown in Fig. 1.

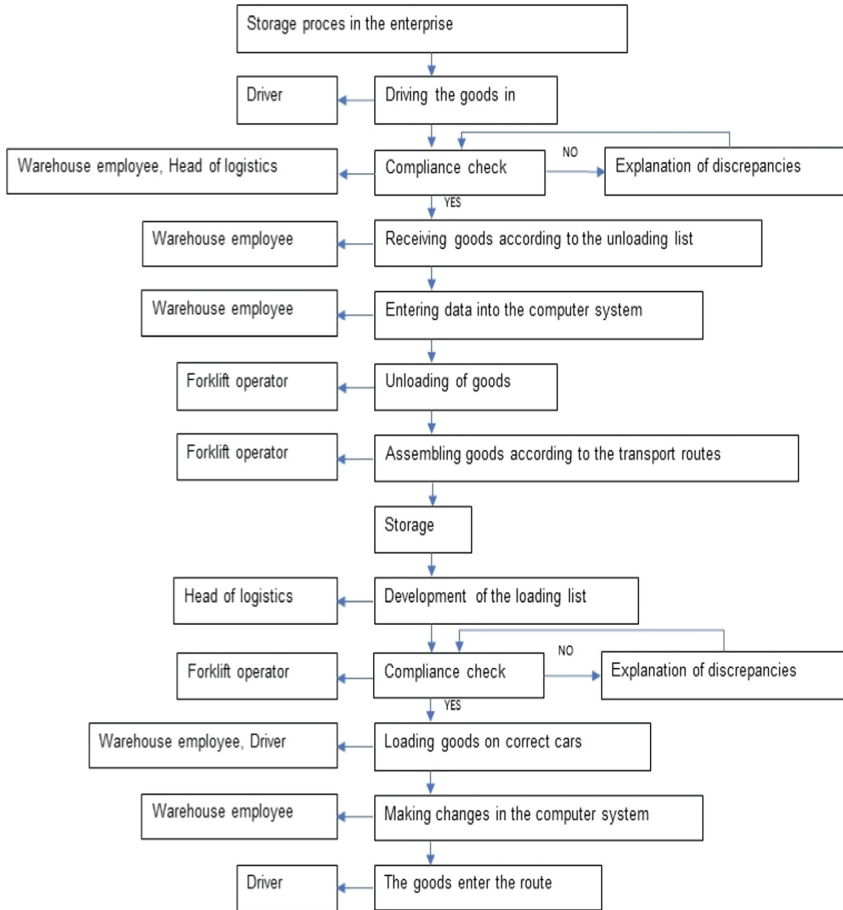


Fig. 1. Map of the storage process in the studied enterprise [22].

3 Analysis and Evaluation of the Storage Process

To conduct the analysis and evaluation of the storage process, selected indicators for assessing logistics processes were used, as presented below [23]. These indicators were then compared with the company's assumptions (Table 2):

$$\text{degree of warehouse occupation} = \frac{\text{number of occupied storage spaces}}{\text{total number of storage spaces}} * 100\% \quad (1)$$

$$\text{cost of storage space} = \frac{\text{storage costs}}{\text{total number of storage spaces}} \quad (2)$$

$$\text{inventory storage costs} = \frac{\text{storage costs}}{\text{average inventory value}} * 100\% \quad (3)$$

$$\text{storage availability} = \frac{\text{real operating time}}{\text{total operating time}} * 100\% \quad (4)$$

$$\text{inventory management index} = \frac{\text{average storage inventory}}{\text{warehouse storage space}} \quad (5)$$

Data on the storage processes of the company under study, necessary for calculating the evaluation indicators, are presented in Table 1.

Table 1. Data for evaluating the performance of storage processes.

Storage criterion	Storage criterion value
Number of occupied warehouse locations	1,059
Total number of storage places	1,200
Storage costs [PLN thousand]	35
Value of average warehouse inventory [PLN thousand]	50
Real operating time of warehouse [h]	505
Total operating time of warehouse [h]	600
Storage area of the warehouse [m^2]	10,000

The warehouse space utilization index determines the percentage of warehouse space occupied on its premises. It provides insights into the extent to which the warehouse area is occupied by inventory.

$$\text{degree of warehouse occupation} = \frac{1059}{1200} * 100\% = 88.3\%$$

This index stands at 88.3%. This result indicates that there is an excess of unnecessary inventory on the warehouse premises, which can block the transit routes, leading to a restriction in the free movement of vehicles.

Another indicator is the average cost of storage space, which calculates the average cost of storing goods in one warehouse location. This allows an economic evaluation of the feasibility of the process.

$$\text{average storage space cost} = \frac{35\,000 \text{ PLN}}{1\,200} = \text{PLN } 29.2$$

The average cost of warehousing for one location is 29.2 PLN, indicating that the warehousing process in the company is economically cost-effective.

The inventory storage cost ratio determines the warehousing costs in relation to the average value of the stored batch at a given time within the warehouse. It is calculated for the economic evaluation of the warehousing process.

$$\text{inventory storage cost index} = \frac{35\,000 \text{ PLN}}{50\,000 \text{ PLN}} * 100\% = 70\%$$

A cost ratio at 70% of the inventory value means that the costs do not exceed the value of the goods stored in the warehouse, which is a desirable state.

Warehouse availability is an indicator that specifies the frequency and smoothness of warehouse area operations. It is calculated to assess whether there were too many downtime periods that hindered warehouse operations.

$$\text{warehouse availability} = \frac{535 \text{ h}}{600 \text{ h}} * 100\% = 89.2\%$$

An availability value of 89.2% implies that downtime in the warehouse accounted for 10.8% of the working time, indicating room for improvement.

The inventory utilization index determines the ratio of inventory stored in the warehouse during a specific period to the total storage area. It allows the calculation of the inventory value per square meter of storage space.

$$\text{inventory management index} = \frac{50\,000 \text{ PLN}}{10\,000 \text{ m}^2} = 5$$

Table 2 presents actual data, calculated on the basis of the company's current situation, juxtaposed with the limit values adopted by management.

Table 2. Storage evaluation criteria compared with the company's limit values.

Storage criterion	Storage criterion value	Criterion limit value
level of use of the warehouse	88.3%	70%
average cost of storage space	PLN 29.2	PLN 25
index of inventory storage costs	70%	80%
warehouse availability	89.2%	93%
inventory management index	PLN 5/m ²	PLN 6/m ²

As can be seen from Table 2, it is necessary to improve primarily three indicators that do not meet the set standards, i.e., warehouse utilization, storage space cost and warehouse availability.

4 Optimization of Storage Processes

The warehousing processes in the examined company are carried out at a high level of quality and economic efficiency, as confirmed by the analysis of selected indicators. However, since the priority is continuous company development and the pursuit of optimizing economic and quality results, new solutions have been proposed. Technological advancement makes it impossible to remain loyal to traditional methods. This applies to nearly every process, including warehousing [20, 21]. Initially, in the company, product identification within the warehouse relied on the most classic method, namely the use of barcodes in various forms. Using barcodes for identification offers numerous advantages compared to traditional manual identification. These include quick data reading, time-saving during inventory, and streamlining the work of warehouse staff. However, this method of identification also has its disadvantages, including:

- inability to read the information in case of physical damage to the barcode,
- time consumption because the operator needs to approach each item closely,
- every relocation of goods must be recorded by an operator working with a scanner since there is no other way to register changes in the item's location.

These drawbacks pose significant challenges for the company and negatively affect the warehousing process, causing delays, and sometimes even making it impossible. Delays caused by, for example, barcode damage can be particularly troublesome, as it requires generating a new code, which results in both time and financial loss. In light of the limitations of using barcodes, the company decided to introduce RFID radio receivers. RFID technology allows for efficient and accelerated monitoring of the production process, personalization of each product, and delivery to the appropriate end customer.

The most critical step in this process was the implementation of RFID sensors on products entering and leaving the warehouse area to enable automatic registration of their location in the information system. Barcode readers were adapted to allow for working with both barcodes and RFID technology. However, over time, products identified through barcodes were gradually phased out from the warehouse space. Ultimately, an identification system using only RFID tags was created, accelerating the product identification process through automation. Products that previously required scanning by an operator with barcode technology now automatically record their location in real-time, expediting the warehousing process because checking the product's location is no longer an employee's task. An additional positive aspect of this change is the elimination of the introduction of erroneous data into the system by employees, as it minimizes the human factor in the identification process. Simultaneously, employees who were involved in the identification process can be delegated to perform other tasks. Moreover, the benefits of recording and tracking inventory status include [24, 25]:

- automated routing of internal transportation means in the warehouse space,
- real-time material movement updates,
- retained record of receipt and release of products from the warehouse,
- automated creation of documentation on the warehouse processes carried out.

The analyzed company implemented an RFID system to enhance the quality of the warehousing process with respect to specific evaluation indicators that were lower than expected. These indicators included the degree of warehouse utilization, the average cost of storage space, and warehouse availability.

The degree of warehouse utilization was the first indicator that did not meet the required quality level in the warehousing process. The company aimed to minimize its value to 70%, but before the changes were introduced, it reached as high as 88.3%, significantly exceeding the set limit value. The company attributed this deviation from the required norm to the use of barcode identification in the process, which significantly slowed down the emptying of warehouses from products and materials. After the implementation of the RFID system, this process was accelerated, resulting in a noticeable reduction in warehouse occupancy. This made it possible to efficiently allocate additional inventory in case of critical material needs.

The RFID system can also have a positive impact on another indicator, which is the average cost of storage space. It was expected that this indicator would reach a maximum value of PLN 25 per storage space, while the average value during the study period was PLN 29.2. Improving the warehousing process after introducing RFID technology allowed for the retraining of physical workers and their transfer to other positions. Better workforce management led to reduced costs and a reduced need for physical labor. Additionally, the advantage of this change was the opportunity to train warehouse employees for higher positions, which is more economically feasible and less risky than seeking new specialists. A newly hired individual requires more time for adaptation, while a lower-level employee is already familiar with the working conditions in the company and can quickly adapt to new responsibilities.

The use of RFID technology also had a positive impact on the warehouse availability indicator. This indicator was at 89.2%, which is a good result but still insufficient for the company, as its requirements were set at 93%. Improving availability through RFID technology was achieved by using RFID tags in both the warehouse entrance gates and the products received within the warehouse. This significantly accelerated all warehousing processes and reduced downtime, primarily caused by blockages in the warehouse transport aisles and damage to barcodes needed for identification. After introducing RFID technology, both of these problems were gradually reduced. Furthermore, in the later stages of the warehousing process, forklifts and warehouse shelves were also equipped with RFID readers to avoid additional location registration of products, which previously also slowed down the warehousing process. The calculations of the values of all analyzed warehousing evaluation parameters after the application of RFID technology are presented in Table 3.

Calculations of all warehousing evaluation indicators after the implementation of RFID technology are presented below:

$$\text{degree of warehouse occupation} = \frac{791}{1200} * 100\% = 65.9\%$$

$$\text{average cost of storage space} = \frac{29\,000\text{ PLN}}{1\,200} = \mathbf{24.16\text{ zł}}$$

$$\text{warehouse availability} = \frac{560\text{ h}}{600\text{ h}} * 100\% = 93.3\%$$

Table 3. Values of warehouse process evaluation criteria after taking into account optimization with the use of RFID technology

Criterion	Value of parameters before the implementation of RFID technology	Value of parameters after the implementation of RFID technology
Number of occupied warehouse locations	1059	791
Total number of storage places	1200	1200
Storage costs [PLN thousand]	35	29
Real operating time of warehouse [h]	535	560
Total operating time of warehouse [h]	600	600

A comparison of the assessed evaluation indicators before and after the implementation of changes is shown in Fig. 2.

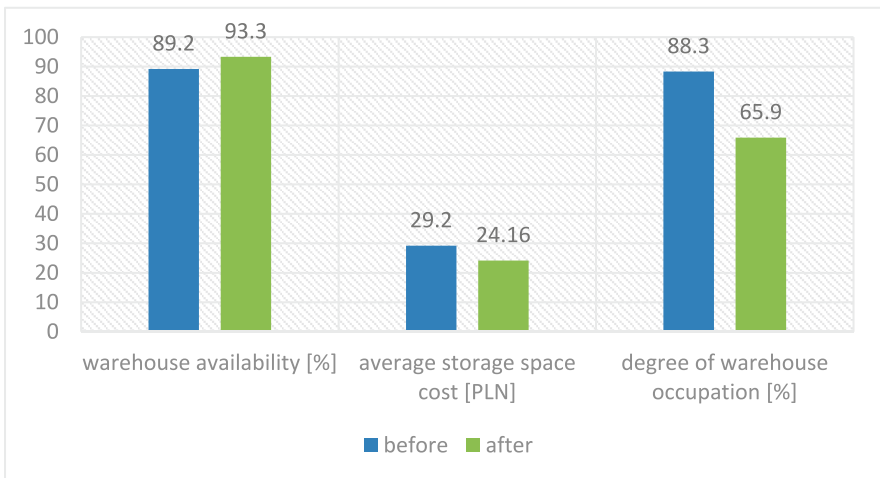
**Fig. 2.** Comparison of indicator values at two stages of functioning of the enterprise.

Figure 2 above shows that the implemented changes in relation to each of the examined indicators were satisfactory. Warehouse availability increased to over 93%, the average storage space cost decreased by PLN 15. The percentage of warehouse space consumption has also decreased, which after the changes amounts to almost 66% and creates additional opportunities for the company.

The implementation of RFID technology had a significant impact on streamlining warehouse processes within the company by eliminating the problems identified during the analysis of the warehousing process. The use of RFID tags greatly accelerated and improved the flow of the process, resulting in the improvement of each of the indicators to the level expected by the studied company.

As shown in Fig. 2, the replacement of barcode with RFID led to increased free space for materials in the warehouse, reduced storage costs, faster warehouse operations, and the optimization of other levels of the company by reducing the labor force's involvement in these processes while increasing the role of automated systems.

5 Summary

The aim of the article was to present a procedure allowing for the analysis and evaluation of selected logistics processes using a manufacturing company as an example. The research focused on a single element of internal logistics – the warehousing process. This approach not only addressed the main research problem by demonstrating how to analyze a company's performance but also provided insights into improving a specific process within the internal supply chain. After a detailed characterization of the warehousing process and mapping its constituent activities, selected performance indicators were calculated. These indicators served as a reference point, first for identifying areas in need of improvement and then for comparing the activities before and after implementing changes.

The warehousing process was improved by replacing traditional barcodes with RFID readers. The implementation of RFID technology helped reduce the warehouse's space utilization, which was one of the primary goals. Additionally, RFID technology streamlined warehouse operations, contributing to increased availability and decreased storage costs, positively impacting the company's economy.

The proposed solution is relatively simple but demonstrates the potential inherent in such changes. The authors also intended to illustrate that systematic assessment of the supply chain reveals discrepancies in process quality compared to modern standards. In the studied company, this led to a restructuring of all logistics processes, which will be the subject of further considerations in the authors' subsequent publications.

References

1. Rodrigues, J.A., Farinha, J.T., Mendes, M., Mateus, R., Cardoso, A.M.: Short and long forecast to implement predictive maintenance in a pulp industry. *Eksploracja i Niezawodność – Maint. Reliab.* **24**(1), 33–41 (2022). <https://doi.org/10.17531/ein.2022.1.5>
2. Chi, B., Wang, Y., Hu, J., Zhang, S., Chen, X.: Reliability assessment for micro inertial measurement unit based on accelerated degradation data and copula theory. *Eksploracja i Niezawodność – Maint. Reliab.* **24**(3), 16 (2022). <https://doi.org/10.17531/ein.2022.3.16>
3. Gola, A., Pastuszek, Z., Relich, M., Sobaszek, Ł., Szwarc, E.: Scalability analysis of selected structures of a reconfigurable manufacturing system taking into account a reduction in machine tools reliability. *Eksploracja i Niezawodność – Maint. Reliab.* **23**(2), 242–252 (2021). <https://doi.org/10.17531/ein.2021.2.4>

4. Alhabib, M.H., Ali, Q.I.: Internet of autonomous vehicles communication infrastructure: a short review. *Diagnostyka* **24**(3), 2023302 (2023). <https://doi.org/10.29354/diag/168310>
5. Kowalak, P., Myśków, J., Tuński, T., Bykowski, D., Borkowski, T.: A method for assessing of ship fuel system failures resulting from fuel changeover imposed by environmental requirements. *Eksploatacja i Niezawodność – Maint. Reliab.* **23**(4), 619–626 (2021). <https://doi.org/10.17531/ein.2021.4.4>
6. Niewczas, A., Móravski, Ł., Rymarz, J., Dębicka, E., Hołyszko, P.: Operational risk assessment model for city buses. *Eksploatacja i Niezawodność – Maint. Reliab.* **25**(1), 14 (2023). <https://doi.org/10.17531/ein.2023.1.14>
7. Górny, A.: Industry 4.0 - safety guidelines in the construction of technical devices. In: Proceedings of the 39th International Business Information Management Association Computer (IBIMA), 30–31 May 2022, Granada, Spain. Theory and Practice in Modern Computing: Vision 2025 in the Era of Pandemic, pp. 130–138. IBIMA (2022)
8. Robert, M., Giuliani, P., Dubouloz, S.: Obstacles affecting the management innovation process through different actors during the Covid-19 crisis: a longitudinal study of Industry 4.0. *Ann. Oper. Res.*, 1–26 (2022). <https://doi.org/10.1007/s10479-021-04457-7>
9. Murawski, J., Szczepański, E., Jacyna-Golda, I., Izdebski, M., Jankowska-Karpa, D.: Intelligent mobility: a model for assessing the safety of children traveling to school on a school bus with the use of intelligent bus stops. *Eksploatacja i Niezawodność – Maint. Reliab.* **24**(4), 695–706, 2022. <https://doi.org/10.17531/ein.2022.4.10>
10. Jafari, N., Azarian, M., Yu, H.: Moving from Industry 4.0 to Industry 5.0: what are the implications for smart logistics? *Logistics* **6**(2), 26 (2022). <https://doi.org/10.3390/logistics6020026>
11. Jamwal, A., Agrawal, R., Sharma, M., Giallanza, A.: Industry 4.0 technologies for manufacturing sustainability: a systematic review and future research directions. *Appl. Sci.* **11**(12), 5725, (2021). <https://doi.org/10.3390/app11125725>
12. Silvestri, L., Forcina, A., Introna, V., Santolamazza, A., Cesarotti, V.: Maintenance transformation through Industry 4.0 technologies: a systematic literature review. *Comput. Ind.* **123**, 103335 (2020). <https://doi.org/10.1016/j.compind.2020.103335>
13. Ghadge, A., Er Kara, M., Moradlou, H., Goswami, M.: The impact of Industry 4.0 implementation on supply chains. *J. Manuf. Technol. Manage.* **31**(4), 669–686 (2020). <https://doi.org/10.1108/JMTM-10-2019-0368>
14. Lewczuk, K.: The study on the automated storage and retrieval system dependability. *Eksploatacja i Niezawodność – Maint. Reliab.* **23**(4), 709–718 (2021). <https://doi.org/10.17531/ein.2021.4.13>,
15. Kozłowski, E., Borucka, A., Oleszczuk, P., Jałowiec, T.: Evaluation of the maintenance system readiness using the semi-Markov model taking into account hidden factors. *Eksploatacja i Niezawodność – Maint. Reliab.* **25**(4) (2023). <https://doi.org/10.17531/ein/172857>
16. Antosz, K., Jasiulewicz-Kaczmarek, M., Machado, J., Relich, M.: Application of principle component analysis and logistic regression to support Six Sigma implementation in maintenance, *Eksploatacja i Niezawodność – Maint. Reliab.* **25**(4) (2023). <https://doi.org/10.17531/ein/174603>
17. Woschank, M., Rauch, E., Zsifkovits, H.: A review of further directions for artificial intelligence, machine learning, and deep learning in smart logistics. *Sustainability* **12**(9), 3760 (2020). <https://doi.org/10.3390/su12093760>
18. Górny, A.: Developing Industry 5.0 to effectively harness production capacities. *Manage. Syst. Prod. Eng.* **31**(4), 456–463 (2023)
19. Knefel, T., Nowakowski, J.: Model-based analysis of injection process parameters in a common rail fuel supply system. *Eksploatacja i Niezawodność – Maint. Reliab.* **22**(1), 94–101 (2020). <https://doi.org/10.17531/ein.2020.1.11>

20. Borucka, A., Grzelak, M.: Application of logistic regression for production machinery efficiency evaluation. *Appl. Sci.* **9**(22), 4770 (2019). <https://doi.org/10.3390/app9224770>
21. Grzelak, M., Borucka, A., Guzanek, P.: Application of linear regression for evaluation of production processes effectiveness. In: Machado, J., Soares, F., Trojanowska, J., Ivanov, V. (eds.) *icieng 2021. LNME*, pp. 36–47. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-78170-5_4
22. Polakowski, K.: *Inteligentne łańcuchy dostaw – nowe oblicze logistyki*, Niepublikowana praca dyplomowa, Wojskowa Akademia Techniczna, Warszawa (2023)
23. Twaróg, J.: *Mierniki i wskaźniki logistyczne*, IliM, Poznań (2003)
24. Unhelkar, B., Joshi, S., Sharma, M., Prakash, S., Mani, A.K., Prasad, M.: Enhancing supply chain performance using RFID technology and decision support systems in the Industry 4.0—a systematic literature review. *Int. J. Inf. Manage. Data Insights* **2**(2), 100084 (2022). <https://doi.org/10.1016/j.jjime.2022.100084>
25. Costa, F., Genovesi, S., Borgese, M., Michel, A., Dicandia, F.A., Manara, G.: A review of RFID sensors, the new frontier of internet of things. *Sensors* **21**(9), 3138 (2021). <https://doi.org/10.3390/s21093138>



Comparison of Different Production Systems Approaches of a Manufacturing Line in the Aeronautical Sector

Carmen de Vilanova Diego¹ , Miguel Ortega-Mier¹  , Tamara Borreguero² ,
Álvaro García-Sánchez¹ , and Carlos García-Castellano Gerbolés¹ 

¹ Universidad Politécnica de Madrid, Madrid, Spain
miguel.ortega.mier@upm.es

² Airbus D&S, Getafe, Spain

Abstract. In the recent years, flexibility has become more important within our industrial systems. This yields to more complex decision making during this industrial system's design. In this work, we present a method to support this decision making by presenting a set of indicators that enable the quantitative comparison of a set of industrial system designs for a pulse line, based on the number of stations selected. To achieve this, two well-known problems in process optimization have been utilized jointly: the Simple Assembly Line Balancing Problem and the Resource Constrained Project Scheduling Problem. A preliminary study was conducted on an exemplary production line from the aeronautical industry. Subsequently, we progressed to develop valuable insights encompassing both problems. To achieve this, two metrics were introduced: lead time and the number of hours worked. These metrics facilitated the generation of data illustrating how the number of hours worked varies with cycle time, lead time, and the number of stations. The outcome is a set of indicators and graphs that provides more precise and well-founded information, helping in the decision making of which approach is more suitable based on the specific needs and constraints of each project.

Keywords: Pulse lines · Docking lines · Comparison · MILP · Aeronautical sector

1 Introduction

The design of an industrial systems is one of the key elements for any manufacturer to achieve higher levels of efficiency and quality. In the aeronautical sector, this is especially relevant, as any industrial set up requires a high level of investment and therefore needs to be used for a long period of time. Therefore, the recent studies relevant to the design of the production line in this sector [1]. Nevertheless, that long term paradigm is being currently challenged by the need of more flexibility to adapt to more and more frequent program production ramp up or ramp down in short periods of time.

In this paper, we will present a joint study of two problems related to the design of an industrial system and its actual implementation. In the design, the Assembly Line

Balancing Problem (ALBP) is used to decide the number of stations that our product will go through. This decision has a major impact in investment needs (number of stations) but also on other aspects that will be discussed in Sect. 2. Afterwards, the second problem presented, the Resource Constrained Project Scheduling Problem (RCPSP) provides information on how efficient the operation of a given industrial system will be.

Traditionally, the design of an industrial system has focused on the ALBP and on the qualitative benefits yielding from a higher number of stations. Nevertheless, from the conclusions of our study we can infer that the joint use of ALBP and RCPSP can provide more useful information for the decision maker. This additional information is more important in the current context, where the flexibility of a line is also a requirement to be taken into account during its design, as shown in many studies [2].

This joint analysis of the ALBP and RCPSP problems is facilitated by the improvement of solution methods, computational capabilities and digitalization. Therefore, it is a clear example of the application of Artificial Intelligence to the analysis of causality and dynamic systems, that was identified by the European Commission has one of the six enabling technologies in Industry 5.0. [3].

Hereinafter the paper will be structured as follows. The next section introduces two manufacturing systems approaches: pulse lines and docking lines. The qualitative benefits of each option are described in Sect. 3, the mathematical models for the two problems we have referred and are presented: the Assembly Line Balancing Problem (ALBP) and the Resource Constraint Project Scheduling Problem (RCPSP). In the next section, a case study with real-based data from the aeronautical sector is presented and finally the last section will discuss the conclusions.

2 Different Manufacturing Systems

2.1 Pulse Lines

Flow lines are characterized by following a product-based design, where the product is not static, but moves along the different stages of the manufacturing process [4]. In a flow line, workstations are organized sequentially according to the manufacturing steps, thus establishing a value stream that facilitates the synchronization of the production process.

Within the flow lines, pulse lines are lines where the product moves between stations following a constant rhythm [1]. That rhythm, called takt time, is equal to the line's delivery rate. This model has several advantages, coming mainly from the fact that only a small number of operations is done in each station: the use of medium volume racks closed to the line, the definition of a set of operations for specialized operators in a given time, the proximity of tools and equipment to the stations and moderate or low pulse line upgrade costs. Also, the tacked paced production results on ease of control and sequencing of the line, absence of buffers leading to work in progress reduction and an easier communication to the supply chain (more accurate delivery dates and takt based demand).

However, pulse lines also have some disadvantages. Firstly, if a problem occurs at one workstation, it can affect the operation of the entire production line, causing

interruptions and delays. In addition, they are more prone to gaps or inefficiencies in the work sequence:

2.2 Docking Lines

Docking type lines can be classified as static lines based on fixed position arrangements. In this type of line, the product does not move during the entire cycle time and it is the workers, tools and equipment that move around the product to perform the tasks [5].

According to the above classification, docking lines are defined as stand-alone, single model lines and can be manual or automated depending on the complexity of the part. This approach is used when the product is bulky or heavy, which makes it difficult to move.

These types of lines have advantages and disadvantages in their implementation. Among the advantages is the possibility of achieving maximum saturation of skilled labour around the product, which allows for greater efficiency and utilization of rework. In addition, they are suitable for products with precise tolerances or specialized technologies, such as robotics or hydraulics. They are commonly used for prototypes and low production volumes. Finally, another advantage is that they do not require buffers, which can simplify design and reduce space requirements.

However, docking lines also have disadvantages. Firstly, the production rate or takt time is a less relevant element as they are not continuous lines. This can make it difficult to synchronize and manage working time. In addition, a high volume of racks are needed near the lines to store the necessary parts and components. This can take up additional space and increase the complexity of the workflow. Another disadvantage is that visibility of production progress may be lower compared to other types of lines, making it difficult to identify potential problems or waste. In addition, changes in the sequence of work may have consequences that are not immediately visible. Finally, it should be noted that a high investment is required to make improvements or upgrades on this type of line.

In the previous discussion, we have presented the advantages/disadvantages of a docking production system versus a pulse line. Nevertheless, if a pulse line is selected, the next decision will be the number of stations to be used. In most cases, that number if stations is related to the maximum rate capacity expected from the line. In the past, that maximum rate was expected to be constant over time. However, in today's context, the decision of the number of stations needs to consider also the flexibility to ramp up or ramp down of the selected production system. In that sense, it is important to say that the more the line will have more stations, the more it will benefit from the qualitative benefits explained for a pulse line production system. On the contrary, having less stations will lead more to the benefits and drawbacks explained for the docking production system.

3 Associated Problems in the Literature

In this section the two problems we will tackle are presented in more detail: Simple Assembly Line Balancing Problem (ALBP) and Resource Constrained Project Scheduling Problem (RCPSp).

3.1 Simple Assembly Line Balancing Problem

The Assembly Line Balancing Problem or ALBP is a classical problem that consists of distributing a list of tasks over several stations following a series of precedence constraints and optimization criteria. A classification of this type of problem can be made by differentiating between: Simple Assembly Line Balancing Problem (SALBP) and General Assembly Line Balancing Problem (GALBP). SALBP problems are those that use the basic elements mentioned in the section on production line description, while GALBP problems include more complex problems (multiple lines, stochastic times, etc.) that are not included in SALBP problems [6].

The different types of SALBP problems can be classified into the following categories:

- SALBP-I: Consists of assigning a set of tasks to stations given a cycle time such that the number of stations is minimized.
- SALBP-II: Seeks to assign tasks to stations by minimizing a cycle time given the number of stations.
- SALBP-E: Focuses on maximizing line efficiency by minimizing the number of stations per cycle time.
- SALBP-F: Consists of determining whether a feasible solution exists for a given combination of number of stations and cycle time.

On the other hand, from the simple SALBP problem, different constraints can be established depending on the constraint environment in which the system is working. Some of the most common constraints are the following [7]:

- *Zone constraints*: can be either positive if the objective is that certain tasks must go in the same station or negative if what you want to achieve is that certain tasks cannot be assigned to the same station.
- *Attribute constraints*: In the case that the assignment of a task to a station may depend on some attribute of the task, there are constraints that control its assignment to a certain station. An example of such a constraint can be found when considering the space at each station. If data is available on the space required to perform a certain task, a constraint can be formulated so that the sum of the spaces occupied by the tasks does not exceed the space available at the station.
- *Station constraints*: This type of constraint occurs when a task can only be assigned to a certain station or a set of stations that meet specific characteristics.
- *Distance constraints*: These constraints occur when two tasks must be separated by a distance that can be measured in time or space. An example of this type of situation is when you must wait for the paint or glue to dry or for the temperature of the part to decrease.

As can be seen in [8], Kamal establishes four main groups of resolution methods: exact resolution methods, resolution by heuristic method, other simulation methods and resolution by simulation. In exact resolution methods, the most common is the use of Branch and Bound algorithms (MILP models) [9]. Branch and Bound algorithms can be combined with dynamic programming methods [10]. Finally, methods using integer programming have also been studied [11].

Regarding heuristic methods, the use of genetic algorithms was studied by Stall et. al [12]. Other options include Tabu Search algorithms [13], simulation annealing [14] or ant colony optimization [15]. Finally, other methodologies studied include the use of expert systems, knowledge-based systems or the combination of any of these algorithms with simulation models.

In this research, the authors selected the SALBP Type 2 problem because its objective is to minimize the cycle time given a specific number of stations. Time was chosen as a metric for analyzing the line optimization, primarily due to its ease of comparison.

The SALBP-II Model

In this subsection the used SALBP-II model is presented. First are presented the sets, parameters and variables (Tables 1, 2 and 3):

Table 1. Sets of the SALBP-II MILP model.

Name	Description	Index
T	Tasks	t, t'
S	Stations	s

Table 2. Parameters of the SALBP-II MILP model.

Name	Description
D_t	Duration of task t
$ADY_{t,t'}$	1 if task t is precedence of task t'; 0 otherwise

Table 3. Variables of the SALBP-II MILP model.

Name	Description
$x_{t,s}$	1 if task t is assigned to station s; 0 otherwise
tc	Cycle time

The MILP formulation of the SALBP-II problem is presented:

$$\min t_c \tag{1}$$

$$\sum_s x_{ts} = 1 \quad \forall t \in T \tag{2}$$

$$\sum_s s \cdot x_{ts} \leq \sum_s s \cdot x_{t's} \quad \forall t, t' \in T \text{ if } ADY(t, t') = 1 \tag{3}$$

$$\sum_t D_t \cdot x_{ts} \leq t_c \quad \forall s \in S \tag{4}$$

$$x_{t,s} \in \{0, 1\} \quad \forall t \in T \quad s \in S \tag{5}$$

The objective function (1) seeks to minimize the cycle time given the constraints explained below. Constraints (2) force each task to be assigned to a station only once, i.e., the same task cannot be assigned to two or more stations. Constraints (3) ensure that the precedence relationships displayed in the precedence network are met. Constraints (4) state that the sum of the duration of the tasks cannot exceed the cycle time of the line. Constraints (5) state that the assign variable is binary, i.e. it only takes as values 0 or 1.

3.2 Resource Constrained Project Scheduling Problem

The Resource-Constrained Project Scheduling Problem (RCPSP) is a combinatorial optimization problem that involves determining a timeline indicating the start and finish times of a set of tasks, given constraints on task precedence and available resources.

There are various ways to classify this type of problem. A first approach would be based on the type of resources, which can be renewable or non-renewable. On the other hand, classification can be done based on whether the objective function is expressed in temporal, economic terms, or if it is a multi-objective function. Finally, classification can be made in terms of information availability, depending on whether it is deterministic or non-deterministic [16].

To study the resolution methods of the RCPSP, we rely on the analysis conducted by Kolisch (1996) [17] which categorizes resolution methods into several types. Firstly, it highlights contributions to problem resolution through dynamic programming [18], zero-one programming [19], branch and bound techniques [20] and integer programming methods [21].

On the other hand, it establishes four types of resolution methods using heuristic approaches. The first involves priority-based algorithms [22] followed by truncated Branch & Bound algorithms [23], disjoint graph methods [24], and metaheuristic methods. In this last category, notable mentions include simulated annealing [14], tabu search, LNS search [25] and genetic algorithms [26].

The RCPSP Model

In this subsection the used RCPSP model is presented. First are presented the sets, parameters and variables (Tables 4, 5 and 6):

The MILP formulation of the RCPSP problem is presented:

$$\min \sum_t t \cdot x_{n+1,t} \tag{6}$$

$$\sum_t x_{j,t} = 1 \quad \forall j \in J \tag{7}$$

$$\sum_j \sum_{t2=t-Pj+1} u_{j,r} \cdot x_{j,t2} \leq C_r \quad \forall t \in T, \quad \forall r \in R \tag{8}$$

Table 4. Sets of the RCPSP model.

Name	Description	Index
J	Tasks	j, j'
R	Resources	r
T	Time available	t

Table 5. Parameters of the RCPSP model.

Name	Description
P_j	Duration of task j
$ADY_{j,j'}$	1 if task j is precedence of task j' ; 0 otherwise
C_r	Total capacity of the resource
$u_{r,j}$	Capacity needed from a resource r to complete task j

Table 6. Variables of the RCPSP model.

Name	Description
$x_{j,t}$	1 if task j is assigned to slot t , 0 otherwise

$$\sum_t t \cdot x_{j,t} - \sum_t t \cdot x_{j',t} \leq P_j \quad \forall j, j' \in ADY_{(j,j')} \quad (9)$$

$$x_{j,t} \in \{0, 1\} \quad \forall j \in J, \quad \forall t \in T \quad (10)$$

The objective function (6) seeks to minimize the cycle time given the constraints explained below. Constraints (7) force each task to be assigned to a time slot t , i.e., the same task cannot be in two or more stations. Constraints (8) ensure that the maximum capacity of the resources is not exceeded. Constraints (9) make sure that the precedence relations are followed. Constraints (10) state that the assign variable is binary, i.e. it only takes as values 0 or 1.

4 Case of Study

In order to carry out this research we will use data relating to a real production line in which an aircraft component is produced. This line is composed of 85 tasks and 121 precedence links. Figure 1 shows the line tasks with their precedence links. The colors refer to a three-station solution of the SALBP.

The initial step involved programming algorithms for both problems and testing them with the studied production line. Our aim was to conduct a preliminary analysis,

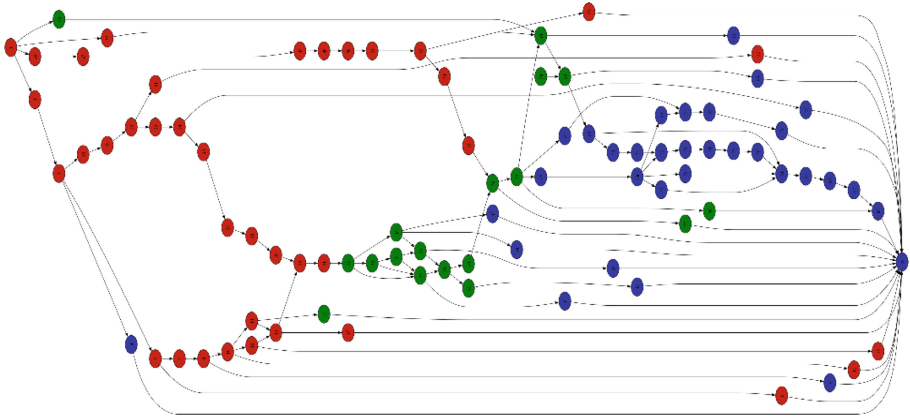


Fig. 1. Node diagram of the studied line with colored stations

using cycle time as a measure, to examine solutions for both problems. For SALBP, we investigated how cycle time varied based on the number of stations, while for RCPSP, we sought to understand how the constrain on the number of workers impacted task distribution and the cycle time for a single station. As mentioned, this is a simple and preliminary study, but it is necessary and insightful to progress towards combining both problems into a more robust tool.

4.1 Simple Assembly Line Balancing Problem Results

Firstly, we studied the resolution of the line balancing problem for the line in question. In figure two, two subplots are presented, illustrating how the cycle time and resolution time vary with the number of stations. Subsequently, we proceed to examine how the variation in the number of stations affects the cycle time (Fig. 2).

Number of stations	Cycle time (min)
3	228.64
4	171.49
5	137.19
6	114.32
7	97.98
8	85.75

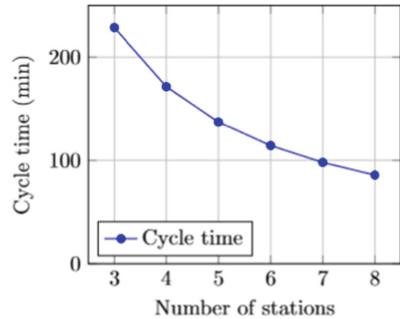


Fig. 2. SALBP Results (time in minutes)

It is expected that as the number of stations increases, the minimum cycle time will decrease. As observed, this expectation holds true in our model, with a significant

difference in cycle time between three stations, which is 228.64 min, and eight stations, which is 85.75 min.

4.2 Resource Constrained Project Scheduling Problem Results

In this section, the resolution of the Resource-Constrained Project Scheduling Problem for the line will be examined. To obtain the minimum amount of resources for a given cycle time, it is necessary to iterate through various resource availabilities and check the feasibility for that cycle time. Ultimately, the problem's solution is depicted in a Gantt as the one on Fig. 3, below.

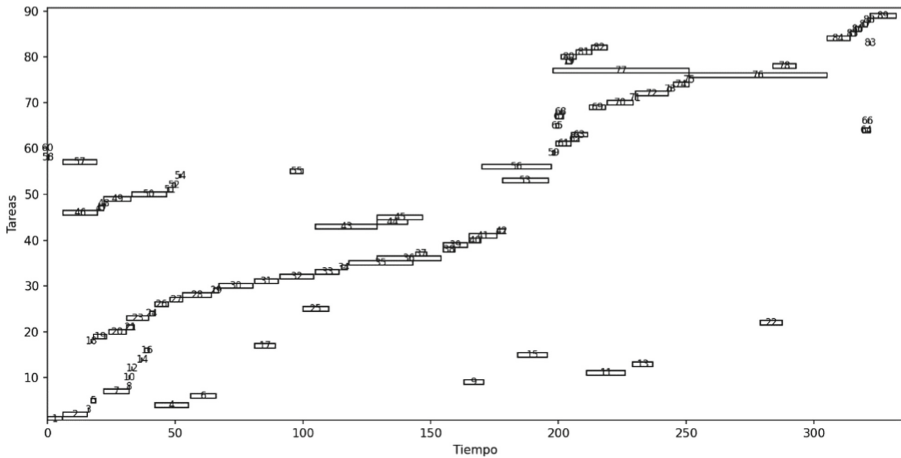


Fig. 3. Gantt Diagram resulting from RCPSP analysis (time in minutes)

4.3 Combination of the Two Problems

In the following section, we will seek to integrate both models in order to obtain a mechanism capable of generating comparisons between different types of production lines. To achieve this, the introduction of two novel metrics will be imperative: lead time and labour hours. Both metrics are derived from the resolution of the SALBP and RCPSP problems, respectively.

The SALBP provides us with the minimum cycle time given a number of stations. This cycle time is determined by the station that requires the maximum time to complete the tasks. However, in terms of production analysis, the product is not considered finished until it has passed through all stations. Also, in a pulse line, the product will be in all the stations a time equal to the cycle time even if the tasks for that station are completed in advance. Therefore, we can translate the cycle time into lead time as follows:

$$\text{Lead time} = \text{Cycle time} \times \text{Number of Stations} \quad (11)$$

On the other hand, the RCPSP allows for the consideration of the number of resources utilized in each production line, which is a crucial data point for conducting productivity analyses. However, to facilitate comparisons, it is valuable to express this metric in temporal or labour hours terms. In the pulse line, we assume that operators will be assigned to the station for all the cycle time. In consequence, the labour hours for a station can be achieved as per Eq. (12):

$$\text{Labour Hours} = \text{Resources needed per station} \times \text{Cycle time} \quad (12)$$

Once we have these two metrics in place, we can start using the two models to compare different production lines. To do this, we take the line we want to study and, for a given number of stations, we perform the *Simple Assembly Line Balancing Problem*. As a result, we will get the distribution of tasks to stations that minimizes the cycle time. After, we calculate the detailed scheduling of each station using the RCPSP to check what is the minimum number of workers needed per station to achieve a certain cycle time. For each line balancing result, we repeat the RCPSP for a set of cycle times, which include the minimum cycle times and other higher values.

Once we have the RCPSP solutions for all the stations of a given cycle time, the labour hours for the line for that set up of stations and cycle time is calculated as per Eq. (12).

In this work, the separation of the stations resulting from the SALBP problem to its own dataset and the iteration of the RCPSP problem has been done by hand. However, in further investigation the goal would be to merge the two problems in one algorithm that provides these results from a “blank” line.

The results from this combined study of SALBP and RCPSP for different designs of a pulse line, depending on the number of stations, can be seen in the two graphs below. In the first one we are focusing on the lead time vs labour hours and how this relation changes depending on the number of stations. In the second graph, the focus is on the cycle time vs labour hours. These graphs provide information on how much the labour hours would increase for a given lead time or cycle time when changing the number of stations.

These graphs are meant to be used as tools for the designers of the production system to see which approach works best for the line at hand. A line with only one station would be closer to a docking line approach whereas a line with multiple stations would be closer to a pulse line approach.

As an example, in Fig. 5 we can see that the line with one station is more suited for a cycle time of around 340 min. Shorter cycle times lead to a less efficient use of the resources, as the need to speed up will result on some resources being allocated to the station to work only short periods of time. On the contrary, higher cycle times will lead to higher costs as whenever the cycle time is longer to the time needed to complete the station, the difference will be non-productive labour time. The same pattern can be seen for the configuration of three stations: that line is more suited for cycle times between 250–350 min.

Also, we can see that for a cycle time of 225 min, we could use a solution of three to five stations. Three and five stations are similar in labour cost, and four stations is less expensive in that sense. However, the lead time is higher for the 5 stations solution than

for the three stations, leading to a difference in work in progress cost. To end with, the design with three stations will not allow shorter cycle times while the 5 and 4 station configurations do have that option. In summary, for a given delivery rate of 225 min, we may go for a 3 to 5 station system depending on other variables like the work in progress cost, the variability of the cycle time needed for other phases of a program and the non-recurrent cost of the stations (Fig. 4).

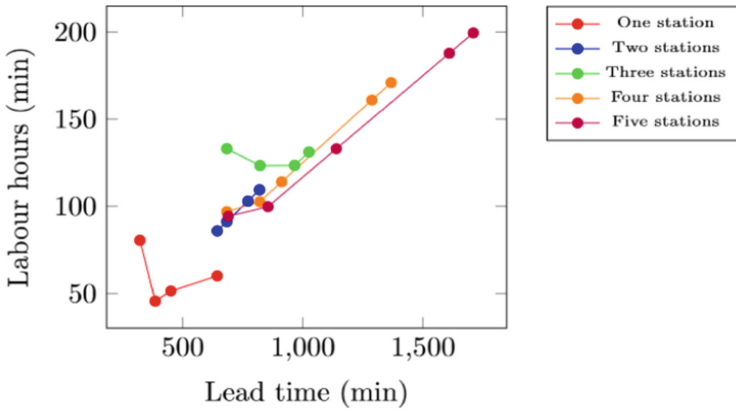


Fig. 4. Lead Time vs Labour hours (time in minutes)

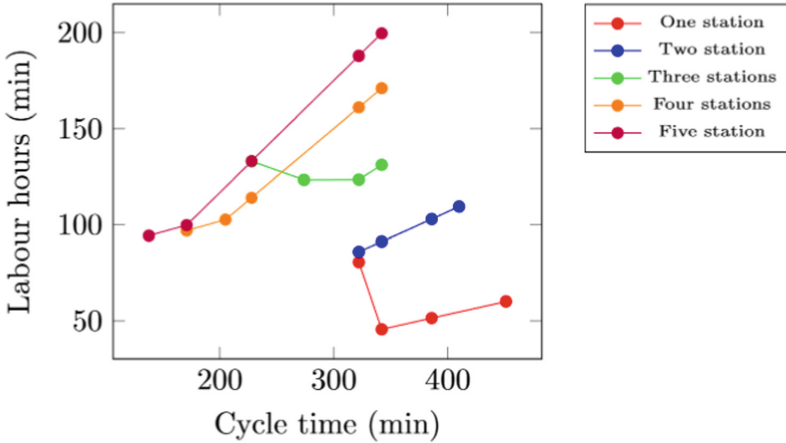


Fig. 5. Cycle Time vs Labour hours (time in minutes)

5 Conclusions

This paper is conducted to explore and compare different manufacturing system designs in terms of number of stations, achievable cycle times and labour cost per unit produced. This comparison is made possible by using two classical optimization problems known as

Simple Assembly Line Balancing Problem and Resource Constrained Project Scheduling Problem. The first one aims to distribute the tasks between stations, minimizing the cycle time given an exact number of stations. The second problem considers the resources needed to satisfy all the tasks assigned to a station, given a station cycle time.

In order to carry out this research we used data from a real production line in which an aircraft component is produced. This line is composed of 85 tasks and 121 precedence links, forming a problem size larger than some of those previously explored with these techniques [27]. While solving the SALBP problem on the line we measured how the minimum achievable cycle time was reduced when adding more stations. Furthermore, with the RCPSp problem we added the resource dimension, and we got a Gantt diagram that showed the optimal setup for the tasks in each station given different numbers of maximum resources available. Once we had the two algorithms for each problem working it was time to move to the next stage.

The final aim of this investigation was to find a way to combine the two problems, a combination, with some exceptions [28], largely unexplored in the past, and achieve a quantitative tool for comparing the different line design options. We made this possible by introducing two new metrics known as lead time and labour hours. We merged the two problems into one by first separating the line into stations using the SALBP and then performing a RCPSp to each station. This led us to two graphs that showed how the labour hours varied for a given lead time depending on the number of stations.

We propose that these two graphs may serve as the foundational model for a decision support tool. This tool could be invaluable for production line designers, enabling them to compare varying methodologies in production line configurations. These methodologies range from designs with fewer stations, aligning with a docking line approach, to those with more stations, akin to a pulse line approach. Such a decision profoundly influences the efficacy of the manufacturing system [29], underscoring the potential utility of this tool in enhancing decision-making processes.

Further lines for investigation could involve incorporating a cost dimension into the study. Currently, the paper emphasizes time management and efficiency, but by introducing hourly wages, we could convert these metrics into tangible costs, thereby enhancing the tool and easing the comparison with other cost contributors, such as the non-recurrent cost related to having more stations. Additionally, an improvement could be made in the overall automation and computational efficiency of the algorithms employed.

Acknowledgements. The authors want to thank the Grant PID2022-137748OB-C31 funded by MCIN/AEI/10.13039/501100011033 and “ERDF A way of making Europe” for the support provided.

References



1. Roussel, S., Polacsek, T., Chan, A.: Assembly line preliminary design optimization for an aircraft. In: The 29th International Conference on Principles and Practice of Constraint Programming, CP 2023 (2023)

2. Zhang, W., Dai, Y., Tian, L.: Impact of capacity flexibility on service product line design. *Ann. Oper. Res.* **312**(2), 1095–1118 (2022)
3. Müller, J. J. E. C.: Enabling technologies for Industry 5.0. European Commission, 8-10. (2020)
4. Neufeld, J.S., Schulz, S., Buscher, U.: A systematic review of multi-objective hybrid flow shop scheduling. *Eur. J. Oper. Res.* **309**(1), 1–23 (2023)
5. Monga, R., Khurana, V.: Facility layout planning: a review. *Int. J. Innov. Res. Sci. Eng. Technol.* **4**(03), 976–980 (2015)
6. Jusop, M., Ab Rasid, M.: A review on simple assembly line balancing type-e problem. *IOP Conf. Ser. Mater. Sci. Eng.* **100**, 012005 (2015)
7. Scholl, A., Fließner, M., Boysen, M.: ABSALOM: balancing assembly lines with assignment restrictions. *Eur. J. Oper. Res.* **200**(3), 688–701 (2010)
8. Uddin, M. K., Lastra, J. L. M. Assembly line balancing and sequencing. In: *Assembly Line—Theory and Practice*, pp. 13–36 (2011)
9. Liu, S.B., Ng, K.M., Ong, H.L.: Branch-and-bound algorithms for simple assembly line balancing problem. *Int. J. Adv. Manuf. Technol.* **36**(1), 169–177 (2008)
10. Walter, R., Schulz, P., Scholl, A.: SALSA: combining branch-and-bound with dynamic programming to smoothen workloads in simple assembly line balancing. *Eur. J. Oper. Res.* **295**(3), 857–873 (2021)
11. Ritt, M., Costa, A.M.: Improved integer programming models for simple assembly line balancing and related problems. *Int. Trans. Oper. Res.* **25**, 1345–1359 (2018)
12. Stall Sikora, C.S., Lopes, T.C., Lopes, H.S., Magatão, L.: Genetic algorithm for type-2 assembly line balancing. In: *2015 Latin America Congress on Computational Intelligence (LA-CCI)*, Curitiba, Brazil, pp. 1–6 (2015)
13. Glover, F., Laguna, M.: *Tabu search background*. In: *Tabu Search*. Springer, Boston (1997). https://doi.org/10.1007/978-1-4615-6089-0_1
14. Eglese, R.W.: Simulated annealing: a tool for operational research. *Eur. J. Oper. Res.* **46**(3), 271–281 (1990)
15. Sulaiman, M.N.I., Choo, Y-H., Chong, K.E.: Ant colony optimization with look forward ant in solving assembly line balancing problem. In: *3rd Conference on Data Mining and Optimization (DMO)*, Putrajaya, Malaysia, pp. 115–121 (2011)
16. Habibi, F., Barzinpour, F., Sadjadi, S.J.: Resource-constrained project scheduling problem: review of past and recent developments. *J. Project Manage.* **3**, 55–88 (2018)
17. Kolisch, K.: Efficient priority rules for the resource-constrained project scheduling problem. *J. Oper. Manag.* **14**(3), 179–192 (1996)
18. Tavares, L.V.: Multicriteria scheduling of a railway renewal program. *Eur. J. Oper. Res.* **25**(3), 395–405 (1986)
19. Patterson, J.H., Huber, W.D.: A horizon-varying, zero-one approach to project scheduling. *Manage. Sci.* **20**(6), 990–998 (1974)
20. Stinson, J.P., Davis, E.W., Khumawala, B.M.: Multiple resource-constrained scheduling using branch and bound. *AIIE Trans.* **10**(3), 252–259 (1978)
21. Doersch, R.H., Patterson, J.H.: Scheduling a project to maximize its present value: a zero-one programming approach. *Manage. Sci.* **23**(8), 882–889 (1977)
22. Kastor, A., Sirakoulis, K.: The effectiveness of resource levelling tools for resource constraint project scheduling problem. *Int. J. Project Manage.* **27**(5), 493–500 (2009)
23. Álvarez-Valdés Olaguibel, R., Tamarit Goerlich, J.M.: Heuristic algorithms for resource-constrained project scheduling: a review and an empirical analysis. In: *Advances in Project Scheduling*, Elsevier (1989)
24. Balas, E.: Machine sequencing via disjunctive graphs: an implicit enumeration algorithm. *Oper. Res.* **17**(6), 941–957 (1969)

25. Borreguero Sanchidrián, T., Portoleau, T., Artigues, C., García-Sánchez, A., Ortega-Mier, M., Lopez, P.: Large neighborhood search for an aeronautical assembly line time-constrained scheduling problem with multiple modes and a resource leveling objective. *Ann. Oper. Res.* (2023). <https://doi.org/10.1007/s10479-023-05629-3>
26. Goldberg, D.E.: *Genetic Algorithms in Search, Optimization and Machine Learning*. Addison-Wesley Longman Publishing Co., Inc. (1989)
27. El Ahmadi, S.E.A., El Abbadi, L., Elrhanimi, S.: Efficiency improvement of automotive assembly lines using simple assembly line balancing problem type-E. *Logforum* **19**(2), 183–193 (2023)
28. Sprecher, A.: A competitive branch-and-bound algorithm for the simple assembly line balancing problem. *Int. J. Prod. Res.* **37**(8), 1787–1816 (1999)
29. Zhao, R., et al.: Digital twins-based production line design and simulation optimization of large-scale mobile phone assembly workshop. *Machines* **10**, 367 (2022)



Cooperation Between Companies in Technology Management Really Matters - Explored Through PLS-SEM Modelling

Elżbieta Krawczyk-Dembicka[✉]  and Wiesław Urban 

Białystok University of Technology, Białystok, Poland
e.dembicka@pb.edu.pl

Abstract. The study aims to investigate the technology management (TM) sphere in metal processing companies engaged in a business cluster. This study presents SEM modelling using the PLS method on data obtained from a survey of companies involved in a business cluster, which allowed to examine the impact of factors important for cooperation on individual stages of TM. This study implies that business cluster engagement can play a beneficial role in the TM sphere in the studied companies. Engagement in the cluster can facilitate knowledge acquisition, leading to strategic and operational advantages. The cluster can play an especially beneficial role when it comes to the initiation of work on a technology – a search for new technologies, and when existing technologies are developed. Companies can obtain precious knowledge from/thanks to participation in a business cluster. Knowledge supporting and allowing innovations appears to play a primary role in achieving advantages from cluster membership; however, this is not applied to most companies in the studied cluster. The SEM model proves that cooperation between business partners in a cluster structure really matters.

Keywords: Technology Management · business cooperation · business cluster · SEM · PLS

1 Introduction

Technological changes can affect individual business entities and entire industries in many ways. This is a main issue when considering innovativeness and product competitiveness. Studying technology management (TM) at the level of business organizations is equipped with much empirical knowledge and a variety of handy concepts, starting from Gregory's [1] TM processes, from technology identification to technology protection. However, the issue of inter-organizational cooperation in the TM field is not particularly intensively studied till now [2]. The most convenient object to study such an issue is a business cluster structure, which exists for inter-organizational cooperation in many important business fields.

A business cluster is a group of companies operating in the same industry sector along with other associated organisations and institutions. Clusters are operating in specific geographic areas, and all interconnected partners in a business cluster aim at some

extraordinary benefits relayed upon cluster participation [3, 4]. The authors report many kinds of advantages obtained by companies engaged in a cluster structure, namely, operating costs decrease, revenue and profit increase, and overall enhanced competitiveness [5]. Additionally, the studies point out advantages in terms of technology upgrades, along with innovations and referred generally to R&D sphere, obtained thanks to business cluster belonging [4–6]. The business cluster structure is peculiar in that simultaneous cooperation and competition occur between partners participating within a cluster [7]; this is a unique type of collaboration [8].

This study aims to comprehensively investigate the TM sphere in metal processing companies engaged in a business cluster. Factors influencing TM in companies along with benefits obtained from companies from/thanks to participation in a cluster are identified. Typical practises used by companies in the field of TM are also identified. The data obtained from the cluster companies allows us to determine a model of how business cluster membership affects the TM sphere in engaged companies.

2 TM Essentials

The TM model by Gregory [1] provides a foundation for further studies and outlines five main TM processes (stages): identification, selection, acquisition, exploitation, and protection. Subsequent researchers have supplemented Gregory's considerations with issues related to knowledge, technology development, organisational level and company strategy, market functioning mechanisms, and technology withdrawal [9–13]. Technologies acquired by companies require adaptation to specific needs, and if they are created from scratch, thorough analysis and development of specific technological assumptions are required. These tasks fall under the area of TM and pose a challenge for many organisations, these issues have been the subject of many scientific studies [14].

Technology is treated as the main driving force of the enterprise, appropriate TM is perceived as tool that creates value for the customer, which at the same time facilitates gaining a competitive advantage [15]. Therefore, it can be concluded that TM plays a key role in economic development [16]. In-depth research by Urban and Krawczyk-Dembicka [17] showed that TM in manufacturing companies from the metal processing industry relied on technology assumptions, modular acquisition, adaptation, and launching a technology. These are interwoven with an economic assessment, and each of these steps is formed by a set of activities that absorb time and employees' efforts. They also indicate that some of the typical activities described in TM concepts, such as knowledge protection activities, may not occur at all, but knowledge itself may play a key role in shaping the TM process.

At each stage of TM, technological competences are also important, as emphasised by Cetindamar et al. [18]. They also pay special attention to the learning process, which includes technological processes occurring directly in the enterprise and outside it. It is also the basis for establishing cooperation with other entities in the fields of knowledge exchange and technology development. Moreover, the manner in which individual TM activities are implemented depends on the competences of managers, which may determine whether they are present in a given enterprise or whether they are omitted. According to Phaal et al. [19], many activities undertaken within TM are embedded

by enterprises in other business processes, e.g., related to supply chain management or new product development processes, which makes it difficult to clearly define the TM framework. Equally, the skilful use of knowledge and experience in enterprises can help in the effective integration of technology with business.

Knowledge in an enterprise plays a fundamental role in gaining a competitive advantage and is also a key factor in the success of an organisation [20]. In technology management, knowledge is present at virtually every stage of the process. It manifests itself in the company's ability to acquire knowledge from the external environment and to create and disseminate it in the internal environment. An important element is the ability to combine both sources of knowledge and use them to develop new technology or modify existing technology [20–24].

Furthermore, companies' ability to develop new specialised knowledge often extends beyond generally recognised business boundaries [25]. This is because the specific nature of a cluster allows companies to cooperate closely with universities, which are sources/suppliers of this new advanced knowledge. Therefore, enterprises have the opportunity to develop their technological resources by using innovative solutions while minimising the risk of failures [26]. Access to external knowledge thanks to cooperation in the cluster has a positive impact on the technological development possibilities not only of a specific enterprise but also the entire cooperation network [27].

Cooperation in the field of TM between various stakeholders of the cluster may create space to intensify R&D activities, which may be a source of innovation and thus lead to the development of new products or processes [28]. A problem may arise when cooperating partners have different goals and motives. According to enterprises, new knowledge generated as part of cooperation requires materialisation and practical application during their business, which, on the one hand, will translate into the economic results of the enterprise and, on the other hand, may increase its competitiveness. However, from the viewpoint of universities, new knowledge should be primarily the subject of scientific publications, which may therefore limit the implementation of the company's goals.

In the case of cooperation in a cluster between various enterprises that are also partners and competitors, the potential for joint activities appears when companies face similar problems facing the industry or see benefits in common interests. In such situations, interorganisational and even intersectoral cooperation works well because of the possibility of finding an interdisciplinary solution. It is worth noting that cooperation between companies generates a sense of mutual trust, which additionally encourages the dissemination and adoption of external knowledge and promotes innovation in products and processes. In addition, enterprises gain access to new specialised knowledge and technologies and overcome barriers in access to information that may be a source of other potential benefits [29].

Overcoming barriers and transferring knowledge between cluster partners can facilitate their adoption of an approach based on open innovation. These types of activities promote knowledge exchange and facilitate access to complementary resources and opportunities. They also contribute to the overall development of knowledge [30]. Close collaboration between the various stakeholders of a cluster can act as a catalyst for solving industry problems while giving companies the opportunity to reduce risks or costs and increase their competitive advantage.

Researchers identify TM as a form of the hidden competitive advantage [31], and this is widely accepted. However, actual TM is very complex [32], and there is a great need in the literature for a better understanding of this issue [16]. In particular, little is known about TM in business clusters, which are increasingly the places where new technologies are being developed.

3 Research Methodology

The Metal Processing Cluster is an initiative gathering together companies operating in the metal processing industry in Poland. The cluster also organises scientific and research units and business environment institutions in its structure. It has been operating continuously since 2007, mainly in the northeastern part of the country. At the time of the research, the business cluster consisted of 74 units, where 60 enterprises qualified for the research process and met the conditions of a business entity conducting production activities related to metal processing.

The survey method was employed, and a research questionnaire with queries scaled in a five-point Likert scale was designed and circulated between respondents exploiting CATI/CAWI techniques; however, a dose of direct meetings with the respondents was performed. The survey participants were company owners, management board representatives, and management staff from technology or production departments. Finally, 54 questionnaires were accepted as valid and handed out for statistical analysis and explorations. The used research tool was assessed in terms of reliability, the Cronbach's α coefficient was obtained at 0.906, which, according to literature reports, indicates a very high degree of internal consistency [33].

This study employs structural equation modelling (SEM) based on the partial least squares (PLS) method. SEM considers and estimates the linear and/or causal relationships between multiple exogenous and endogenous constructs, and it may contribute to moving theory to new levels of understanding and explanations [34]. Wong [35] reported PLS-SEM as a soft modelling approach with no assumptions about data distribution. It is convenient because it accepts small sample sizes and is applicable where a little theory is available and predictive accuracy is paramount. Others advocate that PLS-SEM path modelling, if appropriately applied, is a "silver bullet" for estimating causal models. It is particularly applicable for prediction or theory building, such as in studies that focus on identifying critical success drivers [36]. Some research suggests [37] that PLS-SEM path modelling is appropriate for confirmatory factor analysis and is more reliable and valid than other models.

The SEM application requires the development of a set of latent/unobservable constructs, each parameterised by multiple measured items [34]. The data was explored along with known theoretical deliberations and with the support of qualitative observations made in companies, accompanying questionnaire investigations. Apart from descriptive statistics, the correlation matrix was carefully considered. There were sought factors influencing the TM stages, including practises utilised by the companies participating in the studied cluster. In addition, some identified benefits from engagement in a cluster were recognised as linked to some particular TM stages.

Finally, several variables were considered for SME building. Of the five latent variables with particular research items forming these variables, one direct (not latent) variable is included in the model. The variable Cooperation, four items, represents cooperation among different types of stakeholders that appeared within/thanks to business clusters. Another variable is Knowledge Acquisition, which expresses how companies operating in a cluster obtain knowledge referred to TM thanks to affiliation to the cluster. This variable comprises three items. Active Search of New Technologies describes several methods practised by investigated companies in the “Technology search” TM stage, it consists of four items. Technology Development represents another stage of TM and similarly shows active practises two items. Market Proactivity comprises two research items. It shows expansive companies’ behaviour in new markets and niches, exploiting the potential of cluster membership. Finally, the variable TM Activities Duration is not a latent variable; it represents an effect of cooperation within/thanks to cluster shortening the duration of TM activities. For each of the variables of the model, abbreviated names have been given, as listed below, in brackets, and the average scores (5 points scale) of each research item are presented.

Cooperation (Coopera)

Being engaged in a business cluster, you see that for TM in your company, the following factors are important:

- A chance to establish cooperation with new business partners (3.4)
- An opportunity to cooperate with R&D institutions (2.4)
- An opportunity to cooperate with business support institutions (2.4)
- An opportunity to cooperate with regional governments and other authorities (1.9)

Knowledge Acquisition (Knowled)

Being engaged in a business cluster you achieve:

- Exchange of knowledge and information on technologies between enterprises (3.6)
- Exchange of experiences and good practises among cluster members (3.5)
- Access to specialised training (3.6)

Active Search for New Technologies (AcSearc)

On the “Technology search” stage of TM you practise and see as useful:

- Participation in trade fairs and exhibitions (3.7)
- Analysis of offers from other competitive enterprises (3.1)
- Analysis of the market/industry (3.3)
- Analysis of patent databases (2.1)

Technology Development (TDevelop)

On the “Technology development” stage of TM you practise and see as useful:

- Search for new application possibilities for already implemented technologies (3.2)
- Analysis of the ability to expand the functionality of the already implemented technologies (3.3)

Market Proactivity (MarkProa)

Being engaged in a business cluster, you see that for TM in your company, the following factors are important:

- Business expansion to new markets (3.5)
- Discovering new market niches (3.3)

TM Activities Duration (Time)

Being engaged in a business cluster you achieve:

- Reduced time of TM activities, e.g., thanks to the possibility of acquiring technology components from other companies (2.6)

The literature indicates that a minimum sample size depends on the number of variables making up a latent variable and the number of paths in a structural model. According to Hair et al. [36], in PLS-SEM, the minimum sample size should be calculated as equal to the larger of two following: (1) ten times the largest number of formative indicators used to measure one construct or (2) ten times the largest number of structural paths directed at a particular latent construct in the structural model. As described above, 54 respondents (companies being engaged in a cluster structure) were successfully interviewed, considering the latent variables presented above. Population size meets the minimum requirements.

4 PLS-SEM Modelling

Babin and Svensson [34] underline that SEM is not just about “cause-and-effect” relationships; it is a type of “multiple and interrelated correlational and causal” relationship between constructs forming a model. Model forms complex and sophisticated patterns that need to be considered simultaneously, which explains the investigated phenomenon. The structural model derived from the data gathered from the companies engaged in the business cluster is presented in Fig. 1. The model is initiated by cooperation (Coopera), which is the heart of engagement in a business cluster. It affects the knowledge exchange (variable Knowled) between cluster participants and other stakeholders. Acquired knowledge by companies significantly influences practises in two stages of TM in companies: active search for new technologies (AcSearc) and technology development (TDevelop). In each of the stages, engagement in a business cluster leads to different effects. In the former, this is a reduction of TM stage lead time (Time), and in the latter, this is proactive behaviours of companies on markets (MarkProa). The latter is not exactly a business effect but is indicated by the responds cluster characteristic factor, which is observed in SEM as related to practises on one TM stage.

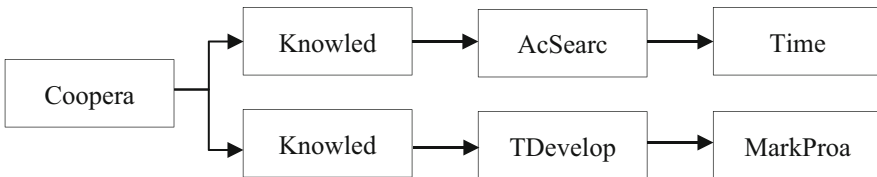


Fig. 1. SEM model design

The proposed SEM model is found to be statistically credible and provides interesting insights into TM in the studied business cluster. The fit and quality indicators are

presented in Table 1. Average path coefficient (APC) P value is less than 0.05, as recommended by Kock [38]. A model's explanatory power is primary presented by Tenenhaus GoF (GoF) [38]. Its level is considered as medium, $GoF = 0.278$, where 0.25 and more are recognised as a medium level. The predictive and explanatory quality of the model can be considered acceptable. P values for linked variables are presented in Table 2 below. All of them are less than the 0.05 level. In the table, path coefficient values are presented as well.

Table 1. Model fit and quality indices.

Indices type	Indices value
Average path coefficient	(APC) = 0.326, P = 0.002
Average R-squared	(ARS) = 0.112, P = 0.098
Knowledge Acquisition (Knowned) Average adjusted R-squared	(AARS) = 0.095, P = 0.118
Active Search of New Technologies (AcSearc) Average full collinearity VIF; acceptable if ≤ 5 , ideally ≤ 3.3	(AFVIF) = 1.411
Tenenhaus GoF; small ≥ 0.1 , medium ≥ 0.25 , large ≥ 0.36	(GoF) = 0.278
Sympson's paradox ratio; acceptable if ≥ 0.7 , ideal = 1	(SPR) = 1.000
R-squared contribution ratio; acceptable if ≥ 0.9 , ideal = 1	(RSCR) = 1.000
Statistical suppression ratio; acceptable if ≥ 0.7	(SSR) = 1.000
Nonlinear bivariate causality direction ratio; acceptable if ≥ 0.7	(NLBCDR) = 0.800

Table 2. Coefficients and p values of the linked variables.

Path coefficients				
	Knowned	Coopera	AcSearc	TDevelop
Knowned		0.279		
AcSearc	0.298			
TDevelop	0.407			
Time			0.219	
MarkProa				0.426
p values				
Knowned		0.013		
AcSearc	0.009			
TDevelop	<0.001			
Time			0.044	
MarkProa				<0.001

5 Discussion

Cooperation and many kinds of networking are typical types of activities performed in a cluster structure. As presented in the data in the methodology section, the cooperation activities are ranged by respondents and are fairly differentiated, e.g. “opportunity to cooperate with R&D institutions”, which is an item in the Cooperation variable, is assessed as 2.4 on 1–5 scale, another one “opportunity to cooperate with regional governments and other authorities” is assessed as 1.9. This goes along with the low level of variance explained by the model, which means that observed paths are applied to a small number of enterprises. One more peculiarity needs to be underlined, among cooperation stakeholders, the authorities appear as an item. This is because the studied business sector is on the list of regional/national smart specialisation and as a result it is a beneficiary of various public aid.

Engagement into a cluster along with different forms of cooperation within and outside the cluster allows the gathering of precious knowledge (variable Knowledge Acquisition, Knowled), which is particularly important at two out of seven TM stages considered in the empirical investigation. These stages are (1) the search for new technologies (AcSearc) and (2) the development of existing technologies (TDevelop). During these two TM stages, there is desired knowledge from outside the companies on many kinds of convenient and proven technologies, the knowledge taken preferably from the practise of others, built on the successes and failures of others, on others’ practical experiences, for example how some technology components work in practise what are technical efficiency and capabilities, and similar. Additionally, in the development stage, how some technologies/technology components can be configured in new product development and improvement of existing ones.

The peculiarity of both mentioned TM stages implies that in each of them, a slightly different type of knowledge might be obtained from/thanks to the cluster. On the technology search stage, domain knowledge is the most desirable, and the issue is which technology solutions would be the most convenient. In addition, the experiences of others are of particular importance. Technology development relies on new applications of existing technologies and their improvements. Companies utilising knowledge obtained through cluster engagement have new ideas and practical solutions/examples and/or tips referred to new possible technology utilisation including product innovations. These active behaviours in the technology development field go along with particular proactivity in the field of new market exploration and niche searching (MarkPro). This attitude is advantageous in terms of long-term business development and competitiveness. The bottom path of the observed model underlines the strategic dimension of TM with a company’s engagement in a business cluster. The path between Knowledge Acquisition (Knowled), Technology Development (TDevelop), and Market Proactivity (MarkProa) shows the strongest links between variables. According to the data presented in Table 2, the path coefficients are 0.407 and 0.426, respectively, and have the highest values in the whole model.

The structural model also implies some particular advantage from the first TM stage. The active search for new technologies leads to the shortened time (Time) of TM activities. This effect applies not only to activities in the first stage of TM but also to all others. The effect has its roots in knowledge possibilities obtainable from/thanks to the business

cluster. A company inspired by others and getting best practices can save a lot of time and work in the technology search, but also in other TM stages, it can be expected on technology selection certainly, and technology acquisition, alike technology development. Time-to-market is a very important issue in the global competition age, which goes along with better flexibility and efficiency in the technology/product development phase [39–42].

Additionally, the reduction of time of TM activities is not ranged by respondents high, av. 2.9 looks as pretty low ranged compared to other factors. As mentioned before, some items from the variable Cooperation (Coopera) are also ranged average pretty low. These should be considered together with a low level of variance. This leads to an important observation: the model describes the behaviours of a small number of companies engaged in the investigated business cluster. These companies are more engaged and are gaining superior benefits from the engagement. What was deduced is consistent with the facts known about the cluster, within it there is an informal group of companies called a “close cooperation group”, probably these companies can probably take real advantage of engagement into the cluster. Moreover, some other cluster members present during public discussions scepticism to benefits achieved thanks to the cluster, they are not from the “close cooperation group”.

6 Conclusions

This study is focussed on the metal processing industry, where rarely disruptive technologies that can revolutionise the industry in a short time appear. Although this is not a technologically advanced and emerging industry, it is very interesting because it can be a great example of a stable industry. In particular, this study has investigated the TM sphere in companies engaged in a business cluster. The study proves that multidimensional cooperation allowed and facilitated by the business cluster leads to obtaining technological knowledge from outside the company, which then shortens TM activities duration and significantly increases market activity. The knowledge possessed by/thanks to the cluster is utilised by companies in two TM stages: the search for new technologies and technology development.

Cluster membership is beneficial for companies in these TM phases (stages) where knowledge plays a special role. The SEM method revealed that architectural knowledge is of primary importance in the TM sphere in companies engaged in a business cluster structure. This is knowledge of how to configure and reconfigure technologies along with existing and new product re-development. In the technology development stage, this kind of knowledge is particularly important. Companies that take advantage of this cluster knowledge behave more actively in markets, search new markets, and discover market niches. This path of the developed model can be perceived as a strategic one; companies take strategic advantages having roots in cluster engagement. The observed chain of influence is important considering long-term business development and therefore should be further investigated. Researchers should also pay special attention to in-depth identification of architectural knowledge and its impact on the creation of new technologies and new products, which may result in the creation of disruptive technologies in the industry in the future.

Acknowledgments. This research was funded by a grant from the Ministry of Education and Science received by the Białystok University of Technology, grant number WZ/WIZ-INZ/3/2022.






References

1. Gregory, M.J.: Technology management: a process approach. *Proc. Inst. Mech. Eng.* **209**, 347–356 (1995)
2. Krawczyk-Dembicka, E.: Process of technology management in SMEs of the metal processing industry—the case study investigation. *Eng. Manage. Prod. Serv.* **9**(1), 18–25 (2017)
3. Porter, M.E.: Location, competition, and economic development: local clusters in a global economy. *Econ. Dev. Q.* **14**(1), 15–35 (2000)
4. Awad, I.M., Amro, A.A.: The effect of clustering on competitiveness improvement in Hebron: a structural equation modeling analysis. *J. Manuf. Technol. Manag.* **28**(5), 631–654 (2017)
5. Hsu, M.-S., Lai, Y.-L., Lin, F.-J.: Effects of industry clusters on company competitiveness: special economic zones in Taiwan. *Rev. Pac. Basin Financ. Mark. Polic.* **16**(3), 1–28 (2013)
6. Porter, M.E.: Clusters and the new economics of competition. *Harv. Bus. Rev.* **76**(6), 77–90 (1998)
7. Grangsjö, Y.: Destination networking: co-operation in peripheral surroundings. *Int. J. Phys. Distrib. Logist. Manag.* **3**(5), 427–448 (2003)
8. Nie, P.Y., Wang, C., Lin, L.K.: Cooperation of firms yielding industrial clusters. *Area* **52**(4), 731–740 (2020)
9. Phaal, R., Farrukh, C.J.P., Probert, D.R.: A framework for supporting the management of technological knowledge. *Int. J. Technol. Manage.* **27**(1), 1–15 (2004)
10. Cetindamar, D., Phaal, R., Probert, D.: *Technology Management Activities and Tools*, 2nd edn. Palgrave Macmillan, New York (2016)
11. Skilbeck, J.N., Cruickshank, C.M.: A framework for evaluating technology management processes. In: PICMET 1997, Portland, OR, July 1997 (1997)
12. Sumanth, D.J., Sumanth, J.J.: The technology cycle approach to technology management. In: Gaynor, G.H. (ed.) *Handbook of Technology Management*. McGraw-Hill, New York (1996)
13. Levin, D., Barnard, H.: Technology management routines that matter to technology managers. *Int. J. Technol. Manage.* **41**(1–2), 22–37 (2008)
14. Lee, H., Kang, P.: Identifying core topics in technology and innovation management studies: a topic model approach. *J. Technol. Transf.* **43**, 1291–1317 (2018)
15. Bandarian, R.: Explaining the competitive advantage in strategic research and technology management for research and technology organisations. *Int. J. Bus. Continuity Risk Manag.* **10**(1), 23–45 (2020)
16. Yubo, S., Ramayah, T., Hongmei, L., Yifan, Z., Wenhui, W.: Analysing the current status, hotspots, and future trends of technology management: using the WoS and Scopus database. *Heliyon* **9**(9), e19922 (2023)
17. Urban, W., Krawczyk-Dembicka, E.: An in-depth investigation of technology management process in the metal processing industry. *Eur. Res. Stud. J. XXIII Spec. Issue* **1**, 115–136 (2020)
18. Cetindamar, D., Phaal, R., Probert, D.R.: Technology management as a profession and the challenges ahead. *J. Eng. Tech. Manage.* **41**, 1–13 (2016)
19. Phaal, R., Farrukh, C.J.P., Probert, D.R.: Technology management process assessment: a case study. *Int. J. Oper. Prod. Manag.* **21**(8), 1116–1132 (2001)
20. Qandah, R., Suifan, T.S., Masa'deh, R., Obeidat, B.Y.: The impact of knowledge management capabilities on innovation in entrepreneurial companies in Jordan. *Int. J. Organ. Anal.* **29**(4), 989–1014 (2021)

21. Quintane, E., Casselman, R.M., Reiche, B.S., Nylund, P.A.: Innovation as a knowledge-based outcome. *J. Knowl. Manag.* **15**(6), 928–947 (2011)
22. Zheng, S., Zhang, W., Wu, X., Du, J.: Knowledge-based dynamic capabilities and innovation in networked environments. *J. Knowl. Manag.* **15**(6), 1035–1051 (2011)
23. Cao, Y., Xiang, Y.: The impact of knowledge governance on knowledge sharing. *Manag. Decis.* **50**(4), 591–610 (2012)
24. Denford, J.S.: Building knowledge: developing a knowledge-based dynamic capabilities typology. *J. Knowl. Manag.* **17**(2), 175–194 (2013)
25. Di Maria, E., De Marchi, V., Spraul, K.: Who benefits from university–industry collaboration for environmental sustainability? *Int. J. Sustain. High. Educ.* **20**(6), 1022–1041 (2019)
26. Scarpellini, S., Portillo-Tarragona, P., Vinuesa, L.M.M., Moneva, J.M.: Green patents in the manufacturing sector: the influence of businesses’ resources and capabilities. *Universia Bus. Rev.* **56**, 18–35 (2017)
27. Fioravanti, V.L.S., Stocker, F., Macau, F.: Knowledge transfer in technological innovation clusters. *Innov. Manage. Rev.* **20**(1), 43–59 (2023)
28. Belderbos, R., Carree, M., Lokshin, B.: Cooperative R&D and firm performance. *Res. Pol.* **33**, 1477–1492 (2004)
29. Murillo-Luna, J.L., Hernandez-Trasobares, A.: Cooperation with the Triple Helix and corporate environmental innovation. *J. Clean. Prod.* **384**, 135479 (2023)
30. Xie, X., Wang, H.: How can open innovation ecosystem modes push product innovation forward? An fsQCA analysis. *J. Bus. Res.* **108**, 29–41 (2020)
31. National Research Council: *Management of Technology: The Hidden Competitive Advantage*. The National Academy Press, Washington, D.C. (1987)
32. Sahlman, K., Haapasalo, H.: Structures of strategic management of technology in a conceptual framework of enterprise practice. *Int. J. Synerg. Res.* **1**(1), 57–76 (2012)
33. DeVellis, R.F.: *Scale Development: Theory and Applications*, 2nd edn. SAGE Publications, London, New Delhi (2003)
34. Babin, B.J., Svensson, G.: Structural equation modeling in social science research. *Eur. Bus. Rev.* **24**(4), 320–330 (2012)
35. Wong, K.K.: Partial least squares structural equation modeling (PLS-SEM) techniques using SmartPLS. *Marketing Bulletin* 24, Technical Note 1 (2013)
36. Hair, J.F., Ringle, Ch.M., Sarstedt, M.: PLS-SEM: indeed a silver bullet. *J. Market. Theor. Pract.* **19**(2), 139–151 (2011)
37. Afthanorhan, A., Afthanorhan, B.W.: A comparison of partial least square structural equation modeling (PLS-SEM) and covariance based structural equation modeling (CB-SEM) for confirmatory factor analysis. *Int. J. Eng. Sci. Innov. Technol.* **2**(5), 198–205 (2013)
38. Kock, N.: *WarpPLS User Manual: Version 6.0*. ScriptWarp Systems: Laredo, Texas (2017)
39. Lu, Y., Loh, H.T., Brombacher, A.C., den Oudenc, E.: Accelerated stress testing in a time-driven product development process. *Int. J. Prod. Econ.* **67**(1), 17–26 (2000)
40. Rafinejad, D.: *Innovation, Product Development and Commercialization*. J Ross Publishing, Plantation (FL), p. 400 (2007)
41. Haddad, C.J.: Concurrent engineering and the role of labor in product development. *Control. Eng. Pract.* **2**(4), 689–696 (1994)
42. Vesey, J.T.: Time-to-market: put speed in product development. *Ind. Mark. Manage.* **21**(2), 151–158 (1992)



Proactive Resource Maintenance in Product-as-a-Service Business Models: A Constraints Programming Based Approach for MFP Offerings Prototyping

Eryk Szwarc¹  , Paulina Golińska-Dawson² , Grzegorz Bocewicz¹ ,
and Zbigniew Banaszak¹ 

¹ Koszalin University of Technology, Koszalin, Poland
eryk.szwarc@tu.koszalin.pl

² Poznan University of Technology, Poznan, Poland

Abstract. This paper delves into Product-as-a-Service (PaaS) business models, with a primary focus on proactively managing strategies designed to ensure the requisite service level availability for Multi-Function Printer (MFP) offerings. Within this framework, we introduce an all-encompassing system that combines predictive analytics, automated resource allocation, and adaptable service scaling to address potential disruptions and enhance the optimization of service delivery. The core issue addressed in this research falls within the realm of resource allocation problems, specifically concentrating on formulating a strategy for designing lease offers that adhere to predefined risk thresholds related to potential failure to provided resources. Through a case study and the outcomes of computer experiments, we illustrate the efficacy of our approach, grounded in constraints programming, in elevating PaaS availability while efficiently utilizing resources. These findings hold considerable value for consistently delivering reliable services in the ever-evolving digital landscape.

Keywords: Proactive Maintenance · Product-as-a-Service · Constraint Satisfaction Problem · MFP

1 Introduction

In Product-as-a-Service (PaaS) business models, the manufacturer retains ownership of the products, offering their functionality to customers for a predefined period of time. The effective implementation of PaaS necessitates repeated product usage through multiple life cycles. From the customer's perspective, PaaS ensures convenient equipment use, as maintenance and service costs are typically incurred by the manufacturer. In return, PaaS providers actively monitor and maintain the products during their usage phase, enabling better control and early awareness of the product's condition. This facilitates the application of suitable strategies for preserving the product's value, with a primary focus on its usage status. When needed, PaaS providers can also restore used products or product components through refurbishment and/or partial rebuilding, as noted in the work of [1].

While PaaS models are undeniably appealing, they are accompanied by several research challenges, as underscored by Sakao et al. [2]. Determining the overall cost of a PaaS offering for producers is a complex task, and there's a compelling need for innovative tools to simplify these calculations. In an ideal PaaS scenario, multiple contracts with customers are involved, and there are remanufacturing or refurbishing phases between these contracts. These intermediate phases are designed to restore a product to its full functionality or upgrade it to meet current market standards, such as improving energy efficiency through module or software modifications. The expenses associated with remanufacturing and repairs are borne by the producers, who must optimize their processes using a lifecycle costing approach.

Accurately setting leasing costs with a limited number of leasing contracts that include remanufacturing in between, requires access to extensive datasets and analytical tools. This can present a current challenge, as highlighted by van Loon et al. [3]. Naturally, at the end of the subscription period or the equipment life, the PaaS provider may handle the decommissioning, removal, and recovery or responsible disposal or recycling of the hardware.

Ensuring the availability of a required service level is of paramount importance for numerous organizations, as any downtime or service degradation can lead to significant financial losses and damage to their reputation. To maintain high service level availability, organizations employ a combination of proactive and reactive strategies: predictive maintenance, proactive maintenance, and preventive maintenance. Predictive maintenance utilizes data-driven, proactive methods to predict when equipment is likely to fail, enabling maintenance to be performed just in time to prevent unplanned downtime. Many PaaS providers use remote monitoring and diagnostic tools to track the real-time status and performance of leased resources, for example in Multi-Function Printers (MFPs). This proactive approach enables them to address issues before they escalate into significant problems. On the other hand, preventive maintenance, being schedule-based, proactively addresses common issues before they become problematic, ultimately extending the lifespan of MFPs.

Since customers do not purchase the product outright in a PaaS model, it is crucial that the product is designed to be durable, minimizing maintenance and replacement costs. This scenario underscores the importance of considering the risks faced by both PaaS providers and customers. These risks encompass dependence on service continuity, potential increased wear and tear on products, as well as various other factors impacting risk, such as the cost of addressing it, potential downtime, its effect on customer satisfaction, and financial losses. This highlights the necessity of conducting a maintenance risk assessment for the MFP PaaS business model, which entails evaluating potential risks and devising strategies to mitigate them.

The research conducted in this study addresses the previously identified needs and expectations with the aim of creating a reference model for the PaaS Provider System - the Consumer of Rented Services (PP-RS for short). Our primary contributions in this context can be summarized as follows:

- We have developed a declarative reference model for PP-RS, enabling the planning of leasing offers while adhering to predefined risk thresholds associated with potential

equipment damage. Additionally, it allows for the assessment of risks related to achieving the required service level for the assumed scale of rented services.

- We have presented the results of computer experiments, demonstrating the practicality of using our approach to generate alternative scenarios for maintaining the expected service quality of rented equipment. It also assists in assessing the risks associated with the scale of rental services and equipment.

In summary, the novelty of our proposed approach results from introducing the PP-RS reference model. These advantages include the model’s open and adaptable structure, which allows for further refinement and extension. It also facilitates the formulation and resolution of both analytical problems (answering questions about what occurs under specific conditions) and synthesis problems (answering questions about what parameters of the modeled system ensure the desired behavior). This approach enables answers to questions such as: What are the risks associated with implementing the planned PaaS offering? What risks do consumers face when accepting a PaaS offer with a specified level of availability? What proactive planning strategy ensures a defined level of utilization for rented equipment/services?

The developed model makes it possible to designate offers that balance the provider’s possibilities with customer expectations. This type of balancing is an element of the total cost of ownership (TCO) cascading model, which can be presented as in Fig. 1. The dashed frame indicates the part where the solution proposed in this work can be used. This means that balancing of PaaS offers is carried out when signing contracts, which results in the maintenance and servicing cost including failure prediction and proactive resources maintenance planning.

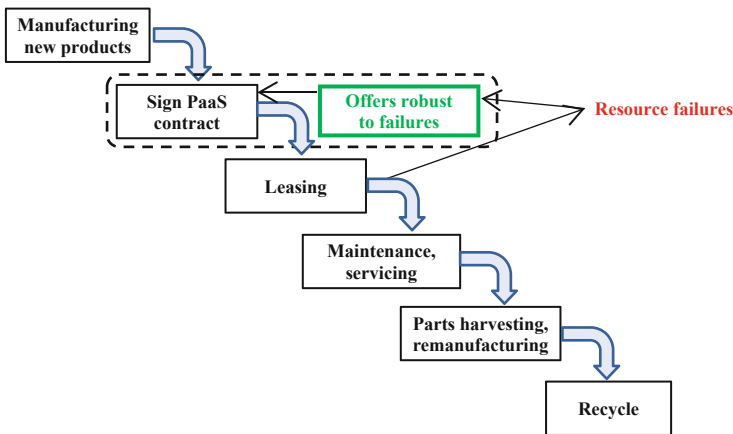


Fig. 1. Total Cost Ownership with proactive resources maintenance planning.

The structure of this study is as follows: Sect. 2 discusses the related work and determines the research gaps in the literature. Section 3 presents the problem formulation. Section 4 introduces a declarative model and provides a formal problem formulation in

terms of constraint satisfaction problems. Section 5 presents a case study with the results of quantitative computer experiments. Section 6 suggests directions for future research.

2 Literature Review

The paradigm of servitization in manufacturing, which has been acknowledged for over three decades [4], revolves around offering solutions and outcomes to customers rather than tangible products. This shift has given rise to three key task-oriented business models: Product-as-a-Service (PaaS) [5, 6], Product-Service-Systems (PSS) [7–10], and Equipment-as-a-Service (EaaS) [11]. PSS involves the integrated delivery of products and services, transitioning enterprises from product-centric to product-service-centric revenue models [12]. PaaS, a subset of PSS [13], retains product ownership with the manufacturer and doesn't transfer it to end users. In the case of EaaS, this model combines both the product and the necessary services for equipment maintenance and operation into a unified offering, with the revenue model based on the actual value provided.

In the PaaS model, manufacturers typically receive compensation based on contracted time periods, which provides an incentive to maximize the product's technical lifespan. A key advantage of the PaaS model, as highlighted by Tukker [14], is that it allows providers to retain control of the products during their usage phase. PaaS providers actively monitor and maintain the products throughout this phase, gaining a deeper understanding of their condition and enabling the implementation of value retention strategies that focus on the product's usage state. This proactive approach also facilitates the refurbishment and partial rebuilding of used products or their components when necessary.

By combining these practices with advanced digital technologies and data analysis, such as the Internet of Things (IoT), Information Technology/Information and Communication Technology (IT/ICT), and big data analytics, they naturally integrate into smart services and proactive service solutions, as emphasized by Sakao and Nordholm [15] and Wenninger et al. [16]. These solutions often become part of comprehensive full-service maintenance contracts, as detailed by Deprez et al. [17]. In these contracts, all maintenance costs are covered over a specified time period, and customers pay a fixed service fee, relieving them of the uncertainty associated with maintenance costs.

Nevertheless, creating data-driven tariff plans based on predictive models calibrated to various machine profiles can be challenging due to the complexity of estimating costs associated with machine-specific characteristics, such as the operational environment. Additionally, service fees should align with the capabilities and expectations of the leasing market. It's essential to note that the literature on appropriate predictive models for these purposes is still in its early stages.

A similar challenge arises when attempting to assess the risks faced by PaaS providers [18]. While there have been some preliminary conceptual attempts to develop decision support frameworks for risk management, comprehensive models are still lacking. Furthermore, the assessment of risks incurred by equipment lessors is a topic that remains largely unexplored.

The review of the literature highlights several significant research gaps, which can be summarized as follows:

- the absence of comprehensive models that can effectively balance the capabilities of PaaS providers with the requirements and expectations of customers renting equipment,
- a lack of methods for proactive maintenance of multifunctional equipment leased to multiple lessors, especially in terms of predictive planning for periodic inspections, replenishments, and consumables,
- inadequate analytical models for multifunctional equipment leased to multiple lessors, which would enable the assessment of risks taken by both PaaS providers and equipment recipients, particularly in the context of random damage.

Addressing these gaps is vital for the development of systems that can support PaaS providers in planning predictive maintenance for MFPs and their customers.

The existing informal concepts are insufficient to replace detailed models that meet the requirements for constructing a reference model PP-RS and solving decision-making problems in this domain.

Models that implement the declarative programming paradigm hold promise for addressing these challenges. Constraint programming strategies used in such models facilitate the formulation of both analysis and synthesis problems, thanks to their inherently open structures.

In this context, this paper builds upon previous work related to preventive maintenance scheduling for multi-skilled human resources [19, 20] and proactive-reactive UAVs mission planning [21, 22], which relied on declarative modeling-driven frameworks. The current research aims to apply some of the experiences gained in those areas to a new context where the primary challenge is to allocate leased equipment in a manner that aligns with the capabilities of the supplier and the expectations of the recipient, all while staying within predefined risk levels.

3 Problem Formulation

PaaS Provider. Given provider offering MFPs in a PaaS model has a set of K various types of devices. Each type of $k_i \in K$ device (resource) is characterized by a set of functionalities $O_i \subseteq O$ (where O is the set of all functionalities available in the provider's offer). The number of units q_i of each type of device k_i held by the provider is known.

The prices c_i of renting one piece of resource k_i (expressed in contractual money units (m.u.)) per contractual time unit (t.u.) are known. The probabilities $p(k_i)$ of failure and the cost of repairing the $VC(k_i)$ of each of the rented k_i devices are also known.

Customer leasing MFPs. A customer C_u considering renting $r_{l,u}$ devices with specific functionalities from the set O (where: $r_{l,u}$ specifies the number of devices offering functionality $o_l \in O$) submits an inquiry to the provider about the offer of MFPs leased by him. The expected rental period specified by the customer includes the time horizon H_u .

The cost of the offer cannot exceed the customer's budget B_u . The costs $EC_u(v)$ of loss of functionalities expected by the customer in a situation related to failure to the rented devices are also known.

Rental Offer. The offer consists in assigning a certain number of $x_{u,i}$ devices k_i to customer C_u (collectively represented by a sequence of X_u), in accordance with the

expected functionalities (defined by the parameter $r_{l,u}$), within a given H_u horizon and with a given B_u budget. In other words, the offer OF_u consists of an assignment of X_u , the total price of F_u offer and the guaranteed level of R_u robustness (explained below).

Robustness of the Offer to Failures of the Rented Devices. Unavailability of a k_i device caused by a failure results in the loss of the O_i functionalities offered by that resource. When these functions are available through other customer-owned devices, the lease offer remains robust in the face of this particular type of malfunction. In such cases, customers maintain access to the functionality, even in the event of a failure. For the purposes of our ensuing discussions, we will designate an occurrence involving the breakdown of a single device as a “failure scenario”. In practice, various failure scenarios can emerge, rendering it unfeasible to replace a defective device in all conceivable instances. As a consequence, the robustness R_u of the rental offer OF_u can have various “levels”.

Let’s assume that the robustness of the offer to the failure of individual R_u devices is calculated as the ratio of the number of failure scenarios, for which the functionalities of the damaged device can be replaced by other rented (at the customer’s disposal) devices, in relation to all possible failure scenarios. This means that $R_u \in [0, 1]$.

- $R_u = 0$ means no robustness, i.e. for each failure scenario of a single device, no other rented device offers the functionality of the defective device,
- $R_u = 1$ it means full robustness, i.e. for each failure scenario of a single device, other rented devices offer the functionalities of the defective device.

Risks Related to the Rental Offer. Every offer is linked to the notion of risk, encompassing both the customer’s and the provider’s perspectives. The premise involves the occurrence of unexpected device failures during the lease period, defined as the unavailability of a randomly designated rented unit of the device (unavailable in any unit within the horizon H_u). In the event of such a failure, the loss of all functionalities provided by the malfunctioned device is assumed.

The customer’s risk of failure v is defined as a pair: $UC_v = (p(v), EC_u(v))$, where: $p(v)$ is the probability of an event v consisting in “that in a given unit of time there will be a failure of one of the devices owned by the customer”, and $EC_u(v)$ is the cost of loss of functionality as a result of damage to any single device.

The provider’s risk is defined as a pair: $UP_v = (p(v), EP(v))$, where: $EP(v)$ is the cost of repairing the device in the event of a failure.

Problem Statement. Taking the previously discussed data (including the client’s budget, risk level, device allocation, provider risk, etc.) and limitations resulting from the relations (including the provider’s offer), the considered problem boils down to the question: Is there an offer OF_u renting PaaS provider’s devices that meet the customer’s expectations C_u (the offered devices are characterized by the functionalities expected by the customer) and do not lead to exceeding the B_u budget at their disposal, while at the same time guaranteeing the expected level of ER_u robustness?, and its derivatives: If so, what are the alternative variants? Which variant results in the highest level of R_u robustness? Which variant gives the most PaaS Provider profit (F_u)? If not, what devices

k_i , in what number, must PaaS Provider have to be able to offer customers a rental that guarantees the expected level of ER_u robustness?

The next Sect. 4 presents a declarative model of the problem under consideration, which allows answering the above questions.

4 Declarative Model

The task of identifying offers that harmonize with the customer's needs and the capabilities of the PaaS Provider (PP) can be conceptualized as a decision problem, and the declarative modeling paradigm offers an effective approach to tackle this challenge.

Parameters:

- K : a set of types of resources that are available from PP, $K = \{k_1, \dots, k_i, \dots, k_{LK}\}$ (where LK is a number of types of resources),
- Q : a sequence whose element q_i determine the number of units of a resource of a given type k_i , $Q = (q_1, \dots, q_i, \dots, q_{LK})$,
- C : a cost sequence whose elements c_i determine the price of renting one unit of the resource k_i per unit of time, $C = (c_1, \dots, c_i, \dots, c_{LK})$,
- O : a set of all functionalities of the set's resources K , $O = \{o_1, \dots, o_l, \dots, o_{LO}\}$,
- \mathbb{C} : a set of customers asking PP for an offer, $\mathbb{C} = \{C_1, \dots, C_u, \dots, C_{LC}\}$ (where LC is a number of customers),
- B : customers budget represented by a sequence whose elements B_u determine the budget of the customers constituting the set \mathbb{C} , $B = (B_1, \dots, B_u, \dots, B_{LC})$,
- ER : expected robustness ER_u of offers prepared by PP for customers constituting the set \mathbb{C} , $ER = (ER_1, \dots, ER_u, \dots, ER_{LC})$,
- OK : functionalities O provided by individual resources of the set K are represented by matrix $OK = [ok_{l,i}]_{l=1\dots LO; i=1\dots LK}$, in which value $ok_{l,i} = 1$ means that resource k_i has functionality o_l and value 0 means the opposite situation,
- OR : customer expectations represented by a matrix $OR = [r_{l,u}]_{l=1\dots LO; u=1\dots LC}$, in which the values of the elements $r_{l,u}$ denote the number of resources with functionality o_l that customer C_u expect,
- H : a sequence of time horizons H_u defining the duration of the offer of customer C_u , $H = (H_1, \dots, H_u, \dots, H_{LC})$.

Decision variables:

- OF : a set of offers proposed by PP for customers constituting the set \mathbb{C} , $OF = (OF_1, \dots, OF_u, \dots, OF_{LC})$, where OF_u is an offer of customer C_u , which consists of: resource assignment X_u , offer price F_u and its robustness R_u (see below): $OF_u = (X_u, F_u, R_u)$,
- X : a set of resource assignments for customers constituting the set \mathbb{C} in accordance with OF offers proposed by PP, $X = \{X_1, \dots, X_u, \dots, X_{LC}\}$, where X_u is assignment (according with the offer OF_u) determining the number $x_{u,i}$ units of resource k_i offered to customer C_u , $X_u = (x_{u,1}, \dots, x_{u,i}, \dots, x_{LC,LK})$,
- F : a set of offer prices proposed by PP for customers constituting the set \mathbb{C} , $F = \{F_1, \dots, F_u, \dots, F_{LC}\}$, where F_u is a price of offer OF_u ,

X_u^* : a set of resource failure scenarios of the offer OF_u , $X_u^* = \{X_u^1, \dots, X_u^v, \dots, X_u^{LA(u)}\}$, where X_u^v determines the number $x_{u,i}^v$ units of resource k_i available to the customer C_u in the event of a failure (failure of one unit of any resource of offer OF_u).

M_u^* : a set of auxiliary variables M_u^v determining whether the proposed offer OF_u provides the expected functionalities for the failure scenario X_u^v ($M_u^v = 1$), $M_u^* = \{M_u^1, \dots, M_u^v, \dots, M_u^{LA(u)}\}$,

R : a set robustness of offers proposed by PP for customers constituting the set \mathbb{C} , $R = \{R_1, \dots, R_u, \dots, R_{LC}\}$, where R_u is the robustness of offer OF_u .

Constraints:

- a number of units $x_{u,i}$ of a resource k_i must not exceed the given limit q_i :

$$\sum_{u=1}^{LC} x_{u,i} \leq q_i, \text{ for } i = 1 \dots LK. \quad (1)$$

- functionalities $ok_{l,i}$ provided by the offer OF_u must be consistent with the expectations $r_{l,u}$ of the customer C_u :

$$\sum_{i=1}^{LK} x_{u,i} \times ok_{l,i} \geq r_{l,u}, \text{ for } u = 1 \dots LC; l = 1 \dots LO, \quad (2)$$

- a price F_u of offer OF_u must not exceed the customer budget B_u :

$$H_u \times \sum_{i=1}^{LK} x_{u,i} \times c_i = F_u, \text{ for } u = 1 \dots LC; \quad (3)$$

$$F_u \leq B_u, \text{ for } u = 1 \dots LC; \quad (4)$$

- considered failure scenarios X_u^v differ from the offer OF_u in that they lack access to any one unit of resource of a given offer:

$$X_u^a \neq X_u^b, \text{ for } u = 1 \dots LC, a, b \in \{1 \dots LA(u)\}, a \neq b; \quad (5)$$

$$x_{u,i}^v \leq x_{u,i}, \text{ for } u = 1 \dots LC, v = 1 \dots LA(u); \quad (6)$$

$$\sum_{i=1}^{LK} x_{u,i}^v = \sum_{i=1}^{LK} x_{u,i} - 1 \text{ for } u = 1 \dots LC, v = 1 \dots LA(u); \quad (7)$$

- functionalities $ok_{l,i}$ provided by the failure scenario X_u^v must be consistent with the expectations $r_{l,u}$ of the customer C_u :

$$\bigwedge_{l=1}^{LO} (\sum_{i=1}^{LK} x_{u,i}^v \times ok_{l,i} \geq r_{l,u}) \Rightarrow (M_u^v), \text{ for } u = 1 \dots LC; v = 1 \dots LA(u); \quad (8)$$

- a robustness R_u of offer OF_u must be greater than the expected (by customer C_u) value OR_u :

$$\frac{\sum_{v=1}^{LA(u)} M_u^v}{LA(u)} = R_u, \text{ for } u = 1 \dots LC; \tag{9}$$

$$R_u \geq ER_u, \text{ for } u = 1 \dots LC. \tag{10}$$

Among the constraints introduced, relations (1)–(4) describe the conditions of an acceptable offer OF_u , i.e. one that provides the functionalities expected by the customer within the scope of his budget. Constraints (5)–(10) concern the relationship between the proposed offer (assignment X_u) and its robustness. Robustness R_u of the offer OF_u is determined as the ratio of the number of failure scenarios ($\sum_{v=1}^{LA(u)} M_u^v$) for which the offer provides the expected functionalities despite the loss of access to one unit of some resource ($M_u^v = 1$) against all possible $LA(u)$ failure scenarios.

This kind of defined model allows answering the following question: Does exist a set of offers OF that meet the expectations OR of set customers \mathcal{C} and do not exceed their budgets B , while at the same time guaranteeing the expected level of robustness ER ?

Related problem can be formulated in terms of the following Constraint Satisfaction Problem (CSP):

$$CS = ((\mathcal{V}, \mathcal{D}), \mathcal{C}), \tag{11}$$

where: $\mathcal{V} = \{x_{u,i}, x_{u,i}^v, F_u, R_u, M_u^v | u = 1 \dots LC; i = 1 \dots LK; v = 1 \dots LA(u)\}$, a set of decision variables representing assignment X , failure scenarios X_u^* , offer prices F and their robustnesses R ; \mathcal{D} is a set of domains of decision variables: $x_{u,i}, x_{u,i}^v, F_u \in \mathbb{N}$, $R_u \in [0, 1]$, $M_u^v \in \{0, 1\}$; \mathcal{C} is a set of constraints specified in inequalities (1)–(10).

To solve problem CS (11), one should determine such values of decision variables $x_{u,i}, x_{u,i}^v, F_u, R_u, M_u^v$, for which all the constraints given in the set \mathcal{C} are satisfied. Solving CS means determining the assignments X , which guarantees the customer expectation OR and given level of robustness ER .

5 Case Study

The declarative model, as discussed in Sect. 4, was validated using real data from a PaaS Provider (PP). The validation process entailed an attempt to investigate and analyze rental offers for devices that were available at PP, specifically for a particular group of customers, while ensuring that these offers met their expectations. In other words, the experiments analyze resource assignment X_u , offer prices F_u and their robustness R_u , which will be acceptable both on the side of PP and customers.

For the purposes of the experiments, data from PP were used (Table 1), which has seven types of printers $K = \{k_1, \dots, k_7\}$ providing four functionalities $O = \{o_1, \dots, o_4\}$. PP has the following number of printers at its disposal: $Q = (22, 18, 25, 19, 22, 19, 20)$, which is rented according to the price list: $C = (150, 100, 125, 200, 225, 150, 200)$ – euro/month.

A set of fifteen customers $\mathcal{C} = \{C_1, \dots, C_{15}\}$ applies to PP with an inquiry about a rental offer consistent with their functionality expectations set out in the Table 2.

Table 1. Matrix *OK* of the printer functionality at the disposal of PP.

Functionality	Printer						
	k_1	k_2	k_3	k_4	k_5	k_6	k_7
o_1	0	0	1	1	1	0	1
o_2	1	0	1	0	0	1	1
o_3	1	1	1	1	0	0	0
o_4	1	1	0	1	1	1	1

Table 2. Matrix *OR* of the customers $C_1 - C_{15}$ functionality expectations.

Functionality	Customer														
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}
o_1	2	1	1	1	0	0	1	0	4	2	0	0	1	1	0
o_2	1	1	0	0	2	3	0	2	0	0	1	2	2	3	2
o_3	0	0	0	3	1	4	1	1	2	0	1	0	0	1	2
o_4	0	1	2	1	0	0	1	1	0	2	0	0	0	0	0

Customers specify limitations related to the rental duration of printers, budget constraints, and their expected level of robustness:

- Customer C_1 : $H_1 = 24$ months, $B_1 = 20000$ euro, $ER_1 = 75\%$;
- Customer C_2 : $H_2 = 24$ months, $B_2 = 17000$ euro, $ER_2 = 50\%$;
- Customer C_3 : $H_3 = 24$ months, $B_3 = 22000$ euro, $ER_3 = 50\%$;
- Customer C_4 : $H_4 = 24$ months, $B_4 = 20000$ euro, $ER_4 = 50\%$;
- Customer C_5 : $H_5 = 24$ months, $B_5 = 25000$ euro, $ER_5 = 50\%$;
- Customer C_6 : $H_6 = 24$ months, $B_6 = 20000$ euro, $ER_6 = 50\%$;
- Customer C_7 : $H_7 = 24$ months, $B_7 = 16000$ euro, $ER_7 = 100\%$;
- Customer C_8 : $H_8 = 24$ months, $B_8 = 19000$ euro, $ER_8 = 50\%$;
- Customer C_9 : $H_9 = 24$ months, $B_9 = 20000$ euro, $ER_9 = 75\%$;
- Customer C_{10} : $H_{10} = 24$ months, $B_{10} = 20000$ euro, $ER_{10} = 50\%$;
- Customer C_{11} : $H_{11} = 24$ months, $B_{11} = 22000$ euro, $ER_{11} = 50\%$;
- Customer C_{12} : $H_{12} = 24$ months, $B_{12} = 18000$ euro, $ER_{12} = 50\%$;
- Customer C_{13} : $H_{13} = 24$ months, $B_{13} = 24000$ euro, $ER_{13} = 75\%$;
- Customer C_{14} : $H_{14} = 24$ months, $B_{14} = 22000$ euro, $ER_{14} = 50\%$;
- Customer C_{15} : $H_{15} = 24$ months, $B_{15} = 25000$ euro, $ER_{15} = 25\%$.

In this scenario, the PP must consider the following question:

- Can we create offers that meet customers' expectations regarding functionality, budget limitations, and expected robustness levels?

The developed model provides support in answering these type of question. In order to illustrate the possibilities of its use, let's assume the data collected above, which determine the capabilities of the PaaS Provider, i.e.:

- a set of printers type (K),
 - the number of printers (Q) of the given type k_i ,
 - the rental price (C) of one unit of printer k_i ,
 - a set of all functionalities (O) provided by the printers of set K ,
 - functionalities O provided by the printers of set K represented by the matrix OK ,
- and customer expectations, i.e.:
- budget B of customers \mathbb{C} ,
 - expected robustness ER of the offers prepared by the PP for customers \mathbb{C} ,
 - customer expectations \mathbb{C} represented by the matrix OR ,
 - time horizons (H) defining the duration of the customer's offer.

The considered problem comes down to an analysis problem in which the answer to the following question is sought: Does exist a set of offers OF that meet the expectations OR of set customers \mathbb{C} and do not exceed their budgets B , while at the same time guaranteeing the expected level of robustness ER ?

The answer (solving the CS (11) problem) obtained in the IBM ILOG CPLEX environment (CPU: Intel i7-10510U, 16 GB RAM). The results were obtained in $t = 34.7$ s. The answer to the question is positive, and the offers for individual customers are summarized in Table 3.

For example:

- an offer OF_1 was prepared for customer C_1 , where: one unit of printer k_1 , two units of printer k_5 and one unit of printer k_7 were assigned, for a total price $F_1 = 19200$ euro. Such an offer has robustness $R_1 = 100\%$, i.e. customer C_1 knows that in each of the printers failure scenarios, the remaining printers will provide the expected functionalities,
- an offer OF_2 was prepared for customer C_2 , where one unit of printer k_3 and one unit of printer k_7 were assigned, for a total price $F_2 = 7800$ euro. Such an offer has robustness $R_2 = 50\%$, i.e. customer C_2 knows that in one out of two failure scenarios of the resources available under this offer, the remaining printers will provide the expected functionalities.

The rest offers (OF_3 – OF_{15}) are also meet customers' expectations regarding functionality, budget limitations and expected robustness levels.

The conclusions from the case study are as follows:

- implementation of the model presented in Sect. 4 allows answering analytical questions, i.e. Does exist a set of leasing offers that meet the expectations of customers and do not exceed their budgets, while at the same time guaranteeing the expected level of robustness?
- solving the problem of analyzing the equipment rental offer for a scale of 7 devices for 15 customers allows to conclude that the proposed solution can be used in small and medium-scale enterprises.

Table 3. Offers $OF_1 - OF_{15}$ meeting customer expectations $C_1 - C_{15}$.

Offer OF_u	Printer assignment X_u							Offer price F_u	Offer robustness R_u
	k_1	k_2	k_3	k_4	k_5	k_6	k_7		
OF_1	1	0	0	0	2	0	1	19200	100
OF_2	0	0	1	0	0	0	1	7800	50
OF_3	0	3	0	0	0	0	1	12000	75
OF_4	0	4	0	0	1	0	1	19800	100
OF_5	0	0	2	0	0	3	0	16800	100
OF_6	1	3	3	0	0	0	0	19800	100
OF_7	0	0	1	1	1	0	0	13200	100
OF_8	1	0	1	2	0	0	0	16200	50
OF_9	0	0	3	2	0	0	0	18600	100
OF_{10}	0	1	0	1	0	1	1	15600	50
OF_{11}	1	0	1	0	0	0	0	6600	100
OF_{12}	0	1	1	0	0	2	0	12600	100
OF_{13}	0	0	3	0	0	0	0	9000	100
OF_{14}	1	0	0	0	1	3	0	19800	60
OF_{15}	0	1	1	0	0	2	0	12600	50

6 Concluding Remarks

This paper addresses the challenge of proactive maintenance planning in a Product-as-a-Service (PaaS) system, focusing on ensuring the availability of Multi-Function Printers (MFPs). It introduces a comprehensive framework that combines proactive analytics, automated resource allocation, and adaptive service scaling to identify potential disruptions and optimize service delivery in advance. The primary goal of this research is to develop a reference model that supports computer-aided decision-making. This model allows for the creation of secure offer strategies that do not exceed predetermined risk levels and the selection of secure solutions that adhere to budget and risk constraints in real-world scenarios.

The declarative nature of the model makes it suitable for practical implementation within well-established constraint programming environments like ILOG, ECLiPSe, and Gurobi. Its key advantage lies in its open structure, which allows for the consideration of new relationships between decision variables without sacrificing computational efficiency. In these constraint programming environments, the time needed to solve problems decreases as the number of constraints increases. Case studies showcasing the model's implementation demonstrate its effectiveness in addressing both analysis and synthesis problems. This means that in addition to addressing questions related to analysis, such as creating offers that meet customer expectations regarding printer functionality, budget, and robustness, the model can also handle synthesis problems. These focus on questions

like determining the number and types of devices a PaaS provider should have available to meet the needs of the tenant market.

The limitations of the approach stem from its exclusion of factors related to equipment delivery, including route and schedule constraints, as well as service visits. Future work should expand the model to account for the dynamics of the fleet responsible for deliveries and servicing (see Fig. 1). It should also incorporate uncertainty in operation times and costs (expressed as fuzzy numbers) while aiming to minimize the total cost of maintaining serviced MFPs and meet customer expectations. This means, for example, that assuming that each service vehicle in the PaaS provider's fleet accommodates two-person teams of service technicians, the following two strategies can be considered, i.e. a strategy in which the teams are delivered and picked up by the same vehicle and a strategy in which the teams are delivered they can be picked up by one of the fleet's vehicles by the remaining vehicles and do not require the delivered team to be picked up by the same vehicle. The last strategy, optimizing the movement of fleets involved in the delivery and collection of service teams, in particular taking into account scenarios in which the vehicle delivering the team does not have to be the same as the one receiving it, has received little attention in the literature.

It is also worth noting that the presented approach can be used in many other areas, e.g. related to home care. The escalating, increasingly prevalent demand for home therapies necessitates the construction of a schedule and the daily routes for each medical or nursing/caregivers team to maximize service effectiveness and cost/time efficiency.



References

1. Bressanelli, G., Perona, M., Saccani, N.: Reshaping the washing machine industry through circular economy and product-service system business models. *Procedia CIRP* **64**, 43–48 (2017). <https://doi.org/10.1016/j.procir.2017.03.065>
2. Sakao, T., et al.: Product-as-a-service for critical raw materials: challenges, enablers, and needed research. In: *Going Green: CARE INNOVATION, 2023* (2023). <https://hal.science/hal-04189123>
3. van Loon, P., Van Wassenhove, L.N., Mihelic, A.: Designing a circular business strategy: 7 years of evolution at a large washing machine manufacturer. *Bus. Strateg. Environ.* **31**(3), 1030–1041 (2022). <https://doi.org/10.1002/bse.2933>
4. Baines, T., Lightfoot, H., Benedettini, O., Kay, J.: The servitization of manufacturing: a review of literature and reflection on future challenges. *J. Manuf. Technol. Manag.* **20**(5), 547–567 (2009)
5. Lacy, P., Rutqvist, J.: The Product as a service business model: performance over ownership. In: *Waste to Wealth*. Palgrave Macmillan, London (2015). https://doi.org/10.1057/9781137530707_8
6. Reim, W., Parida, V., Sjödin, D.R.: Risk management for product-service system operation. *Int. J. Oper. Prod. Manag.* **36**(6), 665–686 (2016). <https://doi.org/10.1108/IJOPM-10-2014-0498>
7. Beuren, F.H., Gitirana, M., Cauchick, P.: Product-service systems: a literature review on integrated products and services. *J. Clean. Prod.* **47**, 222–231 (2013). <https://doi.org/10.1016/j.jclepro.2012.12.028>
8. Guo, W., Jiang, P.: Product service systems for social manufacturing: a new service system with multi-provider. *IFAC-PapersOnLine* **52**(13), 749–754 (2019). <https://doi.org/10.1016/j.ifacol.2019.11.205>

9. Marques, P., Cunha, P.F., Valente, F., Leitão, A.: A methodology for product-service systems development. *Procedia CIRP* **7**, 371–376 (2013). <https://doi.org/10.1016/j.procir.2013.06.001>
10. Xinga, K., Nessb, D.: Product-service systems across life cycle transition to product-service systems: principles and business model. *Procedia CIRP* **47**, 525–530 (2016). <https://doi.org/10.1016/j.procir.2016.03.236>
11. Rösler, J., Friedli, T.: A capability model for equipment-as-a-service adoption in manufacturing companies. In: West, S., Meierhofer, J., Ganz, C. (eds.) *Smart Services Summit*. PI, pp. 59–71. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-72090-2_6
12. Tukker, A., Tischner, U.: Product-services as a research field: past, present and future. Reflections from a decade of research. *J. Cleaner Prod.* **14**(17), 1552–1556 (2006). <https://doi.org/10.1016/j.jclepro.2006.01.022>
13. Brissaud, D., Sakao, T., Riel, A., Erkoyuncu, J.A.: Designing value-driven solutions: the evolution of industrial product-service systems. *CIRP Ann.* **71**(2), 553–575 (2022). <https://doi.org/10.1016/j.cirp.2022.05.006>
14. Tukker, A.: Product services for a resource-efficient and circular economy – a review. *J. Clean. Prod.* **97**, 76–91 (2015). <https://doi.org/10.1016/j.jclepro.2013.11.049>
15. Sakao, T., Nordholm, A.K.: Requirements for a product lifecycle management system using internet of things and big data analytics for product-as-a-service. *Front. Sustain.* **2**, 735550 (2021). <https://doi.org/10.3389/frsus.2021.735550>
16. Wenninger, A., Rau, D., Röglinger, M.: Improving customer satisfaction in proactive service design. *Electron. Markets* **32**, 1399–1418 (2022). <https://doi.org/10.1007/s12525-022-00565-9>
17. Deprez, L., Antonio, K., Boute, R.: Pricing service maintenance contracts using predictive analytics. *Eur. J. Oper. Res.* **290**(2), 530–545 (2021). <https://doi.org/10.1016/j.ejor.2020.08.022>
18. Reim, W., Parida, V., Örtqvist, D.: Product-service systems (PSS) business models and tactics - a systematic literature review. *J. Clean. Prod.* **97**, 61–75 (2015)
19. Bocewicz, G., Golińska-Dawson, P., Szwarc, E., Banaszak, Z.: Preventive maintenance scheduling of a multi-skilled human resource-constrained project's portfolio. *Eng. Appl. Artif. Intell.* **119** (2023). <https://doi.org/10.1016/j.engappai.2022.105725>
20. Szwarc, E., Bocewicz, G., Golińska-Dawson, P., Banaszak, Z.: Proactive operations management: staff allocation with competence maintenance constraints. *Sustainability* **15**(3), 1949 (2023). <https://doi.org/10.3390/su15031949>
21. Radzki G., Bocewicz G., Banaszak Z.: Proactive-reactive approach to disruption-driven UAV routing problem. In: Szewczyk, R., Zieliński, C., Kaliczyńska, M., Bučinskas, V. (eds.) *Automation 2023: Key Challenges in Automation, Robotics and Measurement Techniques, AUTOMATION 2023. LNNS*, vol. 630, pp. 51–61. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-25844-2_5
22. Szwarc, E., Wikarek, J.: Proactive planning of project team members' competences. *Found. Manage.* **12**(1), 71–84 (2020). <https://doi.org/10.2478/fman-2020-0006>



Throughput Evaluation of Serial-Parallel Manufacturing Systems for Different Production Flow Strategies

Sławomir Kłos^(✉)  and Justyna Patalas-Maliszewska 

University of Zielona Góra, 65-417 Zielona Góra, Poland
s.klos@iim.uz.zgora.pl

Abstract. Serial-parallel production systems are often used in industrial practice, especially when high process reliability must be guaranteed. The article proposes a simulation model of a serial-parallel production system that was created based on Tecnomatix Plant Simulation software. For the developed model, throughput tests were carried out for various allocations of inter-operation buffer capacity and production flow control strategies. Based on the research results, a methodology for rapid prototyping of serially parallel production systems with specific throughput was proposed. The results of the conducted research can be helpful in quickly determining the assumptions for the construction of serial-parallel production systems in order to achieve specific throughput.

Keywords: Serial-parallel manufacturing system · computer simulation · buffer allocation · production flow strategy

1 Introduction

Simulation modeling of discrete manufacturing processes is important for the design and operation of effective manufacturing systems. This is particularly important for multi-assembly, repetitive production (in industries such as the automotive industry, production of household appliances, machine construction, etc.), which requires efficiency estimation for the purposes of determining the conditions of cooperation of cooperators within the entire supply chain. The use of the computer simulation method makes it possible to estimate the demand for production resources and personnel, allocate and determine the capacity of inter-operation buffers, the number of employees needed, etc. in order to achieve a specific throughput of the designed production system. Serial-parallel production systems are the subject of many studies due to their resilience in the event of failure of production resources and production flow. This article presents the results of simulation studies of a selected configuration of a serial-parallel production system for which specific assumptions were made regarding operation times, inter-operation buffer capacity, production flow strategy and availability (failure reliability) of production resources and personnel. The following are most often taken into account as variable parameters in simulation modeling of discrete production processes:

- t_{ij} operation execution times and $t_{p_{zij}}$, setup times,
- r_{ij} availability (failure rate) of production resources M_{ij} ,
- $d(k)$ size of production batches,
- allocation of resources M_{ij} , capacity of inter-operation buffers B_j ,
- K - number of direct production employees,
- D_{ij} - rules for access to production resources,
- where $i, j, k \in N$.

Depending on the type of production and the specific nature of technological operations, unit times and preparation and completion times (changeovers) in simulation models are determined using available random distributions, which are selected in such a way that they best reflect the actual assumptions of the functioning of the production system.

The aim of the research was to find the relationship between changes in the parameters of production resources and production flow, and the system efficiency and average efficiency of production flow. Simulation models were developed using Tecnomatix Plant Simulation software. The next chapter analyzes the scientific literature related to the study of serial-parallel production systems and formulates the research problem and the model of the serial-parallel production system. The third chapter presents the results of simulation studies. The last chapter discusses the results and proposes a methodology for rapid prototyping of simulation models of serial-parallel production systems, as well as conclusions and directions for further research.

2 Literature Analysis and Model of a Serial-Parallel Production System

Simulation modeling of production systems is the subject of many studies and scientific publications (Mourtzis, 2020; Negahban, 2014). The computer simulation method is one of the important elements of the Industry 4.0 concept, used to create digital twins of production systems. Digital twins provide a physical representation of production resources, the functioning of which can be analyzed in real time (Segovia et al., 2022; Kłos, S. & Patalas - Maliszewska, 2019). Based on digital twins, it is possible to monitor resources that can be used, for example, by a predictive maintenance algorithm (Dinter et al., 2022). By creating a digital twin, manufacturing companies can simulate various scenarios and test manufacturing processes for efficiency or sensitivity to failure states. Digital twins are an important tool enabling the analysis of different variants and configurations of a production system without disturbing the actual manufacturing process (Ebni et al., 2023). Digital twin is becoming a key technology for digital transformation and intelligent modernization of production systems. Digital twin models are being researched due to the area of application, hierarchy, discipline, dimension, universality and functionality (Tao et al., 2022). Model-based systems engineering (MBSE) is an innovative approach to managing the complexity of modern product development that enables the analysis of benefits, barriers and parameters influencing the selection of verification and testing strategies and the use of computer simulation (Bemmami et al., 2021). A typical application of computer simulation methods is the analysis of various production variants based on built models in order to improve the efficiency or productivity of the system

(Guzman-Moratto et al., 2021; Antonelli et al., 2018). The computer simulation method is widely used to improve productivity in the automotive industry (Barrera-Diaz et al., 2018; Varela et al., 2018). Based on the analysis of various concepts of automation of the production system based on simulation models, it is possible to select an automated transport system that guarantees an increase in enterprise profits by up to 30% (Herps et al., 2022). Many publications include research that focuses on increasing the productivity of production systems based on the methodology of building simulation models, and conducting simulation research in order to obtain the most economical, efficient and clean manufacturing process (Sadar et al., 2022; Santos et al., 2021; Trigueiro, 2019). The level of reliability and properties of serial-parallel production systems are often studied using computer simulation (Li et al., 2022). The production flow model, system sensitivity to failures or degradation of production resources due to the low quality of processed materials are analyzed (Zhu et al., 2023; Shen et al., 2022; Zhu et al., 2022; Ye et al., 2020; Kaščak et al., 2022). The computer simulation method is also used in the design of quality control systems and quality assessment of production systems (Diering et al., 2019; Hamrol et al. 2020).

Serial-parallel production systems are characterized by a specific topology of machine arrangement and connection. Figure 1 shows an example of a series, parallel and serial-parallel configuration.

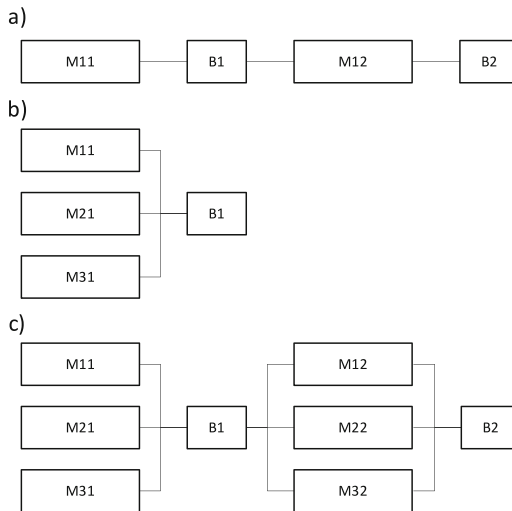


Fig. 1. Production system topology a) serial, b) parallel, c) serial-parallel.

In serial production systems, production resources (M_{11}, M_{22}, \dots) carrying out subsequent technological operations are arranged in a line. In parallel systems, production resources (M_{11}, M_{12}, \dots) are characterized by redundancy and simultaneously carry out the same technological operations. In serial-parallel systems, subsequent stages of technological operations are carried out in sockets composed of a larger number of identical resources. Such systems are resistant to failures of a given resource, because turning off

a given resource may lead to a reduction in production efficiency but will not stop it. Behind each resource or group of production resources, inter-operation warehouses (Bj buffers) are placed, where processed semi-finished products after subsequent stages of the technological process are stored.

The article proposes a model of a serial-parallel production system consisting of three technological operations, each carried out by three identical production resources. Cross-storage is allocated between each resource pair, with buffers shared between different resource pairs. Figure 2 shows a simulation model of serial-parallel production system built based on Tecnomatix Plant Simulation software. The system consists of 9 production resources ($M_{11}, M_{12}, \dots, M_{33}$) and 6 buffers (B_1, B_2, \dots, B_6).

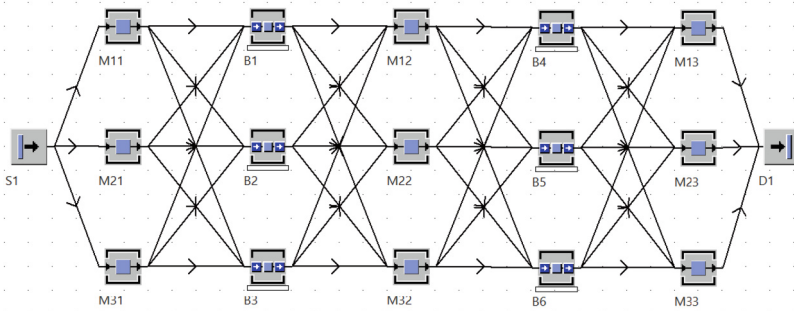


Fig. 2. Model of a serial-parallel production system created using Tecnomatix Plant Simulation

It was assumed that the system would produce four products A, B, C and D. Table 1 shows the times of performing operations for individual products on resources based on the logarithmic-normal distribution, which is a continuous distribution of a random number for which the natural logarithm corresponds to the distribution normal. The operation times generated by this distribution are non-negative real numbers.

Table 1. Operation times on resource groups for individual products $\text{lognorm}(\mu, \sigma)$

Product	Processing time (M_{11}, M_{21}, M_{31})	Processing time (M_{21}, M_{22}, M_{32})	Processing time (M_{13}, M_{23}, M_{33})
A	$\text{lognorm}(480,20)$	$\text{lognorm}(240,20)$	$\text{lognorm}(240,20)$
B	$\text{lognorm}(580,40)$	$\text{lognorm}(360,40)$	$\text{lognorm}(480,20)$
C	$\text{lognorm}(180,20)$	$\text{lognorm}(240,20)$	$\text{lognorm}(120,20)$
D	$\text{lognorm}(280,20)$	$\text{lognorm}(120,20)$	$\text{lognorm}(360,20)$

The log-normal distribution was selected based on the authors' experience and measurements of operation times in metal industry enterprises. Lognormal distribution is

described by the following formula:

$$f(x) = \frac{1}{\sigma_0 x \sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu_0)^2}{2\sigma_0^2}\right) \tag{1}$$

The mean μ is defined as

$$\mu = \exp\left(\mu_0 + \frac{\sigma_0^2}{2}\right) \tag{2}$$

and the standard deviation

$$\sigma^2 = \exp(2\mu_0 + \sigma_0^2) \cdot \left(\exp(\sigma_0^2) - 1\right) \tag{3}$$

The production program based on the proposed model of the production system provides for cyclic production of the following products: A - 10, B - 20, C - 30, D - 15, B - 30, D - 15, B - 10, A - 20, C - 15, B - 15, C - 10, D - 15, B - 20, D - 15. Table 2 presents 3 variants of machine conversions in the model system for which the tests were carried out. In the first variant, changeover times are increasing, in the second they are constant and in the third they are decreasing.

Table 2. Variants of changeover times of machines for which the model tests were carried out

Variant	Setup time (M ₁₁ , M ₂₁ , M ₃₁)	Setup time (M ₂₁ , M ₂₂ , M ₃₂)	Setup time (M ₁₃ , M ₂₃ , M ₃₃)
V1	lognorm(600,20)	lognorm(400,20)	lognorm(200,20)
V2	lognorm(400,20)	lognorm(400,20)	lognorm(400,20)
V3	lognorm(200,20)	lognorm(400,20)	lognorm(600,20)

The main goal of the simulation model research carried out in the next chapter was to analyze the impact of various variants of machine changeovers and production flow control strategies on the throughput of the tested production system model. Based on the research results, a methodology for rapid prototyping of serial-parallel production systems was proposed.

3 Results of Simulation Research

Based on the production system model presented in Fig. 2, a number of simulation experiments were carried out for various allocations of inter-operation buffer capacity, 3 variants of changeover times shown in Table 2 and two strategies for controlling the production flow in the system. Both proposed control systems were based on cyclic access rules. This means that after processing the product, e.g. on the M11 machine, the products are sent one by one to buffers B1, B2 and B3, etc. In the case of a non-blocking controlled system, if e.g. buffer B2 is completely filled, the system moves to the next buffer and checks B3 whether there is space in it, if so, it sends the product to it, if it does not go to buffer B1, etc. In the case of blocking control, if a given buffer is completely filled, the system waits until there is space in it and then sends it to product.

System throughput tests were conducted for various allocations of inter-operation buffer capacity. Table 3 shows the capacity allocations that were used to conduct the research experiments. It was assumed that the capacities of interoperation buffers range from 1 to 5.

The interoperation buffer capacity allocations used in the experiments were selected from 100 randomly generated capacity allocations, for which the system model throughput was determined in such a way as to present the range of throughput changes depending on the buffer capacity allocation. Each experiment was conducted for 10 days of system operation. Then, the capacity allocation variants were sorted to obtain increasing throughput values. Capacity allocations that achieved similar throughput values were discarded. As a result, 26 buffer capacity allocations were adopted for further research, the variants of which are presented in Table 3. For the purposes of the research, one observation per experiment was assumed.

Table 3. Allocations of interoperational buffer capacity for individual simulation experiments

Experiment	B1	B2	B3	B4	B5	B6	Total	Experiment	B1	B2	B3	B4	B5	B6	Total
1	1	1	1	1	1	1	6	14	5	2	1	1	3	1	13
2	1	1	1	2	1	1	7	15	5	3	1	2	2	3	16
3	1	1	1	2	2	2	9	16	2	4	5	5	4	2	22
4	2	1	1	3	4	3	14	17	5	1	5	5	5	5	26
5	2	1	1	1	3	2	10	18	5	1	5	1	5	5	22
6	2	1	2	2	1	3	11	19	5	3	2	2	5	4	21
7	1	2	2	2	1	1	9	20	2	4	3	5	1	2	17
8	1	2	3	4	4	2	16	21	5	1	5	5	1	1	18
9	2	1	3	4	5	3	18	22	5	1	5	5	1	5	22
10	2	3	2	1	5	5	18	23	5	1	5	5	5	1	22
11	5	1	1	5	5	5	22	24	5	1	5	5	5	5	26
12	5	1	1	1	5	5	18	25	5	5	1	1	1	1	14
13	4	2	2	1	1	4	14	26	5	5	5	5	5	5	30

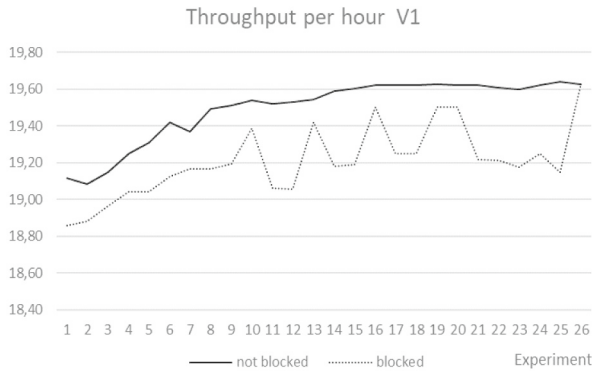
Figure 3 shows the throughput of the system model for the V1 variant of changeover times and two production flow planning strategies.

As shown by the research results presented in the charts in Fig. 3, in the case of variables (decreasing variant V1 or constant changeover times V2), the production control strategy without blocking gives better throughput values for practically all allocations of inter-operation buffer capacity than with blocking.

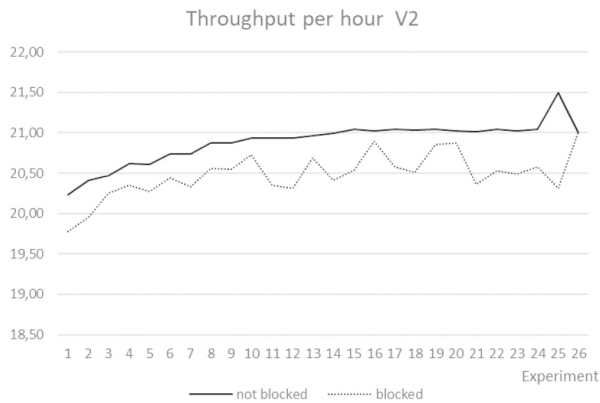
For variants V1 and V2, the use of a blocking production control strategy results in much greater variability of system throughput for different buffer capacity allocations. In the case of the V1 variant, the highest efficiency was obtained for the allocation of maximum buffer capacities ($B1 = 5, B2 = 5, B3 = 5, B4 = 5, B6 = 5$) (both for the flow strategy with and without blocking - Experiment 26). For the V2 variant, the highest model throughput was achieved for experiment 25 with the strategy without blocking (a

much worse result was obtained for the strategy with blocking). The greatest variability in model throughput for individual experiments occurred for the V3 variant with the no-blocking strategy.

a)



b)



c)

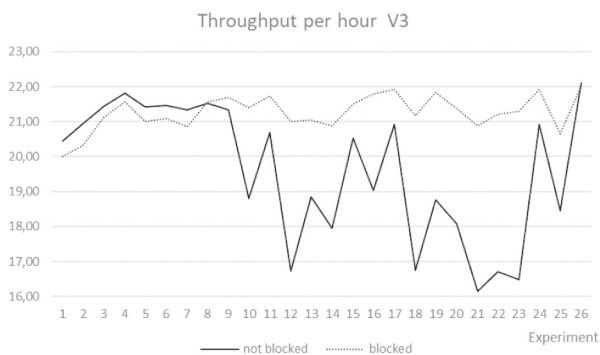


Fig. 3. Productivity per hour for a) increasing b) constant and c) decreasing setup times

From the graph shown in Fig. 3c, it appears that there are buffer capacity allocations for the non-blocking flow strategy that result in a drastic drop in system throughput (for example, experiments 21, 22, and 23) where the system achieves capacity below 17 pcs/h. The highest throughput of the tested model was achieved for the V3 variant (increasing changeover times) for the maximum capacities of inter-operation buffers (experiment 26).

4 Conclusions

The article examines the impact of changing changeover time variants and production flow control strategies in a serial-parallel production system model on throughput using a computer simulation method. Based on the research conducted, the following conclusions can be drawn regarding the tested model:

- in the case of decreasing and constant changeover times, the production flow strategy without blocking gives better efficiency values than with blocking,
- in the case of increasing changeover times, the blocking production flow strategy gives better throughput values for the allocation of large inter-operation buffer capacities,
- in the case of a non-blocking flow strategy with decreasing and constant changeover times, increasing the buffer capacity resulted in increasing system efficiency,
- in the case of the production flow strategy with blocking, for the model variant with increasing changeover times, increasing the capacity of inter-operation buffers resulted in increasing system efficiency,
- in the case of a non-blocking production flow strategy, for the model variant with increasing changeover times, there are variants of buffer allocation that result in a significant reduction in the efficiency of the modeled production system.

Based on the research conducted, a methodology for rapid prototyping of serial-parallel production systems was developed using the computer simulation method. It includes the following steps:

1. Determining the structure of the serial-parallel production system model (production resources, inter-operation buffers, connections, production flow strategies).
2. Determining unit times and changeover times for resources.
3. Determining the maximum and minimum sizes of inter-operation buffers.
4. Generating random allocations of inter-operation buffers based on specific ranges (the larger the capacity range, the greater the number of randomly generated allocation combinations - the number of allocations was arbitrarily set from 100 to 1000).
5. Determining the parameters of simulation tests (products, size of production batches, scope of tests, etc.).
6. Conducting preliminary simulation tests for all randomly generated buffer allocations.
7. Sort the test results in ascending order.
8. Removal of variants for similar throughput values (reduction of the number of cases).
9. Determining the production flow variant (increasing, constant or decreasing changeover times).

10. Selection of the production flow control strategy.
11. Verification of test results for the selected production flow strategy.
12. Select buffer allocations and production flow strategies that achieve maximum model throughput.

As part of further research, the impact of changing the reliability of individual resources on the throughput of a serial-parallel production system will be analyzed.

References

- Antonelli, D., Litwin, P., Stadnicka, D.: Multiple system dynamics and discrete event simulation for manufacturing system throughput evaluation. *Procedia CIRP* **78**, 178–183 (2018). <https://doi.org/10.1016/j.procir.2018.08.312>
- Barrera-Diaz, C.A., Oscarsson, J., Lidberg, S., Sellgren, T.: Discrete event simulation output data-handling system in an automotive manufacturing plant. *Procedia Manuf.* **25**, 23–30 (2018). <https://doi.org/10.1016/j.promfg.2018.06.053>
- Bemmami, K.E., David, P.: Managing the use of simulation in systems engineering: an industrial state of practice and a prioritization method. *Comput. Ind.* **131**, 103486 (2021). <https://doi.org/10.1016/j.compind.2021.103486>
- Diering, M., Dyczkowski, K., Hamrol, A.: Rating system analysis in quality engineering based on fuzzy similarity. *J. Multiple Valued Logic Soft Comput.* **32**(3–4), 277–292 (2019)
- Dinter, R.V., Tekinerdogan, B., Catal, C.: Predictive maintenance using digital twins: a systematic literature review. *Inf. Softw. Technol.* **151**, 107008 (2022). <https://doi.org/10.1016/j.infsof.2022.107008>
- Ebni, M., Hosseini Bamakan, S.M., Qu, Q.: Digital twin based smart manufacturing; from design to simulation and optimization schema. *Procedia Comput. Sci.* **221**, 1216–1225 (2023). <https://doi.org/10.1016/j.procs.2023.08.109>
- Guzman-Moratto, H., Uribe-Martes, C., Neira-Rodado, D.: Improving productivity using simulation: case study of a mattress manufacturing process. *Procedia Comput. Sci.* **198**(2020), 650–655 (2021). <https://doi.org/10.1016/j.procs.2021.12.301>
- Hamrol, A., Kujawińska, A., Božek, M.: Quality inspection planning within a multistage manufacturing process based on the added value criterion. *Int. J. Adv. Manuf. Technol.* **108**, 1399–1412 (2020). <https://doi.org/10.1007/s00170-020-05453-0>
- Herps, K., Dang, Q.-V., Martagan, T., Adan, I.: A simulation-based approach to design an automated high-mix low-volume manufacturing system. *J. Manuf. Syst.* **64**, 1–18 (2022). <https://doi.org/10.1016/j.jmsy.2022.05.013>
- Kašćak, J., Husár, J., Knapčíková, L., Trojanowska, J., Ivanov, V.: Conceptual use of augmented reality in the maintenance of manufacturing facilities. In: Trojanowska, J., Kujawińska, A., Machado, J., Pavlenko, I. (eds.) *MANUFACTURING 2022. LNME*, pp. 241–252. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-99310-8_19
- Kłos, S., Patalas-Maliszewska, J.: Analyses of manufacturing system matrix structure for preventive maintenance using computer simulation. *Acta Mechanica Slovaca* **23**(1), 44–48 (2019). <https://doi.org/10.21496/ams.2019.009>
- Li, Y., Xia, T., Chen, Z., Pan, E.: Multiple degradation-driven preventive maintenance policy for serial-parallel multi-station manufacturing systems. *Reliab. Eng. Syst. Saf.* **230**, 108905 (2023). <https://doi.org/10.1016/j.ress.2022.108905>
- Mourtzis, D.: Simulation in the design and operation of manufacturing systems: state of the art and new trends. *Int. J. Prod. Res.* **58**(7), 1927–1949 (2020). <https://doi.org/10.1080/00207543.2019.1636321>

- Negahban, A., Smith, J.S.: Simulation for manufacturing system design and operation: literature review and analysis. *J. Manuf. Syst.* **33**(2), 241–261 (2014). <https://doi.org/10.1016/j.jmsy.2013.12.007>
- Sadar, M.P., Rajmore, K.G., Rodge, M.K., Kumar, K.: Digital manufacturing approach for process simulation and layout optimization. *Mater. Today Proc.* (2022). <https://doi.org/10.1016/j.matpr.2022.10.003>
- Santos, R., Toscano, C., de Sousa, J.P.: A new simulation-based approach in the design of manufacturing systems and real-time decision making. *IFAC-PapersOnLine* **54**(1), 282–287 (2021). <https://doi.org/10.1016/j.ifacol.2021.08.033>
- Segovia, M., Garcia-Alfaro, J.: Design, modeling and implementation of digital twins. *Sensors* **22**(14) (2022). <https://doi.org/10.3390/s22145396>
- Shen, Y., Zhang, X., Shi, L.: Joint optimization of production and maintenance for a serial–parallel hybrid two-stage production system. *Reliab. Eng. Syst. Saf.* **226**, 108600 (2022). <https://doi.org/10.1016/j.res.2022.108600>
- Tao, F., Xiao, B., Qi, Q., Cheng, J., Ji, P.: Digital twin modeling. *J. Manuf. Syst.* **64**, 372–389 (2022). <https://doi.org/10.1016/j.jmsy.2022.06.015>
- de Sousa Junior, W. T., Barra Montevechi, J.A., de Carvalho Miranda, R., Teberga Campos, A.: Discrete simulation-based optimization methods for industrial engineering problems: a systematic literature review. *Comput. Ind. Eng.* **128**, 526–540 (2019). <https://doi.org/10.1016/j.cie.2018.12.073>
- Varela, M.L.R., et al.: Collaborative paradigm for single-machine scheduling under just-in-time principles: total holding-tardiness cost problem. *Manage. Prod. Eng. Rev.* **9**(1), 90–103 (2018). <https://doi.org/10.24425/119404>
- Ye, Z., Yang, H., Cai, Z., Si, S., Zhou, F.: Throughput evaluation of serial-parallel manufacturing systems based on the impact of heterogeneous feedstocks on machine degradation. *Reliab. Eng. Syst. Saf.* **207**, 107319 (2021). <https://doi.org/10.1016/j.res.2020.107319>
- Zhu, M., Zhou, X.: Hybrid opportunistic maintenance policy for serial-parallel multi-station manufacturing systems with spare part overlap. *Reliab. Eng. Syst. Saf.* **236**, 109304 (2023). <https://doi.org/10.1016/j.res.2023.109304>
- Zhu, M., Zhou, X.: Hypergraph-based joint optimization of spare part provision and maintenance scheduling for serial-parallel multi-station manufacturing systems. *Reliab. Eng. Syst. Saf.* **225**, 108619 (2022). <https://doi.org/10.1016/j.res.2022.108619>



Ensuring the Stability of Production Processes Using Statistical Models

Łukasz Łampika , Dagmara Łapczyńska , Joanna Kocharńska , Anna Burduk^(✉),
and Kamil Musiał 

Wroclaw University of Science and Technology, Wroclaw, Poland
anna.burduk@pwr.edu.pl

Abstract. The stability of production processes is critical for companies to deliver products to customers on time and to specification. In mass production, where a large number of machines and equipment are used, processes are multistage and product variety is high, the possibilities for effective analysis depend largely on the level of implementation of information techniques that can increase the availability of process data. In turn, increased data availability provides a more complete picture of production processes, the changes that are taking place and their impact on quality and stability. With the increasing number of information techniques available, the amount of data generated by the manufacturing industry (process records, events, images, parameters) is expected to grow exponentially. However, access to data alone is not sufficient. To make the data useful for Root Cause Analysis (RCA), it must be analyzed, interpreted and visualized. This paper presents a comparison, evaluation and selection of the type of control cards used to monitor and control the quality performance of manufactured products. It was assumed that the values monitored on the control cards should be able to be represented as sets of non-conforming products (product fractions) in the whole population of manufactured products.

Keywords: Control cards · production stability · Root Cause Analysis

1 Introduction

The control charts are based on the assumption that process variability is due to two types of causes: natural and special causes. Natural causes are always present in the process and are unavoidable under the given conditions. Examples of natural causes are the changing concentration of a worker or changing ambient temperatures. There are usually many such causes, but none of them play a dominant role or show significant changes over time. Special causes affect the process randomly, occur occasionally and are identifiable because they have a significant effect on the process [1–4]. Examples of such causes could be equipment failure, worker error or a change in the quality of supplied components [5–7].

The control charts are designed to distinguish between natural process variability and special variability, thereby capturing quality problems that can reasonably be expected

to be the result of a special cause. A process with points outside the control limits is called an 'unstable process'. The upper (UCL) and lower (LCL) control limits are the same distance from the center line, equal to 3 standard deviations [6, 7].

A control chart can detect a change in a specific cause, but it cannot identify or solve the problem. Therefore, the use of control charts alone is not sufficient [8, 9, 12]. Control charts can indicate an out-of-control condition when one or more points are outside the control limits or when the plotted points form a non-random pattern. There are several types of such arrangements.

A cyclic system appears on the chart when a process is subjected to a cyclic change that causes the value of the measured characteristic to increase and decrease with some regularity [11]. Such a picture of the process is not random, even though the process may not exceed the control limits.

2 Types of Control Cards

There are seven basic types of control cards. Their classification according to the type of values observed and the number of observations in a sample is shown in Fig. 1. The number of observations in a sample is the number of observations that make up a point plotted on a control card. If the number of observations in a sample is 1, this means that each point on the control card is a single measurement observed in the process. A larger number of observations in the sample means that the point on the control chart is the average value of all the observations.

The literature mentions two types of observed values: numeric and attribute values [8]. Numerical values are values that can be assessed numerically and are measurable on a numerical scale. Attribute values can only be described verbally, usually using a scale. Values can only be described verbally, usually using a scale. The advantage of numerical values is the accuracy of the information they provide. Attribute values are characterised by the unambiguousness of the information, especially concerning classifying products into conforming and nonconforming with customer specifications [8–10]. For attribute values, the key to classification is not the number of observations in a sample, but the stability of this number over time. In Fig. 1, the number of observations in a sample is denoted as n and the names of the control card types are shown in the last column [8, 13].

Numerical values are monitored on different control charts depending on the number of observations in the sample. For numerical control charts with the number of observations $n > 10$ in the sample, the \bar{X} -s chart is used, which uses the standard deviation to calculate the control limits and the arithmetic mean of the sample to calculate the central line. For the number of observations $n < 10$, the \bar{X} -R chart is used, where the control limits are influenced by the moving range, which is the average difference between two consecutive samples, and the central line is determined by the arithmetic mean of the samples. For single measurements, i.e., $n = 1$, an x-MR control card was constructed which differs from the \bar{X} -R control chart only in the number of observations.

All control cards for numerical data consist of a pair of two cards: one used to monitor the process mean and the other to monitor the process variability. An exception to this rule is the x-MR card, for which some researchers recommend using only the x card, arguing that process changes visible on the R card are also visible on the x card [13].

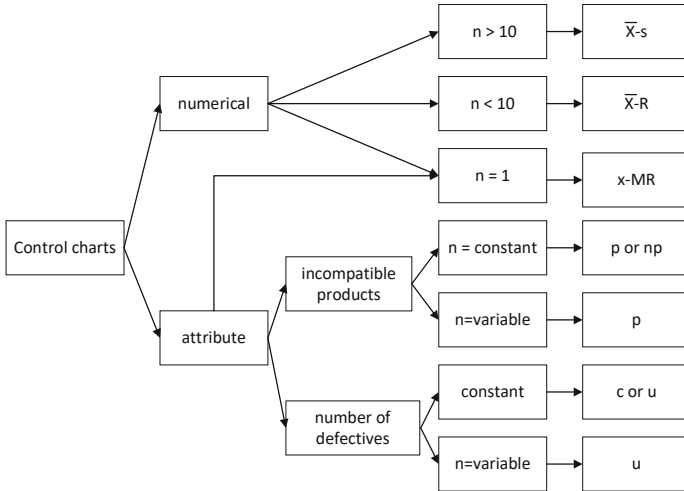


Fig. 1. Basic types of control cards [14–16].

Control charts for numerical characteristics are based on the assumption that the distribution of the characteristic plotted on the chart is approximately normal. Even if the actual distribution is not normal, the central limit theorem means that adjusting the limits of the control charts is correct. [12, 13]. According to this theorem, the distribution of the mean value of the sample tends to follow a normal distribution as the size of the sample increases [12]. The error made when the actual distribution is not normal has been tested by many researchers, including Burr (1967), Schilling and Nelson (1976), Chan, Hapuarachchi and Macpherson (1988) and Yourstone and Zimmer (1992). Their research shows that the normality assumption is sufficiently robust and can be used for sample sizes above four and when the actual distribution is not highly different from normal [13].

Attribute values are divided into those that measure the number of non-conforming products and those that measure the number of defects in a product or group of products. A defect is defined as any fault in the product that is not acceptable to the customer.

A non-conforming product can have multiple defects. As shown in Fig. 1, the x-MR card is the only one that can monitor both numerical and attribute values.

Non-conforming products, both for a fixed and for a variable number of observations in a sample, can be monitored using control cards p . This type of card shows the proportion of non-conforming products in the group of all products in a given sample (fraction). To monitor the number of non conforming products with a fixed sample size, the card np has been designed. The p and np -cards use a binomial distribution, but the measurements must meet the following 4 conditions [17]:

- The range of possible non-conforming items must consist of n different items (the number of items from which the n non-conforming items are derived must be specified);
- Each of the n individual items is classified as having or not having some attribute;

- Let p be the probability that an item has an attribute; p must be the same for all n items in the sample (all items in the sample must have the same probability of being classified as conforming or non-conforming);
- The probability of an item having an attribute is not influenced by whether the previous item had the attribute (observations are independent of each other).

The c card is used to track the number of defects in a sample of defined size, while the u card is used to monitor the number of defects in a product for both constant and variable sample sizes [12, 13]. The c and u control charts are based on a Poisson distribution, but the following conditions must be met to allow the assumption that the statistical distribution adequately matches the distribution of the data collected [17]:

- the measurements must be discrete numbers;
- the counts must occur in a well-defined time or space;
- the counts are independent of each other and the probability of a count is proportional to the size of the area of opportunity (the probability of a defect occurring is independent of where it occurs);
- the occurrences are rare compared to the possible occurrences (the number of occurrences of defects is less than the area of opportunity would suggest).

3 Selecting the Type of Control Card for Mass-Produced Products and Visual Defect Assessment

In order to plot control cards, it is necessary to determine the sample size and frequency. The selection of an appropriate control card is only sometimes evident and straightforward. Manufactured products can be subjected to quality control based on physical and chemical (chemical composition of the product, strength parameters), dimensional and visual characteristics. Therefore, the following should be considered when choosing a control card:

- the statistical distribution on which the card is based;
- type of observed data;
- sampling method;
- sampling costs;
- the accuracy with which the card will detect changes in the process.

In the case of visual assessment, attribute-based assessment (conforming or non-conforming product) is most commonly used. For such data, it is necessary to determine whether the characteristics measured are non-conforming products or defects found on these products. The choice of the type of control card used to monitor sets of non-conforming products is therefore limited to the following cards: $x-MR$, p and np .

Another piece of information used to narrow down the pool of possible control cards to use is the sample size. In this case, the frequency was assumed to be constant, and the sample size variable depended on the production volume. For this reason, a card measuring only the number of non-compliant products cannot be used. The number of non-compliant products without data on the total number of products produced can be misleading. The increase in the number of non-compliant products may be due to increased production and not to a change in the process. The only control cards that

matched the data collected in the model of non-conforming products are the x - MR and p -cards. The x - MR card consists of the x card - called the individual measurements card - and the MR card - called the moving range card. As the name suggests, the x card consists of single measurements, i.e., the sample size is $n = 1$. The MR card measures the differences between successive x card values.

Number cards are based on empirical data to calculate limits. In contrast, attribute cards are based on theoretical distributions, and the p -card's control limits are also strongly dependent on the sample size. This difference means that for attribute cards it is necessary to check whether the theoretical distribution is appropriate for the observed data, which is not necessary in the case of quantitative cards [18–20].

4 An Example to Illustrate the Difference Between the p -Card and the x - MR Card

Table 1 contains 28 measurements representing 28 production days. Each row contains data for the corresponding production day. Column 2 shows the number of non-compliant products detected and column 3 the number of all products inspected on that day. The fraction of non-compliant products, recorded in column 4, is the quotient of the values from column 2 and column 3. These will be the measurement values recorded on the control chart charts. The following columns are calculations for the p and x - MR cards.

The control card contains a central line representing the average value of the measured quality characteristic. The next two horizontal lines are called control limits. The line above the center line is the Upper Control Limit (UCL) and the line below the center line is the Lower Control Limit (LCL). These two lines are calculated and selected so that, for a stable process with natural variability, the points from the samples lie between them. The formula for the value of the center line for a p -card with averaged sample size [12]:

$$\bar{p} = \frac{\sum_{i=1}^m D_i}{\sum_{i=1}^m n_i} \quad (1)$$

m - number of samples

D_i - number of non-compliant products in the sample on the i -th day

n_i - sample size

Substituting the data from Table 2 into Formula (1), we obtain:

$$\bar{p} = \frac{\sum_{i=1}^{28} D_i}{\sum_{i=1}^{28} n_i} = \frac{6961}{226502} = 0.031$$

To calculate the Upper and Lower Control Limits for a p -card with an average sample size, the average sample size must first be calculated:

$$\bar{n} = \frac{\sum_{i=1}^m n_i}{m} \quad (2)$$

After the substitution we get:

$$\bar{n} = \frac{\sum_{i=1}^{28} n_i}{28} = \frac{226502}{28} = 8089.36$$

Table 1. Comparison between the p -card and x - MR card for the sample data from Ronal Company

Days	Number of non-compliant products	Number of products tested	Fraction of non-compliant products	p -card			x - MR card		
				\bar{p}	LCL	UCL	\bar{x}	LCL	UCL
1	349	7177	0.049	0.031	0.025	0.036	0.031	0.012	0.049
2	155	6834	0.023	0.031	0.025	0.036	0.031	0.012	0.049
3	175	6942	0.025	0.031	0.025	0.036	0.031	0.012	0.049
4	123	4573	0.027	0.031	0.025	0.036	0.031	0.012	0.049
5	235	6740	0.035	0.031	0.025	0.036	0.031	0.012	0.049
6	253	7003	0.036	0.031	0.025	0.036	0.031	0.012	0.049
7	208	6965	0.030	0.031	0.025	0.036	0.031	0.012	0.049
8	142	7344	0.019	0.031	0.025	0.036	0.031	0.012	0.049
9	155	7298	0.021	0.031	0.025	0.036	0.031	0.012	0.049
10	184	7245	0.025	0.031	0.025	0.036	0.031	0.012	0.049
11	273	7771	0.035	0.031	0.025	0.036	0.031	0.012	0.049
12	240	7474	0.032	0.031	0.025	0.036	0.031	0.012	0.049
13	214	7756	0.028	0.031	0.025	0.036	0.031	0.012	0.049
14	215	7689	0.028	0.031	0.025	0.036	0.031	0.012	0.049
15	222	7615	0.029	0.031	0.025	0.036	0.031	0.012	0.049
16	153	9956	0.015	0.031	0.025	0.036	0.031	0.012	0.049
17	295	9514	0.031	0.031	0.025	0.036	0.031	0.012	0.049
18	327	9408	0.035	0.031	0.025	0.036	0.031	0.012	0.049
19	249	9514	0.026	0.031	0.025	0.036	0.031	0.012	0.049
20	210	9626	0.022	0.031	0.025	0.036	0.031	0.012	0.049
21	312	9189	0.034	0.031	0.025	0.036	0.031	0.012	0.049
22	433	9513	0.046	0.031	0.025	0.036	0.031	0.012	0.049
23	388	9269	0.042	0.031	0.025	0.036	0.031	0.012	0.049
24	254	8725	0.029	0.031	0.025	0.036	0.031	0.012	0.049
25	241	8898	0.027	0.031	0.025	0.036	0.031	0.012	0.049
26	230	8868	0.026	0.031	0.025	0.036	0.031	0.012	0.049
27	350	8780	0.040	0.031	0.025	0.036	0.031	0.012	0.049
28	376	8816	0.043	0.031	0.025	0.036	0.031	0.012	0.049

The value of the average sample size does not have to be a natural number, and fractions will be important in calculating control limits. To calculate them, as in the case of number cards, three times the deviation of the estimator \bar{p} is used, but in the case of

the p -card, this is because they work well in practice [12].

$$LCL = \bar{p} - 3\sqrt{\frac{\bar{p}(1 - \bar{p})}{\bar{n}}} \tag{3}$$

$$UCL = \bar{p} + 3\sqrt{\frac{\bar{p}(1 - \bar{p})}{\bar{n}}} \tag{4}$$

After substituting the values into Formulas (3) and (4), we obtain:

$$LCL = \bar{p} - 3\sqrt{\frac{\bar{p}(1 - \bar{p})}{\bar{n}}} = 0.031 - 3\sqrt{\frac{0.031(1 - 0.031)}{8089.36}} = 0.025$$

$$UCL = \bar{p} + 3\sqrt{\frac{\bar{p}(1 - \bar{p})}{\bar{n}}} = 0.031 + 3\sqrt{\frac{0.031(1 - 0.031)}{8089.36}} = 0.036$$

After calculating the main parameters of the p control card, the same must be done for the x - MR card.

The center line of the x card is the arithmetic mean of the individual measurements and is calculated using the formula [12]:

$$\bar{x} = \frac{\sum_{i=1}^m x_i}{m} \tag{5}$$

x_i - value of a single measurement.

After substituting the fractional values of the non-compliant products for each day in the x_i spaces:

$$\bar{x} = \frac{\sum_{i=1}^{28} x_i}{28} = \frac{0, .857}{28} = 0.031$$

The formulas for the control limits depend on a measure of the moving average range \overline{MR} for a period of m days.

$$MR_i = |x_i - x_{i+1}| \tag{6}$$

$$\overline{MR} = \frac{\sum_{i=1}^m MR_i}{m} \tag{7}$$

$$LCL = \bar{x} - 3\frac{\overline{MR}}{d_2} \tag{8}$$

$$UCL = \bar{x} + 3\frac{\overline{MR}}{d_2} \tag{9}$$

d_2 - constant value.

Substituting the values from Table 1 into Formulae (7), (8) and (9) and finding the d_2 value for $n = 2$ in the statistical tables, meaning that MR is calculated as the difference of two values, we obtain the following:

$$\overline{MR} = \frac{\sum_{i=1}^{28} MR_i}{28} = \frac{0.187}{28} = 0.0067$$

$$LCL = \bar{x} - 3 \frac{\overline{MR}}{d_2} = 0.031 - 3 \frac{0.0067}{1.128} = 0.031 - (2.66)(0.0067) = 0.012$$

$$UCL = \bar{x} + 3 \frac{\overline{MR}}{d_2} = 0.031 + 3 \frac{0.0067}{1.128} = 0.031 + (2.66)(0.0067) = 0.049$$

The data from Table 1 allows to plot the *p*-card and *x-MR* card together in Fig. 2. The boundaries on the *p*-card are much narrower, and therefore, a significant number of points are outside the control limits. The *x-MR* card shows a stable process. There is no point outside the control limits. The span of the limits for the *p*-card is more than 3 times smaller than for the *x-MR* card. The *p*-card shows 10 points outside the control limits.- They represent $10/28 = 0.36$ of all observations. In practice, this means that each of these points should be analyzed for a specific cause.

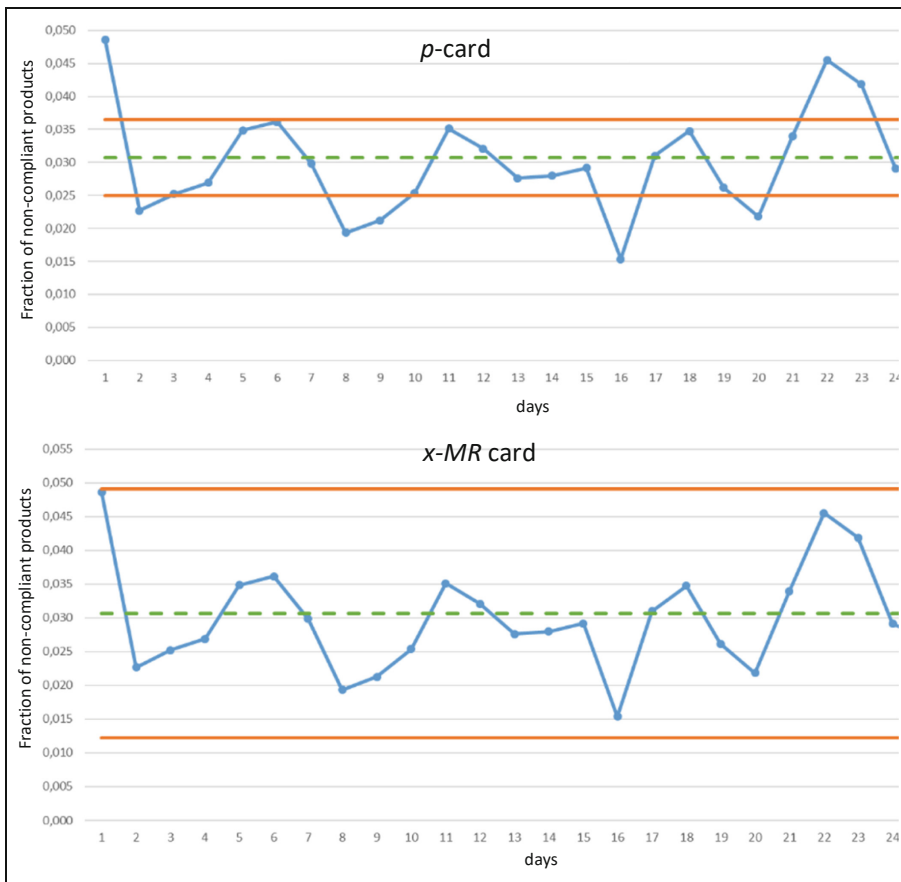


Fig. 2. *p* and *x-MR* control charts for example data.

The significant difference in the choice of control limits forces us to consider which of them is correct, allowing us to effectively separate points with special causes from

the natural variability of the process. Too narrow limits can increase the number of false signals, which can lead to a decrease in the commitment and confidence of the company's employees. At the same time, many false signals mean increased costs in searching for the sources of these alarms [21]. In turn, limits that are too wide make it difficult to detect more minor process changes and provide no opportunity to eliminate them and thus improve the process [22, 23].

Another set of data has been prepared to better understand how the p -card limits are calculated. This is the same data, but the number of non-compliant products and the number of inspected products have been divided by 3. This action allows the same values to be maintained for the proportion of non-compliant products; only the sample size is reduced. This can be related to a situation where the process has not changed but the number of orders has decreased. The proportion of non-compliant products in the population is the same, but fewer products have been tested. The data are shown in Table 2.

Looking at Table 2, it can be seen that only the values of the p -card control limits have changed. The centre line for the p -card has remained unchanged because the proportion of non-conforming products in the controlled products has not changed. The calculations for the x -MR card did not change, as this card does not depend in any way on the sample size, but only on the individual measurements from which the limits and the centreline are calculated. The spread between the ULC and LCL of the p -card is 0.02, whereas previously it was 0.011. It has almost doubled. A significant difference, given that the proportion of non-compliant products has stayed the same. This sensitivity to sample size follows from Eqs. (3) and (4):

$$LCL = \bar{p} - 3\sqrt{\frac{\bar{p}(1 - \bar{p})}{\bar{n}}}$$

$$UCL = \bar{p} + 3\sqrt{\frac{\bar{p}(1 - \bar{p})}{\bar{n}}}$$

The width of the card limits p is inversely proportional to the sample size n . If p is constant, this is the only factor affecting the control limits.

Figure 3 shows plotted control charts for the modified data. They show how significantly the changed control limits of the p -card have affected the process image. Of the previous 10 points, 6 remain out of limits. The process is still not stabilized, but it is conceivable that the sample size can be further reduced until the p -card shows a stabilized process. At the same time the x -MR card has not changed and therefore, the process remains stable.

The argument against using p -type control charts is to be sure whether the theoretical model they are based on corresponds to the data we observe. The need for verification is not a reason to reject using p -cards. However, the above example shows that the statistical model on which the p -card is based does not match the observations presented and, more importantly, needs to be more robust to significant changes in sample size that occur under production conditions.

Table 2. Comparison of p and x - MR card for modified data from Ronal Company

Days	Number of non-compliant products	Number of products tested	Fraction of non-compliant products	p -card			x - MR card		
				\bar{p}	LCL	UCL	\bar{x}	LCL	UCL
1	116	2392	0.049	0.031	0.021	0.041	0.031	0.012	0.049
2	52	2278	0.023	0.031	0.021	0.041	0.031	0.012	0.049
3	58	2314	0.025	0.031	0.021	0.041	0.031	0.012	0.049
4	41	1524	0.027	0.031	0.021	0.041	0.031	0.012	0.049
5	78	2247	0.035	0.031	0.021	0.041	0.031	0.012	0.049
6	84	2334	0.036	0.031	0.021	0.041	0.031	0.012	0.049
7	69	2322	0.030	0.031	0.021	0.041	0.031	0.012	0.049
8	47	2448	0.019	0.031	0.021	0.041	0.031	0.012	0.049
9	52	2433	0.021	0.031	0.021	0.041	0.031	0.012	0.049
10	61	2415	0.025	0.031	0.021	0.041	0.031	0.012	0.049
11	91	2590	0.035	0.031	0.021	0.041	0.031	0.012	0.049
12	80	2491	0.032	0.031	0.021	0.041	0.031	0.012	0.049
13	71	2585	0.028	0.031	0.021	0.041	0.031	0.012	0.049
14	72	2563	0.028	0.031	0.021	0.041	0.031	0.012	0.049
15	74	2538	0.029	0.031	0.021	0.041	0.031	0.012	0.049
16	51	3319	0.015	0.031	0.021	0.041	0.031	0.012	0.049
17	98	3171	0.031	0.031	0.021	0.041	0.031	0.012	0.049
18	109	3136	0.035	0.031	0.021	0.041	0.031	0.012	0.049
19	83	3171	0.026	0.031	0.021	0.041	0.031	0.012	0.049
20	70	3209	0.022	0.031	0.021	0.041	0.031	0.012	0.049
21	104	3063	0.034	0.031	0.021	0.041	0.031	0.012	0.049
22	144	3171	0.046	0.031	0.021	0.041	0.031	0.012	0.049
23	129	3090	0.042	0.031	0.021	0.041	0.031	0.012	0.049
24	85	2908	0.029	0.031	0.021	0.041	0.031	0.012	0.049
25	80	2966	0.027	0.031	0.021	0.041	0.031	0.012	0.049
26	77	2956	0.026	0.031	0.021	0.041	0.031	0.012	0.049
27	117	2927	0.040	0.031	0.021	0.041	0.031	0.012	0.049
28	125	2939	0.043	0.031	0.021	0.041	0.031	0.012	0.049

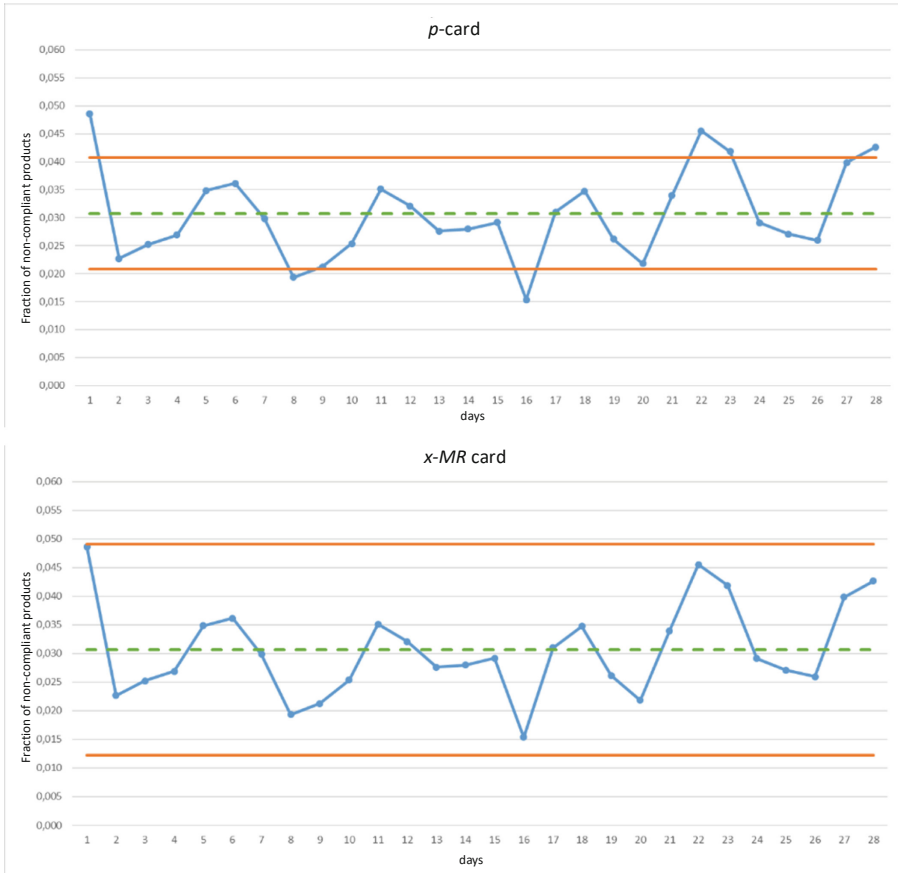


Fig. 3. *p* and *x-MR* control cards for changed sample data

5 Conclusion

This paper provides a comparison, assessment, and selection of control card types employed for overseeing and managing the quality performance of produced goods. The premise is that the values observed on these control cards should be capable of being depicted as sets of non-conforming products (product fractions) within the entire population of manufactured items. Increasing data availability offers a more comprehensive overview of production processes, highlighting the ongoing changes and their effects on quality and stability. As the manufacturing industry continues to benefit from a growing array of information techniques, the volume of generated data, including process records, events, images, and parameters, is anticipated to expand exponentially. Nevertheless, mere access to data is inadequate. For effective Root Cause Analysis (RCA), the data must undergo analysis, interpretation, and visualization to be truly beneficial.

In conclusion, when analyzing sets of non-conforming products (product fractions) in the whole population of manufactured products, using *x-MR* control cards as card

x; individual measurements is recommended. Such a card guarantees control limits resulting from empirical data and simultaneously allows the measure of attribute data, such as the fraction of non-compliant products. For future research the integration of these statistical models with emerging technologies in the field of manufacturing is planned.

References

1. Elovici, Y., Braha, D.: A decision theoretic approach to data mining. *IEEE Trans. Syst. Man Cybernet. Part A Syst. Hum.* **33**(1), 42–51 (2003)
2. Patalas-Maliszewska, J., Kłos, S., Dostatni, E.: Sustainable business model integrated with the enterprise resource planning system: SBM-ERP. *Bull. Polish Acad. Sci. Tech. Sci.* **70**(6) (2022)
3. Antosz, K., Machado, J., Mazurkiewicz, D., Antonelli, D., Soares, F.: Systems engineering: availability and reliability. *Appl. Sci.* **12**(5), 2504 (2022)
4. Krot, K., Iskierka, G., Poskar, B., Gola, A.: Predictive monitoring system for autonomous mobile robots battery management using the industrial Internet of Things technology. *Materials* **15**(19), 6561 (2022)
5. Shewhart, W.A.: In: Deming, W.E. (ed.) *Statistical Method from the Viewpoint of Quality Control*. Dover Publications, New York (1986)
6. Hamrol, A.: Quality engineering challenges on the way to sustainability. *Manag. Prod. Eng. Rev.* **11**(4), 113–120 (2020)
7. Starzyńska, B., Hamrol, A.: Excellence toolbox: decision support system for quality tools and techniques selection and application. *Total Qual. Manag. Bus. Excell.* **24**(5–6), 577–595 (2013)
8. Kotowska, J., Burduk, A.: Optimization of production support processes with the use of simulation tools. In: *Information Systems Architecture and Technology: Proceedings of 38th International Conference on Information Systems Architecture and Technology–ISAT 2017: Part III*, pp. 275–284. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-67223-6_26
9. Górnicka, D., Burduk, A.: Improvement of production processes with the use of simulation models. In: *Information Systems Architecture and Technology: Proceedings of 38th International Conference on Information Systems Architecture and Technology–ISAT 2017: Part III*, pp. 265–274. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-67223-6_25
10. Diering, M., Dyczkowski, K., Hamrol, A.: Rating system analysis in quality engineering based on fuzzy similarity. *J. Multip. Valued Logic Soft Comput.* **32**(3–4), 277–292 (2019)
11. Golinska-Dawson, P., Werner-Lewandowska, K., Kosacka-Olejnik, M.: Responsible resource management in remanufacturing—framework for qualitative assessment in small and medium-sized enterprises. *Resources* **10**(2), 19 (2021)
12. Montgomery, D.C.: *Introduction to Statistical Quality Control*, 6th edn. Wiley, Jefferson (2009)
13. Deming, M.Y.: *Out of the Crisis*, wyd. 3. Massachusetts Institute of Technology, Cambridge (1986)
14. Woodall, W.H., Montgomery, D.C.: Research issues and ideas in statistical process control. *J. Qual. Technol.* **31**(4), 376–386 (1993)
15. Swanson, R.: *The Quality Improvement Handbook: Team Guide to Tools and Techniques*. CRC Press, Boca Raton (1995)
16. Bendell, T.: A review and comparison of Six Sigma and the Lean organisations. *TQM Magazine* **18**(3), 255–262 (2006)

17. Wheeler, D.J.: *Advanced Topics in Statistical Process Control, The Power of Shewhart's Charts*, 2nd edn. SPC Press, Knoxville (2004)
18. Nelson, L.S.: The Shewhart Control Chart – Test for Special Causes. *J. Qual. Technol.* **16**, 237–239 (2018)
19. Western Electric, *Statistical Quality Control Handbook*, Western Electric Corporation, Indianapolis, pp. 149–183 (1956)
20. Champ, C.W., Woodall, W.H.: Exact Results for Shewhart Control Charts with Supplementary Runs Rules. *Technometrics* **29**(4), 393–399 (1987)
21. Kujawińska, A., et al.: Methodology Supporting the Planning of Machining Allowances in the Wood Industry. In: *International Joint Conference SOCO 2017-CISIS 2017-ICEUTE 2017 León*, pp. 338–347. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-67180-2_33
22. Bożek M., Kujawińska A., Rogalewicz M., Diering M., Gościński P., Hamrol A.: Improvement of catheter quality inspection process. *MATEC Web Conf.* **121**, 05002 (2017)
23. Rogalewicz, M., Kujawińska, A., Feledziak, A.: Ensuring the reliability and reduction of quality control costs by minimizing process variability. *Mainten. Reliabil./Ekspluat. Niezawod.* **25**(2) (2023)



Modern Technologies Supporting the Development of the Automotive Industry

Krzysztof Santarek^(✉) 

Warsaw University of Technology, Warsaw, Poland
krzysztof.santarek@pw.edu.pl

Abstract. The content of the paper is the application of Industry 4.0 technologies throughout the entire product life cycle in the example of the automotive industry. Particular attention was paid to the necessity but also to the difficulties of integrating various phases of the product life cycle. A model for the integration of product life cycle phases using PLM IT systems and the product structure models created by them is presented. The paper consists of 6 sections. The first one presents the factors that enable, determine and limit the use of modern technologies in the automotive sector. The second section defines and explains the concepts of product life cycle and product life cycle management. Product life cycle management is a condition for the effective and efficient solution of many problems, especially those related to sustainable development. This requires the integration of activities carried out in various phases of the product life cycle. An example of an approach to solving this problem is discussed in section three. The content of the fourth section is a “map” of the applications of Industry 4.0 technologies against the background of the car life cycle. Section five discusses the possible impact of Industry 4.0 technologies on the future development of the automotive industry. Conclusions and summary are included in section six.

Keywords: Industry 4.0 · modern technologies · automotive industry · product life cycle

1 An Introduction

The automotive industry, originating in Europe at the close of the 19th century, continues to wield considerable influence on the national economies of various European nations, Poland being no exception. Within the Polish economic landscape, the automotive sector stands as a pivotal industry, significantly contributing to employment, industrial production, investments, and exports. Notably, in the year 2021, the automotive sector employed 513.9 thousand individuals in Poland. This employment figure constituted 7.3% of the total workforce within the industry. Throughout this period, the production output in the automotive sector reached 260.8 thousand units, comprising both passenger cars and 178.6 thousand utility vehicles. It is noteworthy that Poland holds a prominent position as one of the leading producers of parts and components for the automotive industry in Central and Eastern Europe. Moreover, in the year 2021, the automotive sector in

Poland secured the second position in terms of the magnitude of investment expenditure [1]. This underscores the sector's enduring significance and robust presence within the nation's economic landscape.

From the very beginning, the automotive industry has been a place of creation and a receptive recipient of significant technical and organizational innovations, starting from Henry Ford's assembly line [2], through various forms of production automation (CNC machine tools, coordinate measuring machines (CMM), industrial robots, Flexible Manufacturing Systems (FMS), Computer Integrating Manufacturing (CIM), et al.), new materials and technologies for their production and processing, advanced product design technologies (PLM, CAD, CAM, CAP, CAQ, et al.), IT systems supporting production management (MRP/ERP, PPC, SCM, CRM, et al.), following just-in-time and lean management [3, 4]. Also currently, the automotive industry is the avant-garde among users (and creators) of innovations conventionally called Industry 4.0. Cars are the most complex products manufactured for mass consumers. This applies to the number of components, the variety of materials from which they are made, as well as the technology of design, production and operation. It is not without reason that the term and concept of Industry 4.0 were born and are intensively developed in Germany, a country with a highly developed automotive and machinery industry [5].

As per the data provided by ACEA (European Automobile Manufacturer's Association), which represents the primary car manufacturers in Europe, the European car industry stands as the most substantial private investor in research and development (R&D). Surpassing even the pharmaceutical and biotechnology sectors, ACEA members alone contributed 32% to the overall European expenditure on R&D in 2020 [1]. Notably, a considerable portion of these expenditures is dedicated to advancing Industry 4.0 technologies. This underscores the pivotal role played by the European automotive sector in driving innovation and technological advancements within the region.

When analyzing the impact of modern technologies on the development of the automotive industry, it is convenient to distinguish factors that condition (force), factors that enable (facilitate), and factors that limit (impede) the development of this industry and the dissemination of modern technologies (in the following, the term modern technologies will be treated as a synonym for Industry 4.0 technologies).

The factors determining the development and dissemination of modern technologies in the automotive industry include:

- large and growing diversity of users' needs, expectations and requirements,
- strong competition in the automotive industry on a global and regional scale,
- availability and rising costs of natural fuels (hydrocarbons),
- a widely accepted paradigm of sustainable development, pressure on environmental protection and the fight against climate change,
- the policy of the EU and Member States supporting activities for sustainable development and, on the other hand, imposing new requirements for producers [6],
- changes in user behaviour regarding the use of means of transport, development and greater availability of public transport and development of individual means of transport (e.g. electric two-wheelers).

Meeting all these requirements is not possible without the development of modern technologies. This is manifested in revolutionary changes in the design of cars, especially

their drive systems (electric cars) and control systems (autonomous cars). The industry, not without resistance, is trying to adapt to these requirements, which becomes possible thanks to factors that enable (facilitate) adaptation to new requirements. These factors include:

- scientific and technical progress, development and increasing availability of new technologies,
- existing research, development and production potential in the automotive industry
- availability of automotive components and developed supply and distribution chains
- existing road and car service infrastructure,
- demographic changes, the growing importance of the so-called human factor, working conditions, ergonomics, and safety, which force automotive companies to look for alternative solutions, including Industry 4.0 technologies.

There are also barriers hindering the dissemination of Industry 4.0 technologies:

- still poor knowledge and awareness of the importance of new technologies among decision-makers and potential users, lack of a clear strategy for technological restructuring of enterprises,
- high costs of acquiring, implementing and operating new technologies about the possible (current) benefits, difficulties in assessing the economic effects of new technologies, lack of practical examples of the use of these technologies, especially in small and medium-sized enterprises,
- lack of stable solutions and the resulting lack of standards,
- competence gap,
- new car design solutions (electric drive) require large investments in infrastructure (production and distribution of electricity, battery charging stations, end-of-life vehicle disposal systems, etc.),
- limited availability of some raw materials necessary for the production of new-generation cars.

The answer to the above problems is innovations (technical and organizational) as well as new approaches to the design, production, operation and use of products after the end of their use, thus covering the entire product life cycle.

The primary objectives of the examined research findings were as follows:

1. To elucidate and scrutinize various product structure models aimed at integrating activities and processes throughout the entire life cycle of an automobile.
2. To pinpoint Industry 4.0 technologies that can be effectively applied at distinct stages of a car's life cycle.
3. To evaluate the potential ramifications of implementing these technologies on the overall effects of the car's life cycle.

2 Product Lifecycle and Product Lifecycle Management

The concept of product life cycle means the time from the moment the idea (concept) of the product is created, through its design, production launch, production, to distribution, sale, use, decommissioning and finally disposal. Generally speaking, three stages can be

distinguished in the product life cycle: production preparation and production, i.e. the beginning of life (BoL); use, i.e. the middle of life (MoL) and withdrawal - the end of use and disposal, i.e. the end of life (EoL), Fig. 1.



Fig. 1. Extended (4-stage) model of a product lifecycle, [7]

Product information is created and evolves at all stages and in all phases of the product life cycle. The product life cycle is a record of the product’s “history” as well as a prediction of its future [7]. The essence of product life cycle management is the integration and coordination of all activities carried out throughout the entire product life cycle, including in particular the management of the information flow about the product that is generated in subsequent stages and phases of the life cycle. The need for product lifecycle management results from many reasons:

- the need for a comprehensive (holistic, systemic, common) approach to all issues related to the design, production, use and disposal of products;
- products and their design, production and operation processes are becoming more and more complicated and require systemic (common) solutions;
- individual stages of the product life cycle are interconnected and cannot be considered and treated in isolation;
- many problems, e.g. related to the product’s impact on the environment, which appear in later stages of the product life cycle, can be effectively solved only at the design stage;

- the service life of many products is long (despite the offer of new products and shortening product life cycles on the market); problems that the user may encounter require solutions at the early stages of the product life cycle;
- the costs of operating a product often exceed the costs of its design and production (as well as the purchase price) many times over, which forces designers and manufacturers to take this fact into account in their decisions;
- increasing importance is attached to problems occurring after the end of product life: collection of used products, recycling, reusing, processing and waste management;
- broadly understood costs incurred during the product life cycle (economic, social, environmental costs) on a global, as well as regional and local scale, have reached a scale that is difficult to accept; their reduction is only possible by looking at the entire product life cycle [7].

3 An Approach to Product Life Cycle Integration

Various product structure models are widely used in subsequent phases and stages of the product life cycle. This concept means a set of product components (parts, subassemblies, assemblies) and their structural, geometric, assembly and other connections. Adopting a unified and unambiguous form of product structure description is a condition not only for the exchange of information between individual stages and phases of the product life cycle, but also for their effective and efficient integration and, as a result, effective management of the product life cycle. Individual phases and stages of the product life cycle use different models of the product structure (called views), which are logically related to each other. The differences between them result from different degrees of advancement of the product design and readiness to start production (see the Manufacturing Readiness Level - MRL model [8]), different information needs of individual stages and phases of the product life cycle, as well as from adopting different perspectives of the product view.

The starting point is the product model created in the PLM system during the design of the product structure (Fig. 2). It constitutes the so-called engineering view (usually presented in the form of a series of interconnected models), including:

- functional structure (specification) of the product (it shows what the product will do and how it will work) [9],
- the structural model of the base product, showing how the product is built, what elements it consists of, what are the spatial (location), and geometric (e.g. dimensional) connections between them, etc.
- structure of product variants and varieties, and also:
- 3D digital model(s) of the product,
- 2D assembly and construction drawings of assemblies, subassemblies, parts, etc.

Product structure models can be in the form of a tree graph (Fig. 2), presented in graphical or tabular form, as well as 2D and 3D geometric drawings. These models are subject to multiple changes during design, which results primarily from the iterative approach to design and the related need to manage technical changes (product design), requirements management, configuration management, and product options and variants.

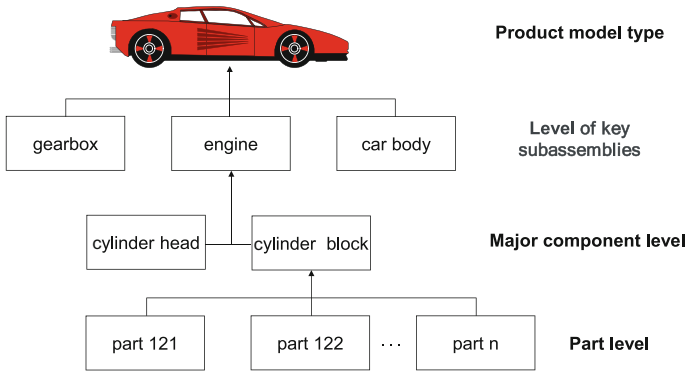


Fig. 2. Diagram of the product structure model (engineering view) source: own work

In subsequent stages and phases of the product life cycle, other product structure models are also used, derivatives of those created in the structural design process. They constitute a subset (“slice”) of models presenting the product structure resulting from design and construction work, enriched with additional elements resulting from the needs and specificity of a particular phase and stage of the product life cycle (Fig. 3). As a rule, product structure models are accompanied by numerous additional information and documents, containing descriptions of processes, methods of operation, instructions for performing operations, lists of additional components that are not part of the product structure (e.g. workshop aids, auxiliary and consumable materials, etc.), lists of technological machines and their specifications, etc. [7].

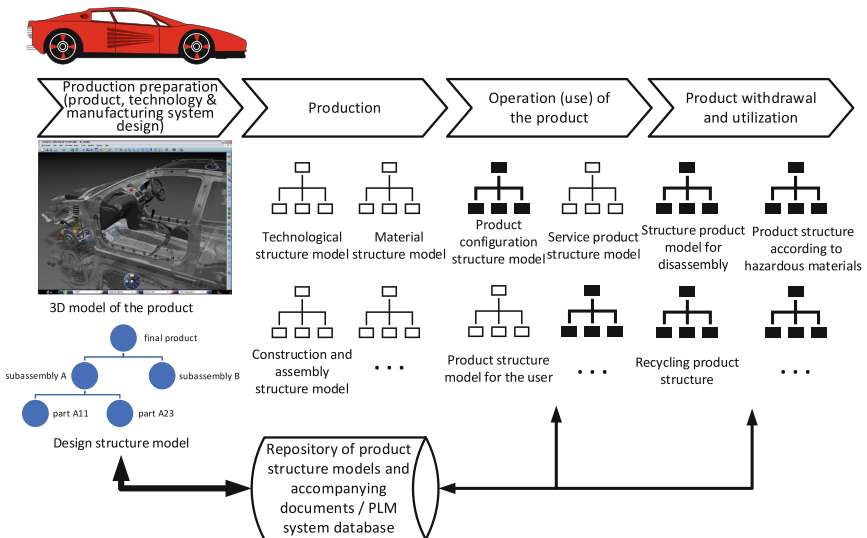


Fig. 3. Product structure models created and used in the product life cycle. Source: own work

In the production phase, examples of product structure models include:

- construction and assembly structure showing the sequence of product creation, including its assembly,
- technological structure, supplemented with descriptions of technological processes (processing, assembly, maintenance, control, etc.) for product elements, production time standards, material consumption standards, specification of workshop aids (tools, devices and handles, etc.), auxiliary materials, technological machines, etc.
- material structure, containing a list of all components of the product, including raw materials and materials,
- structure of repeatability of materials, parts, components and assemblies included in many final products,
- product structure for supply purposes (materials, raw materials; elements, sub-assemblies and commercial assemblies, manufactured in cooperation, etc.)

In the exploitation phase, the following product structure models are useful:

- product configuration structure (intended for sale)
- product structure with an indication of spare parts and parts subject to repair, along with accompanying inspection and repair instructions, a list of special equipment, time standards for inspection and repair activities, etc.
- product structure with an indication of auxiliary and consumable materials, their substitutes, replacement instructions, etc.
- product operating instructions (for the purchaser-user of the product), specification of consumables and a list of parts for self-replacement along with operating instructions,
- inspection, maintenance and repair instructions with a list of parts subject to replacement, tools used (for vehicle service centres), etc.,

The processes after the end of vehicle operation may also require specific structure models, such as:

- product structure according to assemblies, subassemblies and parts along with instructions for their disassembly, identification (product identification, manufacturer, year of production, etc.), assessment of the technical condition and the possibility of further use,
- product structure according to the materials used (e.g. recyclable or not),
- product structure according to parts, components and assemblies that can be reused after possible repair, regeneration, etc.
- product structure according to parts, components and assemblies requiring replacement without the possibility of repair and regeneration,
- material structure of the product, indicating materials and elements that may pose a threat to people and the environment (hazardous materials) and methods of handling them, recycling, storage, neutralization, disposal, etc.

4 Application of Industry 4.0 Technologies in the Car Life Cycle

Industry 4.0 technologies have (or can have) applications throughout the entire life cycle of a car. Currently, most cases (and possibilities) of applications concern the design and production stages. Relatively fewer examples of applications of Industry 4.0 technology

can be indicated at the stage of use (operation) and after the end of product operation. However, it should be remembered that we are only at the beginning of the process of developing and disseminating Industry 4.0 technologies. This statement applies not only to the automotive industry.

An additional difficulty in illustrating and analyzing examples of the applications of Industry 4.0 technologies in the automotive industry (and not only there) is that we are dealing with not one but many technologies (we can therefore talk about a kind of technological “bonsai”, Fig. 4) and the fact that in practical applications we encounter many different technologies at the same time.

Table 1 shows a “map” of applications of selected Industry 4.0 technologies against the background of the car life cycle. Among many technologies, those that currently have (or may have) the most significant applications in the automotive industry were selected [10]:

1. Artificial Intelligence, including Machine Learning [11],
2. Processing of Large Data Sets (Big Data) [12].
3. Cloud Computing [13],
4. Internet of Things and Radio Frequency Identification[14, 15],
5. Virtual and Augmented Reality [16],
6. Simulation and Digital Twins [17, 18]
7. Advanced and Intelligent Robots (cobots, collaborative robots) [19]
8. Additive Technologies (incl. 3D printing) [20]

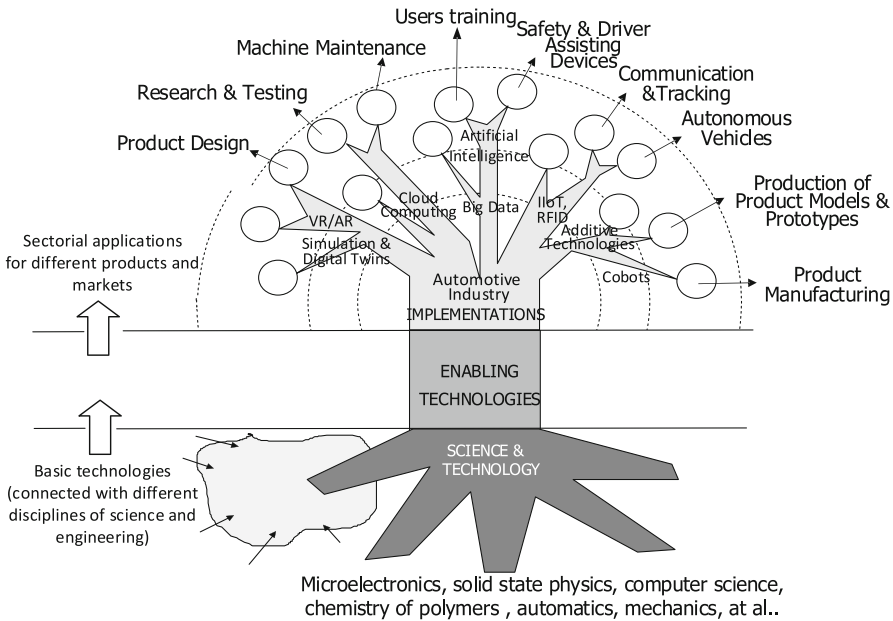


Fig. 4. Industry 4.0 - technological “bonsai”. Source: own work

Table 1. Examples of applications of Industry 4.0 technologies in the life cycle of a car.

Industry 4.0 technologies	Stages of the car life cycle			
	Production preparation (product design)	Production	Operation (use) of the product	Product withdrawal and utilization
(1) Artificial Intelligence	<ul style="list-style-type: none"> DSS for design engineers Design of products, processes, tools & manufacturing systems, Knowledge Based Engineering MBSE 	<ul style="list-style-type: none"> Intelligent CAM NC machines & processes PPC systems QC system Machine maintenance (incl. supervision and diagnosis of machines, processes and tools) 	<ul style="list-style-type: none"> safety & driver assisting systems selecting & completing vehicle equipment user training car monitoring & damage diagnosis 	<ul style="list-style-type: none"> assessment of the condition of vehicles and their parts identification of parts and materials qualification of parts for further use selection of recycling, regeneration processes, etc.
(2) Big data	<ul style="list-style-type: none"> market analysis markets & technology forecasting registration and analysis of the results of research and tests of products and their parts patent data bases search and analysis analysis of design solutions for similar products, 	<ul style="list-style-type: none"> recording of data on the course of processes machine maintenance supervision and diagnostic systems of machines, processes and tools production planning and control 	<ul style="list-style-type: none"> recording and analysis of data on the technical condition of a car registration and analysis of data regarding the history of product operation registration and analysis of user behaviour 	<ul style="list-style-type: none"> analysis of data about products in operation and at the end of operation forecasting needs and possibilities regarding products for further use, parts for regeneration and materials for recovery
(3) Cloud Computing	<ul style="list-style-type: none"> PLM systems in the cloud services supporting design (e.g. optimization calculations, simulations, etc.) remote collaboration of people in different locations and at any time Web 2.0 services 	<ul style="list-style-type: none"> machine and process control maintenance services production management (ERP systems) material flow control supplier and distribution network management (SCM) new production models (e.g. MaaS) 	<ul style="list-style-type: none"> controlling autonomous vehicles remote vehicle monitoring (including safety issues) remote vehicle diagnostics 	<ul style="list-style-type: none"> management of reverse logistics processes (used cars withdrawal) management of recycling, remanufacturing, etc. processes
(4) IIoT, RFID	<ul style="list-style-type: none"> product research and testing coding and identification of documents, elements of models, prototypes, etc. 	<ul style="list-style-type: none"> supervision and diagnostics of machines, processes and tools identification and tracking of the flow of materials, parts and finished products, workshop aids, etc. records of material stocks, workshop aids and fixed assets 	<ul style="list-style-type: none"> vehicle condition supervision and diagnosis communication with road infrastructure 	<ul style="list-style-type: none"> identification and tracking of products and their components for reuse, regeneration, materials for recovery or disposal
(5) VR/ER	<ul style="list-style-type: none"> design of products and their components process design, project visualization simulation of the operation of products and their components verification, validation and testing 	<ul style="list-style-type: none"> virtual manufacturing support for machine operators assembly support support for maintenance services, machine retooling, etc. visualization of production flow 	<ul style="list-style-type: none"> presentation of products to future buyers user training user support in operation support of service and repair service employees 	<ul style="list-style-type: none"> support for product disassembly support for processes after the end of product operation

(continued)

Table 1. (continued)

<p>(6) Simulation & Digital Twins</p>	<ul style="list-style-type: none"> · products design and visualisation · research and testing of products and their components · validation and verification of designed systems (products, manufacturing systems, etc.) 	<ul style="list-style-type: none"> · virtual manufacturing · production flow control · visualization and assessment of implemented/planned changes in production systems 	<ul style="list-style-type: none"> · training and support for car users and services · identification of components and causes of product failure · troubleshooting prevention 	<ul style="list-style-type: none"> · employee training and process support after the end of product operation · control of industrial processes after the end of product operation · visualization and assessment of changes in the organization of processes after the end of product operation
<p>(7) Cooperative Robots</p>	<ul style="list-style-type: none"> · development of models, prototypes, preparation of product trial series · conducting research and tests 	<ul style="list-style-type: none"> · machine operation · assembly processes · development and testing of new processes 	<ul style="list-style-type: none"> · processes of disassembly and assembly of repaired products · assembling, packing, and distributing parts, components, etc. 	<ul style="list-style-type: none"> · disassembly processes of end-of-life products
<p>(8) Additive Technologies.</p>	<ul style="list-style-type: none"> · production of models, prototypes · possibility of simplifying the product structure · easier design changes to the product and their verification 	<ul style="list-style-type: none"> · parts production (small series) · rapid tooling · rationalization (simplification) of production processes 	<ul style="list-style-type: none"> · production of spare parts, product repair 	<ul style="list-style-type: none"> · parts regeneration · recovery/processing of materials for additive technologies)

source: own work

More detailed information about these technologies and their applications can be found in the series of publications “Industry 4.0” published by the Polish Economic Publishing House [21] as well as in the expert opinion of the Production Engineering Committee of the Polish Academy of Sciences “Industry 4.0 in enterprises from the automotive industry, current status and development prospects” Warsaw 2023 [10].

Modern technologies stimulating the development of the automotive industry are not limited only to the so-called Industry 4.0 technologies. They do not currently determine the quality of manufactured cars, productivity, environmental impact, costs, etc. Equally important, and in many cases even more important, are “classic” technologies. This term does not mean that they are less important or less modern. In the automotive industry, as in many other industry sectors, there is a rapid development of many other technologies, including new materials and their processing, parts processing and assembly, surface treatment, and many others. A separate problem is the diversity of technologies used in the automotive industry and the automotive components industry supporting it. This is related not only to the high complexity of cars (measured, among others, by the variety and number of parts, their geometry, precision of machining and assembly, etc.) but also to the large number of materials with different and specific properties. This includes, among others: parts made of rubber, plastics and composites, glass, raw materials and chemical materials, electrical and electronic components, software, and others. A special issue is changing the concept of the car, especially its drive system. The development

of cars with hybrid, electric and hydrogen drives requires specific technologies being still a subject of intensive research and development, not widely yet used or even not known in the automotive industry. Looking from the perspective of the life cycle of a new generation car (i.e. with new drive sources), new technologies (not previously used on a wider scale in the automotive industry) are or will be necessary for the production of batteries, electric motors, control systems, construction and operation of infrastructure (e.g. battery charging stations), electricity generation, recovery of materials from end-of-life vehicles, their disposal, etc. The development of new-generation cars will create a demand for new services, which will also require new technologies, often not yet known today. Examples include autonomous vehicles and their control systems, safety and driver assistance systems, vehicle traffic management systems, etc.

5 The Impact of Industry 4.0 Technologies on the Development of the Automotive Industry

What will be the impact of Industry 4.0 technology on the future of the automotive industry? The answer to this question is not simple, because the technologies themselves are constantly changing (improving) - they have not yet reached a state of maturity, new technologies appear and, above all, there are many other factors, including external ones: geopolitical, economic, social, ecological, et al. that can change any forecast. It is also worth noting that when trying to predict the future of technologies in the short term, we tend to overestimate their advantages and in the long term underestimate their consequences.

Table 2 includes an evaluation of the anticipated impact resulting from the application of selected Industry 4.0 technologies throughout the life cycle of a car. This evaluation encompasses economic, organizational, ecological, and social effects, among others. The assessment process considered key factors such as the current state of technology development (Technology Readiness Level - TRL), the extent of their current applications, and the awareness among users and decision-makers, particularly investors. Additionally, the complexity of the technology and its potential integration with other non-Industry 4.0 classified technologies (not explicitly listed in Table 2) were taken into account.

Table 2. The impact of selected Industry 4.0 technologies on the car’s life-cycle effects.

Industry 4.0 technologies	Stages of the car life cycle			
	Production preparation (product design)	Production	Operation (use) of the product	Product withdrawal and utilization
(1) Artificial Intelligence				
(2) Big data				
(3) Cloud Computing				
(4) IIoT, RFI				
(5) VR/ER				
(6) Simulation & Digital Twins				
(7) Cooperative Robots				
(8) Additive Technologies.				

Meaning of symbols:
 Possible impact on the car’s life cycle effects

- the biggest
- significant
- average
- possible, although currently difficult to assess

source: own work

Employing artificial intelligence methods, particularly machine learning, in machine operations necessitates the deployment of advanced sensors, data collection and analysis systems, cloud computing for remote monitoring of machine conditions, utilization of the Internet of Things, and virtual or extended reality systems. Integration with Computerized Maintenance Management System (CMMS), Enterprise Resource Planning (ERP), and potentially other systems is also imperative.

The aforementioned evaluations are the results of preliminary research on this topic and were conducted through the application of technology development forecasting methods. In the specific case under consideration, expert methods, scenario methods, and systematic technology monitoring methods proved to be most effective [15].

By analyzing the current state of Industry 4.0 technologies and the dynamics of their changes, several possible scenarios for the development of the automotive industry can be presented [22–25]:

- popularization of electric cars,
- development of autonomous (intelligent) vehicles,
- intensification of competition among manufacturers of final products (OEM) and entire supply chains,
- growing requirements of customers and, consequently, emphasis on increasing production flexibility, customization of products and involving users in the product design process (co-design),
- the priority of sustainable development,
- integration of processes throughout the product life cycle,
- development of technology, organization and management towards a smart factory (digital integration),
- development of new concepts of production systems (including Manufacturing as a Service - MaaS),
- increasing the role of the human factor (human resources are becoming a rare and expensive resource in many industries of developed countries), taking into account their capabilities and needs to a much greater extent than currently, development towards Industry 5.0 - automated, intelligent production systems that take into account the capabilities and needs of people [27, 28].

6 Summary and Conclusions

The automotive industry is a receptive recipient of new technologies. This applies in particular to Industry 4.0 technologies. There are many factors that force, enable and, on the other hand, hinder their application. Large automotive companies can demonstrate many examples of successful implementations of Industry 4.0 technologies. There is little reliable information on this subject, apart from the promotional materials of the companies themselves. There are even fewer publications containing the results of empirical research on technologies, their implementation processes and the effects obtained. The available information indicates that these are generally local solutions, not integrated, supporting primarily the design and production processes, to a lesser extent the operation processes and, to a small extent, the processes implemented after the end of the car's life. The paper presents the rich possibilities of using Industry 4.0 technologies throughout the entire life cycle of a car: from concept, through structure design, production, and operation to decommissioning and reuse of materials and vehicle components, with a minimum amount of development. A "map" of Industry 4.0 technology against the background of the car life cycle was presented. Particular attention was paid to the necessity but also to the difficulties of integrating various phases of the product life cycle. A model for the integration of product life cycle phases using PLM IT systems and the product structure models created by them is presented. The use of PLM systems that generate basic technical data about the product can be a starting point for creating applications integrated with PLM systems and using product databases from PLM systems in all phases and stages of the car life cycle.






References

1. Automotive Industry Report 2022/2023. Polish Automotive Industry Association (2023)
2. Curzio, V.: Henry Ford. Oxford University Press (2013)
3. Womack, J.P., Jones, D.T., Roos, D.: The Machine That Changed the World: The Story of Lean Management. Harper Perennial (1990)
4. Roser, C.: “Faster, Better, Cheaper” in the History of Manufacturing. From the Stone Age to Lean Manufacturing and Beyond. CRC Press (2017)
5. Schwab, K.: The Fourth Industrial Revolution. Currency (2017)
6. Fit for 55 – A Set of Proposals to Revise and Update EU Legislation. <https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/>. Accessed 22 Nov 2023
7. Santarek, K., Duda, J., Oleszek, S.: Product Life Cycle Management. PWE, Warszawa (2022). in Polish
8. Manufacturing Readiness Level (MRL) Deskbook. ver.2.2.1, OSD Manufacturing Technology Program October 2012. https://www.dodmrl.com/MRL_Deskbook_V2_21.pdf. Accessed 15 Oct 2023
9. ICAM Architecture Part II-Volume IV - Function Modeling Manual (IDEF0). AFWAL-TR-81-4023, Materials Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433, June 1981. <https://apps.dtic.mil/sti/tr/pdf/ADA137422.pdf>. Accessed 15 Oct 2023
10. Bojar, W., et al.: Expert opinion of the Production Engineering Committee of the Polish Academy of Sciences “Industry 4.0 in Enterprises from the Automotive Industry: Current Status and Development Prospects. KIP PAN, Warszawa (2023). <https://doi.org/10.24425/147337>; <https://publikacje.pan.pl/book/147336/przemysl-4-0-w-przedsiębiorstwach-z-branzy-motoryzacyjnej-stan-obecny-i-perspektywy-rozwoju>. In Polish
11. Russell, S., Norvig, P.: Artificial Intelligence. A Modern Approach, 3rd edn. Prentice Hall, Upper Saddle River (2010)
12. Hwang, K., Chen, M.: Big-Data Analytics for Cloud, IoT, and Cognitive Learning. Wiley, New York (2017)
13. Castro-Leon, E., Harmon, R.: Cloud as a Service. Understanding the Service Innovation Ecosystem. Apress, Hillsboro (2016)
14. Sandler U. (ed.): The Internet of Things. Industries 4.0 Unleashed. Springer, Heidelberg (2016). <https://doi.org/10.1007/978-3-540-78731-0>
15. Gładysz, B., Grabia, M., Santarek, K.: RFID from the Concept to the Implementation. A Polish Perspective. PWN, Warszawa (2016). In Polish
16. Jung, T., tom Dieck, M.C. (eds.): Augmented Reality and Virtual Reality. Empowering Human, Place and Business. Springer, Cham (2018). <https://doi.org/10.1007/978-3-319-64027-3>
17. Bangsow, S.: Manufacturing Simulation with Plant Simulation and SimTalk. Springer, Heidelberg (2010). <https://doi.org/10.1007/978-3-642-05074-9>
18. Tao, F., Liu, A., Hu, T., Nee, A.Y.C. (eds.): Digital Twin Driven Smart Design. Academic Press (2020)
19. Karabegović, I., Banjanović-Mehmedović, L. (eds.): Industrial Robots: Design, Applications and Technology. Nova Science Publishers, New York (2020)
20. Gibson, I., Rosen, D.W., Stucker, B.: Additive Manufacturing Technologies. Rapid Prototyping to Direct Digital Manufacturing. Springer, Heidelberg (2010). <https://doi.org/10.1007/978-1-4419-1120-9>
21. The Polish Society of Production Engineering. <https://www.pwe.com.pl/serie-wydawnicze/przemysl-40-ryszard-knosala-poleca>. Accessed 15 Sept 2023

22. McKinsey & Company. Automotive Revolution – Perspectives Towards 2030. Advanced Industries (2016). <https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/disruptive-trends-that-will-transform-the-auto-industry/de-de>. Accessed 29 Oct 2023
23. Industry 4.0 in Automotive. Digitizing the End-to-End Automotive Value Chain. Deloitte Insights (2020). <https://www.deloitte.com/cbc/en/our-thinking/insights/industry/automotive/auto-news-supplement.html>. Accessed 29 Oct 2023
24. Seven Vital Industry 4.0 Automotive Technologies (2023). <https://acerta.ai/blog/key-technologies-for-automotive-industry-4-0/#:~:text=7%20key%20Industry%204.0%20automotive%20technologies%201%201.,Big%20data%20analytics%20...%207%207.%20Artificial%20Intelligence>. Accessed 07 Sept 2023
25. Sahay, S., Tiwari, A.: Industry 4.0 in Automotive Industry: Top Applications, Benefits, and Examples (2022). <https://www.birlasoft.com/articles/industry-4.0-automotive-manufacturing>. Accessed 17 Sept 2023
26. Myszor, P.: The leader was under pressure. A powerful industry invests in new technologies (in Polish: Lider znalazł się pod presją. Potężna branża inwestuje w nowe technologie). <https://www.wnp.pl/motoryzacja/lider-znalazl-sie-pod-presja-poteczna-branza-inwestuje-w-nowe-technologie,628496.html>. Accessed 04 Nov 2023
27. dos Santos, Z.G., Vieirab, L., Balbinotti, G.: Lean manufacturing and ergonomic working conditions in the automotive industry. *Proc. Manuf.* **3**, 5947–5954 (2015)
28. The Future of Work in the Automotive Industry: The Need to Invest in People’s Capabilities and Decent and Sustainable. International Labour Organisation, Geneva (2021)



Failure Analytics of Defects in Mechanical Engineering Parts Using Root Cause Analysis: Case Study

Khrystyna Berladir^{1,2} , Tetiana Hovorun¹ , Justyna Trojanowska³ ,
Vitalii Ivanov^{1,2} , and Angelina Iakovets² 

¹ Sumy State University, 116, Kharkivska St., Sumy 40007, Ukraine
kr.berladir@pmtkm.sumdu.edu.ua

² Technical University of Kosice, 1, Bayerova St., 08001 Presov, Slovak Republic

³ Poznan University of Technology, 5, M. Sklodowska-Curie Sq., 60-965 Poznan, Poland

Abstract. The paper is devoted to creating a methodological approach to apply root cause analysis for solving the specific materials science task. The case study determined the causes of the destruction of the elements of the exhaust tract of the gas pumping unit. Root cause analysis was used as a systematic process to identify and address the underlying causes of problems or incidents rather than just addressing their symptoms. In the first step of defining the problem, a destroyed element of the exhaust tract of the gas pumping unit was chosen to discover the causes of its failure. In the second step of collecting the data, the failure analytics of a destroyed element was carried out. In the third step, a mnemonic called 6Ms of production was used to identify as many causal factors as possible. In the fourth step, causal factors were analyzed in detail, and the root causes were determined. In the fifth step, the recommendations for implementing solutions to the abovementioned problem were given.

Keywords: Root Cause Analysis · Fracture · 6Ms of Production · Cause-and-effect Diagram · Process Innovation · Industrial Growth

1 Introduction

Root cause analysis (RCA) can be a valuable tool for solving materials science tasks and addressing various challenges in this field [1]. The several ways in which RCA can be applied in materials science are shown in Fig. 1.

Material Defects and Failures Analysis. When materials fail or exhibit defects, RCA can be used to determine the root causes of these failures. This is crucial for aerospace, automotive, and construction industries to ensure the safety and reliability of materials and products [2].

Quality Control and Process Improvement. RCA can help identify the underlying causes of inconsistencies in material properties or manufacturing processes. By pinpointing the root causes, materials scientists can make process improvements to enhance material quality and consistency [3].

Material Selection and Design Optimization. When developing new materials or optimizing existing ones, RCA can be used to understand why certain materials perform better than others. This knowledge can guide material selection and design decisions [4].

Corrosion and Environmental Degradation Analysis. RCA can help determine the factors leading to the corrosion or degradation of materials exposed to corrosive environments or environmental degradation. This information is essential for developing corrosion-resistant materials and protective coatings [5].

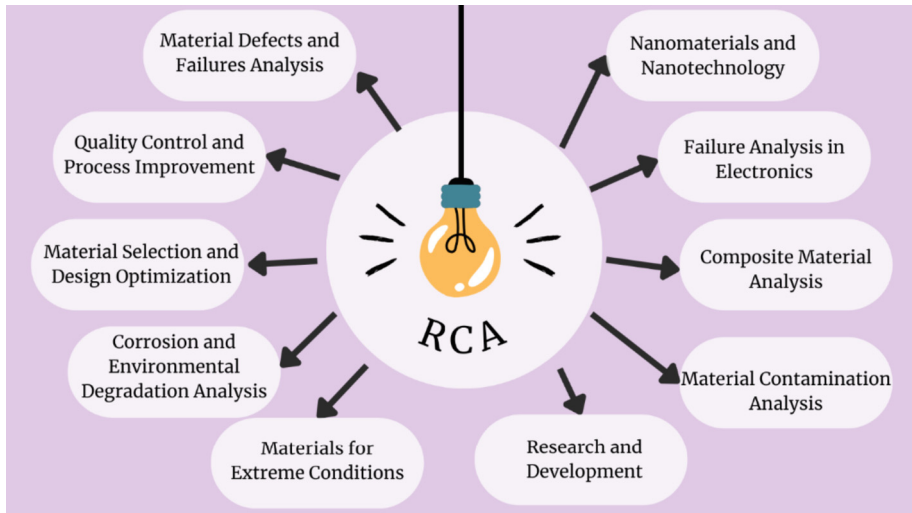


Fig. 1. How RCA can be applied in solving materials science tasks.

Materials for Extreme Conditions. In industries like energy (e.g., nuclear, oil, and gas), where materials must withstand extreme conditions, RCA can investigate material degradation and guide the selection of materials capable of withstanding these conditions [6].

Research and Development. RCA can be applied in materials research to understand why certain experimental results or material properties differ from expectations. It can lead to insights for further research and development efforts [7].

Material Contamination Analysis. When materials become contaminated, whether in a laboratory or industrial setting, RCA can help identify the sources of contamination and prevent future occurrences [8].

Composite Material Analysis. In the design and use of composite materials, RCA can help understand why delamination, fiber breakage, or other issues occur and guide improvements in composite manufacturing processes [9].

Failure Analysis in Electronics. In the electronics industry, where materials are subjected to thermal, electrical, and mechanical stresses, RCA can diagnose and resolve failures in materials such as semiconductors, circuit boards, and solder joints [10].

Nanomaterials and Nanotechnology. When working with nanomaterials, unexpected properties and behaviors can occur. RCA can be used to explore why certain nanomaterials behave as they do and develop applications based on these properties [11].

In all these applications, RCA typically involves a systematic approach to gathering data, analyzing the problem, identifying the root causes, and proposing solutions or improvements [12]. It often requires interdisciplinary collaboration between materials scientists, engineers, and other experts. The goal is not only to address immediate issues but also to advance the field by understanding the fundamental factors influencing material behavior [13].

This paper aimed to create a comprehensive methodological approach to apply root cause analysis for solving the specific materials science task. The case study determined the causes of the destruction of the elements of the exhaust tract of the gas pumping unit [14].

The following tasks were solved to realize the set goal. Firstly, applying the knowledge of a general set of steps with related tools, which is inherent in root cause analysis, a comprehensive methodology was developed to solve a specific material science problem – to discover the reasons for the destruction of a part [15]. Secondly, according to a developed methodology, a step-by-step analysis of the root causes was carried out, which included five main steps. And finally, the obtained results were analyzed discussed, relevant conclusions were drawn, and recommendations were given.

2 Research Problem

In this work, RCA was used as a systematic process to identify and address the underlying causes of problems or incidents rather than just addressing their symptoms [16].

In summary, root cause analysis is a structured approach to problem-solving that goes beyond addressing immediate symptoms to understand and eliminate the fundamental causes of issues. Its goal is to enhance processes, prevent future problems, and promote a culture of continuous improvement and learning (Fig. 2).

The general methodology of conducting RCA usually includes five steps: definition of the problem, gathering data, identifying causal factors, identifying root causes, and recommending, and implementing solutions [17]. The task was analyzed three types of causes: physical, human, and organizational. The main inputs of the RCA method are all objective failure data; similar failures may also be considered during the analysis process [18]. Based on these data, it was developed a detailed methodology to solve a specific material science problem – to discover the reasons for the destruction of a part (Fig. 3).

In the first step of defining the problem, a destroyed element of the exhaust tract of the gas pumping unit was chosen to discover the causes of its failure [19, 20]. In the second step of collecting the data, the failure analytics of a destroyed element was carried out. In the third step, a mnemonic called 6Ms of production was used to identify as many causal factors as possible. In the fourth step, causal factors were analyzed in detail, and the root causes were determined. In the fifth step, the recommendations for implementing solutions to the abovementioned problem were given.



Fig. 2. The main goals of root cause analysis.

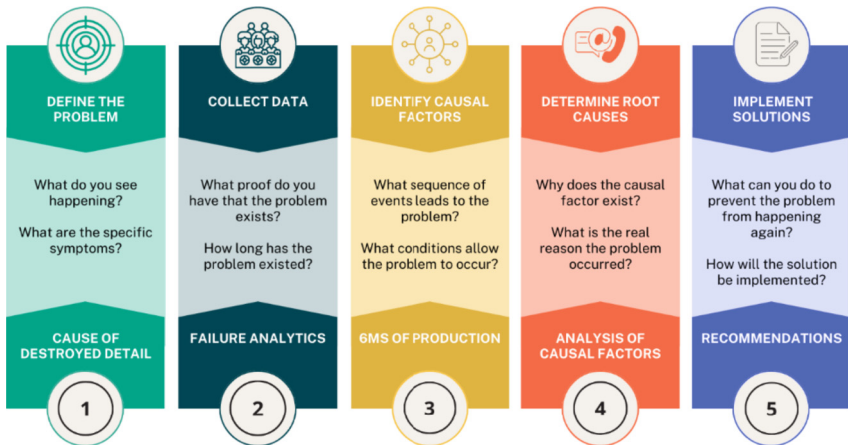


Fig. 3. Methodological approach to apply RCA for solving the materials science task.

3 Results and Discussion

3.1 Define the Problem

The research object is a destroyed element of the exhaust tract of the gas pumping unit, which worked for three years during the operation (Fig. 4). The gas temperature of the gas pumping unit was 400–470 °C.

The problem is establishing the causes of the destruction of elements of the exhaust tract of the gas pumping unit.

3.2 Collect Data

Failure analytics of the research object was done using macroscopic inspection, microscopic examination, compositional material testing, and physical testing.



Fig. 4. Destroyed element of the exhaust tract of the gas pumping unit.

3.2.1 Chemical Analysis of Material

The chemical composition of the material is presented in Table 1. According to AISI standards, the analyzed steel corresponds to the AISI 321 type. It belongs to the class of austenitic stainless steels with a grain score of 5–6 (according to DSTU 8972:2019). It is high-quality steel in terms of the content of harmful impurities.

Table 1. Chemical composition of the material of the research object, % wt.

C	Si	Mn	Cr	Ni	Mo	Cu
0.05	0.26	1.12	17.20	9.70	0.13	0.26
Ti	Co	Al	N	Nb	P	S
0.48	0.19	0.077	0.011	0.020	0.037	0.010

Chromium-nickel steels of the austenitic class have good weldability, but due to low thermal conductivity, they are prone to forming cracks during welding. The quality of welding and the possibility of the formation of hot cracks are strongly influenced by the state of the metal upon delivery [21, 22].

3.2.2 Macroanalysis

A visual inspection of the material of the exhaust tract showed that the formation of initial cracks is determined by defects formed during the manufacture of the product:

- many welded joints,
- occurrence of thermal factors in operating conditions,
- unstable level of stress and its dynamism.

The nature of the propagation of cracks in the zones of the welded joint of different technological executions is shown in Fig. 5.



Fig. 5. Formation and development of cracks in the zone of welded joints.

In some areas, entire fragments of the material of structural elements fell out, which is characteristic of the brittle destruction of the material (Fig. 6).



Fig. 6. Falling of structural elements.

The fracture area of the stiffening rod in the pinch zone and the fracture surface formed by the development of a fatigue crack are shown in Fig. 7. The chaotic formation and development of cracks suggested that the material of the product experienced vibration [23].

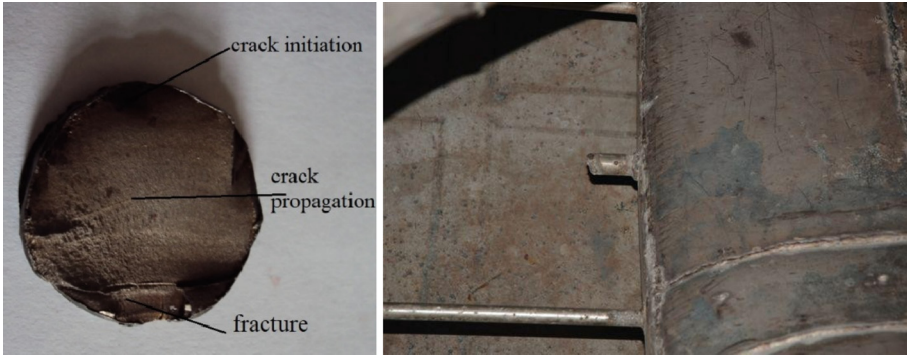


Fig. 7. Fatigue fracture of the stiffness rod.

3.2.3 Microanalysis

The study of microstructure, microhardness measurement, and the nature of crack propagation in the material's structure was carried out [24].

The microphotographs (Fig. 8) showed that the change in the density of slip lines in the structure of the material, as well as the change in microhardness ($H\mu$ 322 – 272) in different areas, can be concluded about the different levels of the stress state acting on the product due to vibration.

An example of inhibition of crack development with the manifestation of plastic deformation at the top of the crack is shown in Fig. 9.

The influence of temperature from the gas environment (450–470 °C) should reduce the initial value of the fatigue limit of steel σ_{-1} based on 10^7 cycles by more than 20%. At the same time, heating causes a more intense multiplication of crystal lattice defects (dislocations and vacancies). The nucleation and development of cracks at variable frequency-force regimes also accelerate. As a result, the material's durability at such frequency-power regimes may be reduced. In [25], it was noted that AISI 321 steel with an increase in the load frequency up to 1000 cycles/min showed a sharp decrease in cyclic strength.

Analyzing the nature of crack development, it can be noted that it was mainly intragranular in nature (Fig. 10), and intercrystalline fracture was manifested in places.

A fractographic feature of fractures of structural elements (Fig. 11) was the presence of smoother surfaces, characteristic of the initial development of cracks at the first stage and roughness at the second, forming a relief in the form of protrusions, which is characteristic of the formation of the surface of the «crack» of the sample material.

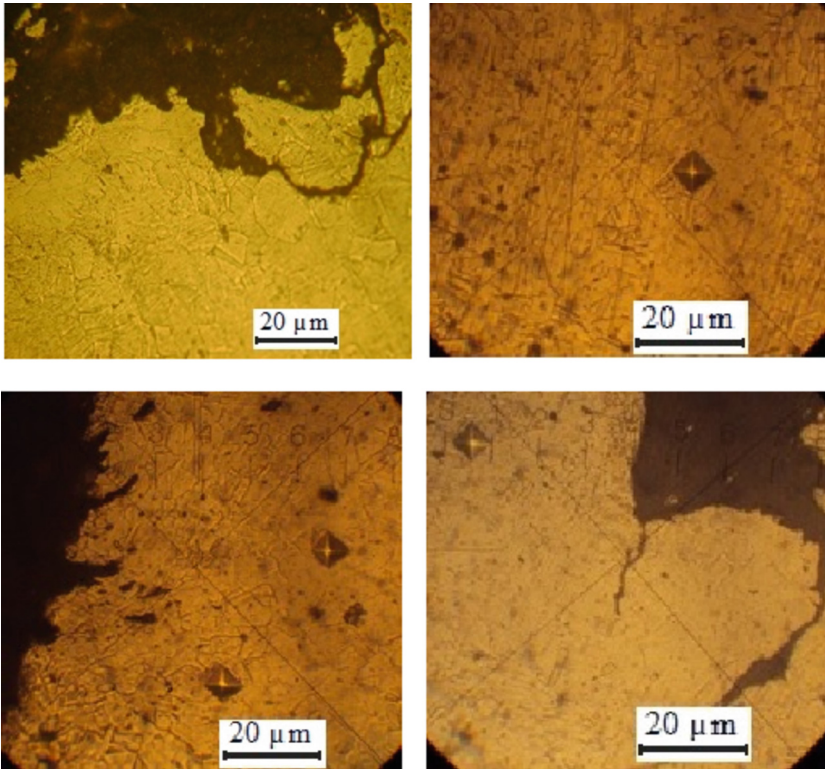


Fig. 8. Distribution of slip lines in the material in different zones during the operation of the exhaust tract.

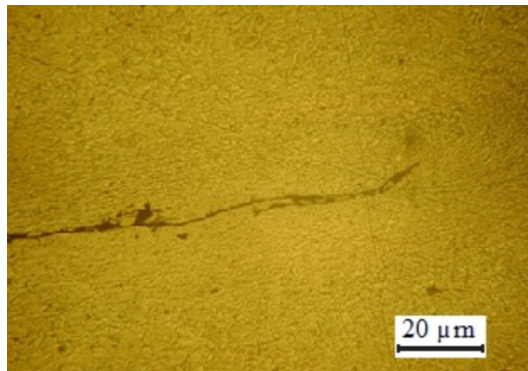


Fig. 9. Inhibition of crack development.

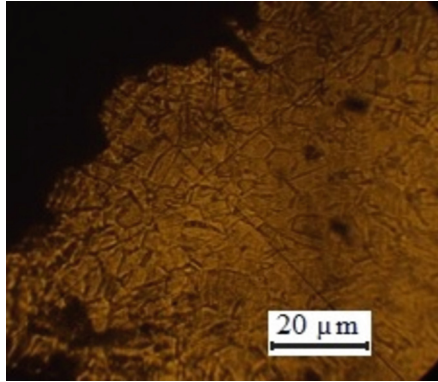


Fig. 10. Intergranular nature of crack development.

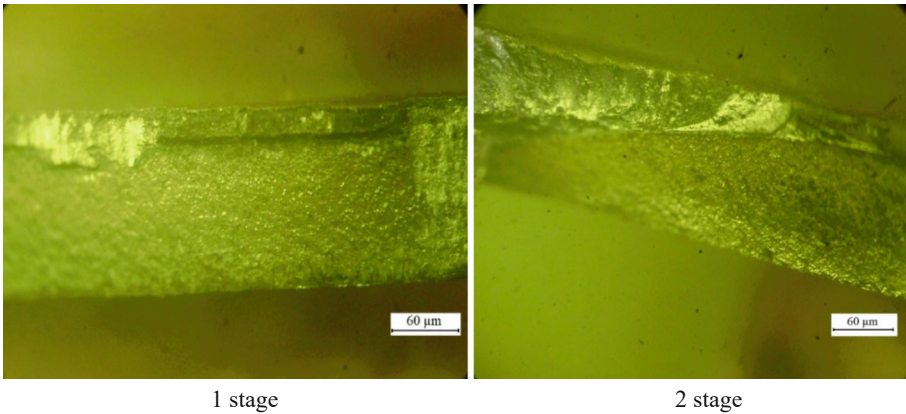


Fig. 11. Nature of destruction by material thickness.

3.3 Identify Causal Factors

Cause assessments begin with an initial examination of obvious physical causes, then examine human factors, and then move on to examine hidden management or root causes. The mnemonic of the 6Ms of production – Manpower, Method, Machine, Material, Milieu, and Measurement- was used to build a Cause-and-effect diagram (Fig. 12).

Thus, using the 6Ms of production and building a cause-and-effect diagram, all possible factors that can affect the destruction of the part were identified.

3.4 Determine the Root Causes

To determine the root causes the find factors must be analyzed.

Manpower. The most sought-after characteristic of an employee in modern economic conditions is the presence of knowledge, abilities, and skills that can be effectively used in his professional activity, that is, a certain level of education. Education either increases

the worker's productivity in each workplace or makes him capable of doing work whose results are of higher value and, therefore, better paid. It is a man, and his ability to work that is the main element of production [26].

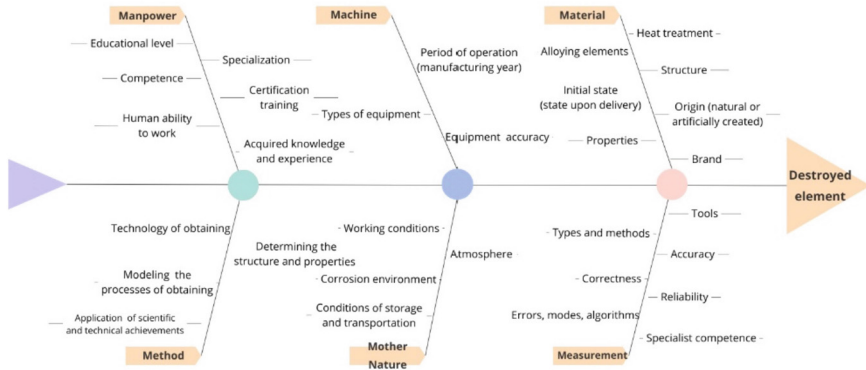


Fig. 12. Cause-and-effect diagram based on 6Ms production.

Competence is the degree of qualification of an employee that allows him to solve the tasks before him successfully. It determines the employee's ability to perform his functions qualitatively and flawlessly in normal and extreme conditions, to learn new things successfully, and to adapt to changing conditions quickly [27]. The basis of professional competence is professional suitability; it is a set of mental and psychophysiological characteristics of a person, necessary for effective professional activity. However, the ability to perform professional duties alone is not enough to achieve the organization's goals, because no matter how qualified an employee is, his productivity also depends on his desire to work or motivation to work.

Machine. One of the indicators affecting the quality of the manufactured products is the accuracy of the equipment, technological devices, and equipment on which the product is manufactured. To eliminate the influence of this indicator on the quality of manufactured products, systematic inspections are carried out. The main task of checking the technological accuracy of the equipment operated by production sites is to check the parts manufactured on this technological equipment for compliance with the design documentation and technological documentation, to establish the causes of non-conformities, and to eliminate them. The term of operation of the equipment is the activity related to the production equipment, starting, or stopping the equipment, its intended use, transportation, repair, modification (reconstruction, modernization), supervision, and maintenance, including cleaning.

Material. The choice of material is a very responsible task, which often determines the reliability and durability of the product. The unsatisfactory quality of machines, devices, and equipment results from incorrect material selection and incorrectly assigned processing. The selected material must provide the necessary structural strength, have optimal technological properties, and be the cheapest, non-deficient, and environmentally friendly. There is a relationship and interdependence of the product's design, the material, and the technology of its manufacture. The design of each part, unit, and

machine goes through three equally important and interdependent stages: design, selection of material, development of manufacturing technology. To guarantee the high competitiveness of the product, it is necessary to adhere to the main principle: the highest possible functional quality at the lowest possible cost. The optimal selection of the part material is carried out according to the following interrelated and interdependent criteria: geometric parameters; material capacity; mechanical and technological properties of the material; reliability and durability of the product; cost and availability of material; environment protection; and waste disposal.

Method. The correct choice of material not only gives certain properties to a specific product but also opens the possibility of using new technological processes. Geometric parameters are a factor that primarily determines the manufacturing technology of the product, which affects the choice of a specific material. The technological properties of the metal should ensure the best product quality at the lowest costs. When designing the manufacturing process of a part, an important issue is the choice of the most rational workpiece. The volume of the subsequent mechanical processing and all subsequent labor and financial costs to produce the part depend on the choice of the workpiece, that is, the establishment of the method of obtaining it, its shape, the number of allowances, etc. Methods of property research can be divided into two groups: methods of direct research of material properties; and methods of secondary or indirect research. The first group of research methods includes many metals, with the help of which it is possible to directly observe the structure of materials, and determine their mechanical properties, individual physical and chemical properties. Research methods of the second group are based on a connection between the internal structure of materials and their physical, chemical, and technological properties. With the introduction of computer modeling, costs are reduced, and the complexity of designing and mastering the production of new complex products is reduced. Expenses for the preparation of technological documentation are reduced by 30 – 40%. The production time of new complex products is reduced by more than 35%.

Measurement. The development of measurement methods is carried out based on initial data, which include purpose (field of application, name, and characteristics of the applied quantity, etc.), requirements for measurement error (considering all its components: methodical, instrumental, subjective), measurement conditions (set in the form of nominal values and limits of the range of influencing values) and others. Industrial measurements have relatively low accuracy, are sufficient for practical purposes, and are performed by devices whose devices correspond to their purpose and working conditions. Laboratory measurements are characterized by high accuracy due to using more advanced methods and devices and accounting for possible errors.

Mother Nature. The working conditions of the part can be diverse: static, cyclic, dynamic loads, deformations due to stretching, compression, bending, twisting, low or high temperatures, aggressive chemical environments, frictional features, for example, in a vacuum, etc. Corrosion is a phenomenon that is often a companion of almost any metals and products made from them. It results from oxidation and spontaneous destruction under the influence of external chemical and electrochemical factors. When choosing the product's material, it is necessary to comply with the requirements of life safety and environmental protection, which are fixed by law in the form of state standards and technical conditions. Such materials and technological processes that do not

harm the environment and human health should be used. The factors that contribute to the preservation of quality include factors that affect the material or part during transportation, storage, and consumption. It is necessary to consider the impact of packaging, transportation conditions, storage, and preservation of goods.

3.5 Recommend and Implement Solutions

Summarizing the results of the failure analytics, identifying as many causal factors as possible, and further analyzing them, the root causes were established, and based on it, the recommendations were given.

- During the welding work, it is necessary to monitor compliance with the recommended technological process (choice of electrode material, its diameter, welding mode, seam geometry, etc.).
- Conduct defectoscopic quality control of the welded joint.
- When starting the gas pumping unit and periodically during its operation, it is necessary to control vibration by frequency and amplitude of oscillations.
- When forming welded joints, it is necessary to avoid the overlapping of thermally affected zones that form residual stresses of the same sign.

4 Conclusions

In this research, a comprehensive methodological approach was used to apply root cause analysis for solving the specific materials science task. The case study determined the causes of the destruction of the elements of the exhaust tract of the gas pumping unit. Root cause analysis can be a valuable tool for solving materials science tasks and addressing various challenges in this field.

The general methodology usually includes five steps: definition of the problem, gathering data, identifying causal factors, identifying root causes, and recommending and implementing solutions. The task was analyzed three types of causes: physical, human, and organizational.

A visual inspection of the material of the exhaust tract showed that the formation of initial cracks is determined by defects formed during the manufacture of the product. The microstructural analysis showed that the change in the density of slip lines in the structure of the material, as well as the change in microhardness in different areas, can be concluded about the different levels of the stress state acting on the product due to vibration.

The mnemonic of the 6Ms of production – Manpower, Method, Machine, Material, Milieu, and Measurement - was used to build a Cause-and-effect diagram. The main inputs of the RCA method are all objective failure data; similar failures may also be considered during the analysis process.

Summarizing the results of the failure analytics, identifying as many causal factors as possible, and further analyzing them, the root causes were established, and based on it, the recommendations were given.

The future directions are devoted to improving the methodology of RCA for solving the specific materials science task.

Acknowledgement. The research was partially supported by the Polish National Agency for Academic Exchange within the project “Digitalization in mechanical engineering” (agreement no. BNI-UE-2023-2). The authors appreciate the support of the International Association for Technological Development and Innovations and Research and Educational Center for Industrial Engineering (Sumy State University).

The research was funded by the EU NextGenerationEU through the Recovery and Resilience Plan for Slovakia under the projects No. 09I03-03-V01-00101 and 09I03-03-V01-00094.

References

1. Jansen, J.: Root cause analysis: success in failure. *Plast. Eng.* **70**(7), 20–26 (2014)
2. Tonkonogyi, V., Holofieieva, M., Holofieiev, Y., Klimov, S., Naumenko, Y., Dašić, P.: Prediction of defects in the structure of non-metallic heterogeneous materials. *J. Eng. Sci. (Ukraine)* **10**(2), C19–C25 (2023). [https://doi.org/10.21272/jes.2023.10\(2\).c3](https://doi.org/10.21272/jes.2023.10(2).c3)
3. Prokopovych, I.V., Kokhanov, A.B., Khamitov, V.M., Tikhenko, V.M., Dašić, P.: Standardizing life cycle organization: a synergetic quality management approach. *J. Eng. Sci.* **10**(1), B1–B7 (2023). [https://doi.org/10.21272/jes.2023.10\(1\).b1](https://doi.org/10.21272/jes.2023.10(1).b1)
4. Rahim, A.A., Musa, S.N., Ramesh, S., Lim, M.K.: A systematic review on material selection methods. *Proc. Inst. Mech. Eng. Part L: J. Mater.: Design Appl.* **234**(7), 1032–1059 (2020). <https://doi.org/10.1177/1464420720916765>
5. Renpu, W.: Oil and gas well corrosion and corrosion prevention. In: Renpu, W. (eds.) *Advanced Well Completion Engineering*, 3rd edn. pp. 617–700. Gulf Professional Publishing (2011). <https://doi.org/10.1016/B978-0-12-385868-9.00018-X>
6. Golgovici, F., Tudose, A.E., Diniasi, D., Nartita, R., Fulger, M., Demetrescu, I.: Aspects of applied chemistry related to future goals of safety and efficiency in materials development for nuclear energy. *Molecules* **28**, 874 (2023). <https://doi.org/10.3390/molecules28020874>
7. Adityawarman, T., Soedarsono, J.W., Kaban, A.P.S., Suryadi, Rahmadani, H., Riastuti, R.: Integrating the root cause analysis to machine learning interpretation for predicting future failure. *Heliyon* **9**(6), e16946 (2023). <https://doi.org/10.1016/j.heliyon.2023.e16946>
8. Rodriguez, J.: Step 6: part I—root cause analysis. In: Rodriguez, J. (eds.) *CAPA in the Pharmaceutical and Biotech Industries*, pp. 101–141. Woodhead Publishing (2016). <https://doi.org/10.1016/B978-1-907568-58-9.00009-6>
9. Fu, Y., Yao, X.: A review on manufacturing defects and their detection of fiber reinforced resin matrix composites. *Composites Part C: Open Access* **8**, 100276 (2022). <https://doi.org/10.1016/j.jcomc.2022.100276>
10. Tan, C.-M., Chen, H.-H., Wu, J.-P., Sangwan, V., Tsai, K.-Y., Huang, W.-C.: Root cause analysis of a printed circuit board (PCB) failure in a public transport communication system. *Appl. Sci.* **12**, 640 (2022). <https://doi.org/10.3390/app12020640>
11. El-Kady, M.M., et al.: Nanomaterials: a comprehensive review of applications, toxicity, impact, and fate to environment. *J. Mol. Liq.* **370**, 121046 (2023). <https://doi.org/10.1016/j.molliq.2022.121046>
12. Yue, W., Chai, J., Wan, X., Xie, Y., Chen, X., Gui, W.: Root cause analysis for process industry using causal knowledge map under large group environment. *Adv. Eng. Inform.* **57**, 102057 (2023). <https://doi.org/10.1016/j.aei.2023.102057>
13. Reid, I., Smyth-Renshaw, J.: Exploring the fundamentals of root cause analysis: are we asking the right questions in defining the problem? *Qual. Reliab. Eng. Int.* **28**(5), 535–545 (2012). <https://doi.org/10.1002/qre.1435>
14. Relich, M., Nielsen, I., Gola, A.: Reducing the total cost at the product design stage. *Appl. Sci.* **12**(4), 1921 (2022). <https://doi.org/10.3390/app12041921>

15. Siwak, P., Garbiec, D., Rogalewicz, M.: The effect of Cr₃C₂ and TaC additives on microstructure, hardness and fracture toughness of WC-6Co tool material fabricated by spark plasma sintering. *Mater. Res.* **20**(3), 780–785 (2017)
16. A Guide to Root Cause Analysis in Manufacturing. <https://epoptia.com/root-cause-analysis-in-manufacturing/>. Accessed 10 Nov 2023
17. Kowalski, M., Zawadzki, P., Hamrol, A.: Effectiveness of automatic CAM programming using machining templates for the manufacture of special production tooling. *Stroj Vestn.-J. Mech. E* **67**(10), 475–489 (2021). <https://doi.org/10.5545/sv-jme.2021.7285>
18. Paprocka, I., Krenczyk, D., Burduk, A.: The method of production scheduling with uncertainties using the ants colony optimisation. *Appl. Sci.* **11**(1), 171 (2020)
19. Patalas-Maliszewska J., Krebs I.: Model of the tacit knowledge transfer support tool: CKnow-board. In: Communications in Computer and Information Science, 2016, 22nd International Conference on Information and Software Technologies, ICIST 2016 Druskininka 13 October 2016, vol. 639, pp. 30–41 (2016). https://doi.org/10.1007/978-3-319-46254-7_3
20. Popișter, F., Popescu, D., Păcurar, A., Păcurar, R.: Mathematical approach in complex surfaces toolpaths. *Mathematics* **9**, 1360 (2021). <https://doi.org/10.3390/math9121360>
21. Hinz, M., Pietruschka, J., Bracke, S.: Uncertainty Quantification of Different Data Sources with Regard to a LSTM Analysis of Grinded Surfaces. https://doi.org/10.3850/978-981-18-8071-1_p408-cd
22. Iliescu, F., Popescu, S., Dragomir, M., Dragomir, D.: Public–private partnership in the water sector in Romania: success or failure? *Water Supply* **13**(5), 1249–1256 (2013). <https://doi.org/10.2166/ws.2013.134>
23. Root Cause Analysis - Tracing a Problem to Its Origins. <https://www.mindtools.com/ag6pkn9/root-cause-analysis>. Accessed 10 Nov 2023
24. Viswanathan, R.: *Damage Mechanisms and Life Assessment of High Temperature Components*, 1st edn. ASM International (1989)
25. Bocewicz, G., Nielsen, L., Gola, A., Banaszak, Z.: Reference model of milk-run traffic systems prototyping. *Int. J. Prod. Res.* **59**(15), 4495–4512 (2021). <https://doi.org/10.1080/00207543.2020.1766717>
26. Trojanowska, J., Husár, J., Hrehova, S., Knapčíková, L.: Poka yoke in smart production systems with pick-to-light implementation to increase efficiency. *Appl. Sci.* **13**(21), 11715 (2023). <https://doi.org/10.3390/app132111715>
27. Adamczak, M., Kolinski, A., Trojanowska, J., Husár, J.: Digitalization trend and its influence on the development of the operational process in production companies. *Appl. Sci.* **13**(3), 1393 (2023). <https://doi.org/10.3390/app13031393>



Consumer Awareness and Customization of Footwear in the Context of the Idea of Industry 4.0: Analysis of Survey Results

Karolina Wrześniowska^(✉)  and Cezary Grabowik 

Silesian University of Technology, Gliwice, Poland
karolina.wrzesniowska@polsl.pl

Abstract. This article focuses on the study of the relationship between consumer awareness and footwear customization in the context of the idea of Industry 4.0. An analysis of the results of a survey was conducted, focusing on key aspects such as consumer preferences for personalized products and the level of understanding of Industry 4.0 terminology. 261 respondents participated in the survey, including 223 (85.4%) women and 38 (14.6%) men. The purpose of the article is to conduct a survey and formulate conclusions based on the research hypothesis. The purpose of the survey is to learn about and assess the level of consumer awareness of shoe buyers vs. its impact on the development of shoe customization. The results show significant relationships between social factors and consumer awareness, particularly highlighting the influence of gender, age, education, and place of residence on purchase preferences. The analysis aims to provide a deeper understanding of the factors determining consumer choices in the context of product personalization and the implications of Industry 4.0 ideas on consumer awareness.

Keywords: Survey · Footwear Consumer Awareness · Footwear Customization

1 Introduction

Industry 4.0 is transforming industrial sectors, including the footwear industry, with innovations that affect production and consumption. This study focuses on consumer awareness and personalization in the footwear sector in the context of Industry 4.0. Despite the growing interest in consumer choices, the Polish footwear market lacks research. The limitations in the research method were a result of the costs and time required for statistical studies on a European scale.

Online shopping has gained increasing popularity among consumers, especially in the context of the significant rise in online purchases due to the COVID-19 pandemic. According to a report by [1], one in ten respondents increased their footwear expenses during the pandemic. Additionally, 34% of respondents admitted to not purchasing footwear online before the pandemic, with 24% doing so less frequently. The main deterrent for not purchasing clothing and footwear online is the inability to try them on, cited by 74% for footwear and 67% for clothing. The evolving information society in

Poland is driving more online transactions, with a rising number of entities recognizing the Internet as a crucial distribution channel.

The “young adults” segment constitutes a fundamental group forming the online community, with 50% of internet users aged 18–24 and an additional 24% in the 25–32 age range, as indicated by [2]. This segment represents over 18% of the Polish population [3] and is, therefore, an attractive group for businesses operating online. Understanding the purchasing behavior of this group presents significant opportunities for further development.

Online shopping is gaining increasing interest among consumers [4, 5]. It is essential to note that this trend may result in poorly fitting footwear, leading to foot deformities.

The results of a study conducted by Rahman [6] clearly indicated that participants did not feel comfortable buying shoes online, with most using the Internet solely for product information.

Research by Branthwaite and Chockalingam [7] clearly shows that the shape of footwear influences impaired function, and poorly chosen shoes can lead to pain and pathology.

A comprehensive definition of ill-fitting footwear and optimal assessment methods are lacking. Results indicate a link between online shopping and foot issues, underscoring the importance of education and advanced production technologies. Customized footwear emerges as a viable solution, emphasizing the need for an individualized approach. Survey analysis is vital for grasping consumer needs and guiding the footwear market’s evolution in the age of modern technologies.

2 Aim of the Study, Hypotheses, and Research Questions

This section highlights two main research areas: assessing consumer awareness among footwear users and examining the relationship between this awareness and the trend of footwear customization in Industry 4.0. The study aimed to identify the factors influencing purchase decisions, preferences, and the impact of consumer awareness on the footwear customization market. The hypothesis suggests that despite advancements, consumers may not always be aware of the positive effects of proper footwear use on foot comfort and deformation reduction.

Properly defined research questions are crucial to achieving the intended research objective. They allow the identification of research areas in which it is necessary to conduct research work, problems that need to be resolved or clarified.

1. Is there statistically significant difference in the propensity to purchase footwear between those with a college degree and those with a high school education?
2. Is there statistically significant correlation between the incidence of foot deformities and the age of respondents?

3. Is there statistically significant correlation between the characteristics of customized footwear, such as appearance, lead time, and cost, and the gender of respondents?
4. What is the level of familiarity with terms such as “Industry 4.0,” “customization,” “personalization” and “consumer awareness” in the context of differences in education level, type of work and gender of respondents?
5. what is the group of respondents who consider themselves to be conscious consumers depending on factors such as education, residence, and age?

Due to the form of the questionnaire, which does not include a division between manual labor and white-collar work, the question was narrowed down to education only.

3 Research Method

Survey research, a widely employed method in the social sciences, is vital for examining behavior, attitudes, and beliefs. The choice of this technique, driven by the issues under study and available tools like online forms, facilitates non-contact responses from participants, overcoming geographical constraints. This method efficiently gathers data from respondents, crucial for studying consumer attitudes. The author employed a one-time, anonymous diagnostic survey using online questionnaires shared on social media, forums, and Facebook groups. The voluntary survey consisted of structured, closed-ended questions.

3.1 Respondents

To make the research sample authoritative, several inclusion criteria were defined: footwear consumers, Polish residents of working age (18-59Females/64Males) with access to the Internet - in view of this, the population was estimated based on a survey conducted in 2022 by the Central Statistical Office and amounted to 22,168,642 people [8].

The survey comprised 261 respondents: 85.4% women ($n = 223$) and 14.6% men ($n = 38$). Respondents were divided into two age groups: young adults (18–35 years, 49.4%) and adults (36–59F/65M, 50.6%). Refer to Table 1 for sample details.

Table 1. Analysis of sociogeographic data of the study sample.

		n	%
Gender	Woman	223	85,4%
	Man	38	14,6%
The size of the city (the number of residents)	Up to 50 thousand	51	19,5%
	From 150 thousand up to 500 thousand	46	17,6%
	From 50 thousand up to 150 thousand	96	36,8%
	Over 500 thousand	52	19,9%
	Village	16	6,1%
Education	Primary	2	0,8%
	Secondary	83	31,8%
	Higher	167	64,0%
	Vocational	9	3,5%
Employment	Unemployed	8	3,1%
	Pensioner	2	0,8%
	Unable to work	3	1,2%
	Own business	25	9,6%
	Pupil/student	27	10,3%
	Hired	196	75,1%
Position at work	Mixed	64	24,5%
	Seated	146	55,9%
	Standing	25	9,6%
	Going	26	10,0%

Women dominate respondents (85.4%), suggesting their preferences will shape the footwear market. The majority reside in mid-sized cities (50,000 to 150,000 population, 36.7%). Given the high educational background, those with university degrees (employed, 75.1%) exhibit heightened awareness and quality and comfort demands. Job roles vary, with a substantial proportion engaged in sitting positions (56%), potentially influencing footwear preferences.

3.2 Research Tool

This article unveils survey results on the intricate link between consumer awareness and footwear customization amid evolving preferences and Industry 4.0. The tailored questionnaire, structured into 6 parts with 51 closed questions, covers respondent profiles, footwear experiences, shopping habits, usage patterns, foot-related aspects, and opinions

on customization benefits and challenges. Understanding these dynamics is crucial for industry players.

3.3 Research Procedure

The consumer opinion survey involved two stages: questionnaire preparation and a pilot study. A Google form questionnaire was evaluated by 15 individuals from 1.09–08.09.2023, aiming to ensure its functionality, clarity, and address any ambiguities. Errors and feedback were rectified in the revised version.

The main survey, running from 9.09–29.09.2023, was anonymous, randomly sampled, and began with informing participants about the study's purpose, importance, voluntary, and anonymous nature. Respondents received a free informative brochure as gratitude, covering footwear usage and clarifying survey terms.

3.4 Statistical Methods Used

The chi-square independence test was a key tool for assessing relationships in the research questions, specifically examining statistical significance in consumer opinions. Due to qualitative responses in the survey, a group of chi tests was chosen, employing a two-variable chi-square test (Chi test of independence) for analyzing two qualitative variables [9].

The chi-square independence test is a statistical test used to see if there is a relationship between two categorical variables. This test compares the observed frequency of a categorical combination of two variables with the frequency that would be expected if the two variables were affluent.

The general process of the chi-square independence test includes the following steps:

1. formulation of hypotheses:

The null hypothesis (H_0) assumes there is no relationship between the variables, while the alternative hypothesis (H_1) assumes there is a relationship.

2. Cross-tabulation:

A crosstab is created for at least two categorical variables, which shows the number of cases for each combination of categories.

3. Calculating chi-square values:

For each cell in the table, the difference between the observed value and the expected value E_{ij} (1) is calculated, this difference is squared, and then divided by the expected value [9]. The sum of these values for all cells gives the chi-square test statistic χ^2 (2).

$$E_{ij} = \frac{\text{RowTotal} \cdot \text{ColumnTotal}}{\text{GrandTotal}} \quad (1)$$

where:

Row Total is the sum of the observed frequencies in the same row as cell i, j .

Column Total is the sum of the observed frequencies in the same column as cell i, j .

Grand Total is the total number of observations in the entire table.

$$\chi^2 = \sum \frac{(O_{ij} - E_{ij})^2}{E_{ij}} \quad (2)$$

where:

O_{ij} is the observed frequency in cell $i j$.

E_{ij} is the expected frequency in cell $i j$.

The sum is taken over all cells in the table.

The expected frequency E_{ij} for each cell is often calculated based on the assumption of independence between the two categorical variables.

4. Determination of degrees of freedom:

Degrees of freedom are related to the number of categories in each variable and are used to determine the chi-square distribution. The degrees of freedom are determined by Formula (3):

$$df = (r - 1) \cdot (c - 1) \quad (3)$$

where:

r is the number of categories (levels) in one variable.

c is the number of categories (levels) in the other variable.

5. Calculating the Cramér's Factor V_c :

After calculating the chi-square statistic, calculate the Cramer Factor using Formula (4). The Cramer Factor is a measure of the strength of the relationship between categorical variables, which is a normalization of the chi-square statistic [10]. It helps determine how related the variables are, regardless of the size of the crosstab. The value of the Cramer Factor $V_c < 0.3$ - the relationship is weak, $V_c < 0.5$ - the relationship is moderate, $V_c > 0.5$ - the relationship is strong.

$$V_c = \sqrt{\frac{\chi^2}{n_{\min(k-1), (r-1)}}} \quad (4)$$

where:

χ^2 is the chi-square test statistic.

n is the total number of observations.

k is the number of columns (categories) in the contingency table.

r is the number of rows (categories) in the contingency table.

For a 2×2 cross table, a phi factor is used, with the formula:

$$\phi = \sqrt{\frac{\chi^2}{n}} \quad (5)$$

where:

χ^2 is the chi-square statistic, and n is the number of total observations.

The phi coefficient is useful when we want to assess the degree of relationship between two binary variables and see if there is any relationship between them.

4 Customization and Industry 4.0: Exploring the Intersection in the Context of Consumer Theories

The footwear industry is introducing innovative technologies, including 3D shoe printing, related to Industry 4.0. While there are prototypes built entirely with 3D printing, there are challenges related to the practicality of this approach, according to [11]. Mass

production of shoes faces limitations due to the variety of models and complexity of the process. Nevertheless, the use of robotics in production can improve shoe quality, reducing the need for shoe retouching by 80%. Although full automation is currently not cost-effective, the growing trend of collaborative robotics is opening prospects for effective interaction between robots and humans, which could be key to improving production processes.

Consumer consciousness theory has evolved over the years, from Maslow's original hierarchy of needs models [12] to more contemporary theories such as consumer perception theory. Consumer perception is a dynamic cognitive process involving the perception, selection, interpretation, and processing of stimuli from the shopping environment. Both individual and social factors play a key role in this process [13]. A change in the view of the consumer as individual receiving stimuli from the environment and interpreting them in the context of his or her own experiences became the foundation of this theory. This outlook has dynamized the analysis, drawing attention to the subjective aspects of product perception [14].

In the era of Industry 4.0, where digital technologies, artificial intelligence and production personalization play a key role, the theory of consumer awareness must adapt to modern realities. The consumer is now more informed discerning and eager for personalized shopping experiences [15].

Personalization and cauterization are two related, but different concepts related to tailoring products or services to individual customer preferences. Here is a short characterization of the differences between the two:

- Personalization involves tailoring products or services to individual customer preferences and needs, creating a unique and individualized experience. Customers actively participate in the process by stating their preferences and selecting items that align with their tastes [16].
- Customization is the adjustment of standard products or services, enabling customers to make modifications within predefined parameters or options set by the manufacturer [17].

Purchasing decisions related to customization strongly influence the psychological aspects of customers, satisfying a variety of psychological needs [18]. Customization allows customers to express their individuality by customizing products according to their own preferences. The consumer feels an atmosphere of co-creation together with the product brand. This participation in the production process can build strong emotional ties between the consumer and the brand and extend the reach of mass customization [19].

Footwear consumer behavior, encompassing purchasing decisions, control, and user experience, is influenced by accessibility, knowledge, and a connection with the consumer market [20]. Informed consumers prioritize quality, considering factors like materials, workmanship, and design, making decisions based on comfort and technological features [21]. Social awareness extends beyond fashion, encompassing safety, ethics, and ecological values [22]. An informed footwear user possesses knowledge about types of footwear, prioritizes comfort and quality, and understands the impact of fit on foot health. Regular care and practices like shoe rotation contribute to durability, while improper use may lead to foot deformities [23].

5 Customization and Industry 4.0: Exploring the Intersection in the Context of Consumer Theories

The questionnaire study explored both consumer awareness in the context of Industry 4.0 and preferences regarding footwear customization. The results provide insights into factors influencing consumer decisions and identify areas crucial for future marketing strategies and the development of products tailored to consumer expectations.

5.1 Analysis of Consumer Awareness Depending on the Education, Place of Residence, and Age of Respondents

The first step was to analyze the level of consumer awareness, considering key factors such as education, place of residence and age of respondents. The aim is to identify relationships between these variables and the answer to the survey question: “Are you an informed consumer?” This introduction will enable us to better understand how various social factors can influence consumers’ perceptions and preparation for market activities. The results (Table 2) indicate that respondents have varying levels of awareness related to the analyzed characteristics of the study group.

Table 2. Analysis of survey responses exploring consumer awareness according to their characteristics.

Characteristics of respondents		I am aware		I am not aware		I do not know if I am aware	
		n	%	n	%	n	%
Gender	Woman	93	35,6%	43	16,5%	87	33,3%
	Man	17	6,5%	5	1,9%	16	6,1%
The size of the city (the number of residents)	Up to 50 thousand	22	8,4%	10	3,8%	19	7,3%
	From 150 thousand up to 500 thousand	35	13,4%	19	7,3%	42	16,1%
	From 50 thousand up to 150 thousand	19	7,3%	8	3,1%	19	7,3%
	Over 500 thousand	25	9,6%	9	3,5%	18	6,9%
	Village	9	3,5%	2	0,8%	5	1,9%
Education	Primary	–	–	–	–	2	0,8%
	Secondary	30	11,5%	19	7,3%	34	13,0%
	Higher	76	29,1%	28	10,7%	63	24,1%
	Vocational	4	1,5%	1	0,4%	4	1,5%

(continued)

Table 2. (continued)

Characteristics of respondents		I am aware		I am not aware		I do not know if I am aware	
		n	%	n	%	n	%
Employment	Unemployed	3	1,2%	–	–	5	1,9%
	Pensioner	1	0,4%	–	–	1	0,4%
	Unable to work	1	0,4%	–	–	2	0,8%
	Own business	10	3,8%	4	1,5%	11	4,2%
	Pupil/student	8	3,1%	8	3,1%	11	4,2%
	Hired	87	33,3%	36	13,8%	73	28,0%
Age	18–35 years of age	51	19,5%	32	12,3%	46	17,6%
	36–65 years of age	59	22,6%	16	6,1%	57	21,8%

Women exhibit higher consumer awareness (35.6%) than men (6.5%). City residents, particularly in areas with over 500,000 inhabitants (9.6%) and 50,000 to 150,000 inhabitants (13.4%), show heightened awareness. Higher education individuals (29.1%) are more aware consumers than those with secondary (11.5%) or primary (0.8%) education, potentially due to enhanced analytical skills. Employed individuals (33.3%) claim higher awareness than the unemployed (1.2%) or retirees (0.4%), highlighting the impact of professional activity on information access. Younger individuals (18–35 years old) declare greater awareness (19.5%) compared to older counterparts (22.6%), potentially influenced by modern trends and technologies.

5.2 Analysis of Knowledge of Issues Such as “Industry 4.0”, “Customization”, “Personalization” and “Consumer Awareness” Depending on Sex and Gender

The next research question concerned the analysis of knowledge of terms such as: “Industry 4.0”, “customization”, “personalization” and “consumer awareness” in the context of differences in the level of education, type of work and gender of respondents. First, a general analysis of the knowledge of concepts among all respondents was performed. The relationships between the data are presented in Table 3.

Table 3. Analysis of the level of knowledge of terms related to the subject matter of the work.

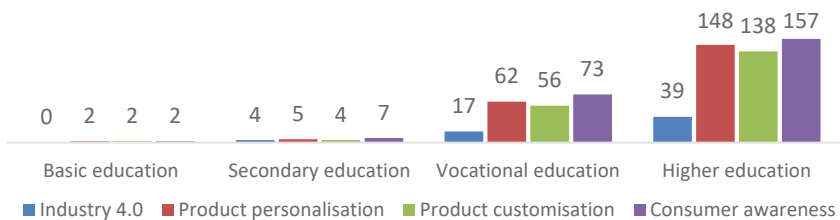
<i>Terms</i>		n	%
I am not familiar with the concept	Industry 4.0	178	68%
	Product personalisation	24	9%
	Product customisation	32	12%
	Consumer awareness	4	2%
I am familiar with the concepts	Industry 4.0	60	23%
	Product personalisation	217	83%
	Product customisation	200	77%
	Consumer awareness	239	92%
I do not understand the term	Industry 4.0	23	9%
	Product personalisation	20	8%
	Product customisation	29	11%
	Consumer awareness	18	7%

Respondent education, particularly in “Industry 4.0” concepts, is crucial. Most respondents (68%) lack awareness of “Industry 4.0,” with only a minority (23%) familiar with it. Product personalization (83%) and customization (77%) are highly popular, reflecting a growing interest in personalized shopping.

Consumer awareness is high, indicating understanding of purchasing significance. However, theoretical knowledge does not necessarily correlate with a pro-consumer attitude.

The analysis explores the relationship between terminology knowledge, education level, and gender, presented graphically for clarity.

First, the relationship between respondents’ education was analyzed (Figs. 1, 2, and 3).

**Fig. 1.** Relationship between knowledge of definitions and level of education.

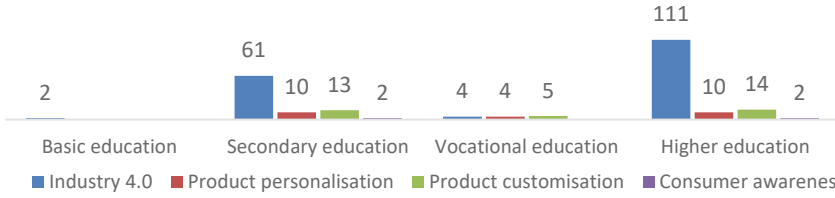


Fig. 2. Relationship between the lack of knowledge of definitions and the level of education.

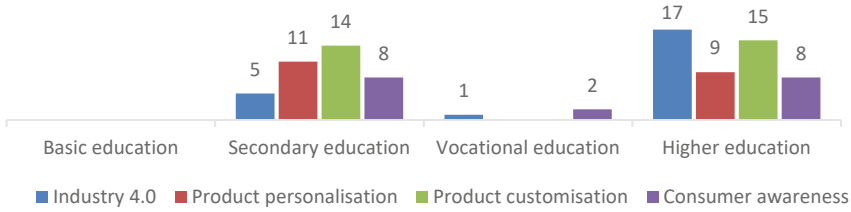


Fig. 3. Relationship between misunderstanding of definitions and level of education.

Figure 1 depicts the correlation between education levels and knowledge of definitions, revealing higher education’s positive association with awareness. This pattern is consistent across product personalization and customization. Figure 2 illustrates significant knowledge gaps, particularly at secondary and higher education levels, emphasizing the need for targeted interventions. Figure 3 explores the relationship between misunderstanding and education, noting instances at primary and vocational levels. Misunderstandings in personalization, customization, and consumer awareness vary across educational tiers, particularly at primary and secondary levels.

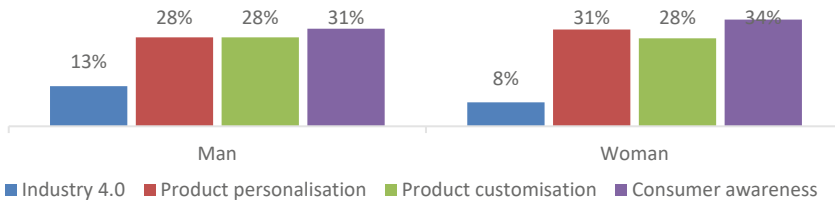


Fig. 4. Relationship between knowledge of definitions and gender of respondents.

Figure 4 displays gender-based knowledge distribution. Women show slightly higher knowledge in product personalization and consumer awareness, while men exhibit greater Industry 4.0 knowledge. Figure 5 reveals higher ignorance among women across categories, notably in Industry 4.0, with 76% women compared to 69% men. Figure 6 depicts gender differences in misunderstanding, slightly favoring women and notably in Industry 4.0.

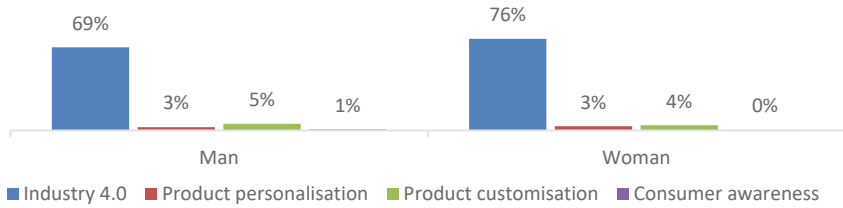


Fig. 5. Relationship between ignorance of definitions and gender of respondents.

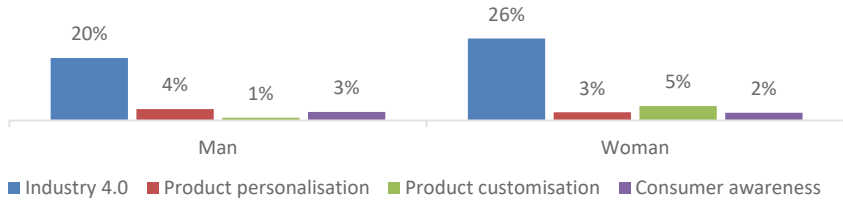


Fig. 6. Relationship between misunderstanding of definitions and gender of respondents.

In summary, data suggests gender disparities in understanding, ignorance, and knowledge, emphasizing the need for targeted education for a more uniform understanding across genders.

5.3 Analysis of Research Questions Using the Chi-Square Test of Independence

Research Question #1: Is there a statistically significant difference in the tendency to have custom-made footwear between people with higher education and people with secondary education?

1. Null hypothesis (H0): There is no statistically significant relationship between education and the tendency to have custom-made footwear.
2. Alternative hypothesis (H1): There is a statistically significant relationship between education and the tendency to have custom-made footwear.

Table 4. Cross-tabulation for research question 1 with empirical data.

Education	I have no opinion	I do not care about	I care about	total
Secondary Education	12	7	64	83
Higher Education	14	18	135	167
Total	26	25	199	250

For the data in Table 4, the next characteristics were calculated using formula (2-4) and the Excel function (= chi.test):

- The chi-square statistic is $\chi^2 = 2.3$
- Probability is $p = 0.3059068376$
- The degrees of freedom are $df = 2$
- Cramer Factor is $Vc = 0.097343708$

Based on the analysis of the results of the chi-square test, it can be concluded that there is no statistically significant relationship between education level and footwear preference in the study group. The p-value suggests that the differences in the data are not large enough to reject the null hypothesis of no relationship. Although there is a small relationship ($Vc = 0.0973$), it is not strong, implying that education level is not a key factor influencing footwear preference in this group.

Research Question #2: Is there a statistically significant correlation between the prevalence of foot deformity and the age of respondents?

1. Null hypothesis (H0): There is no statistically significant correlation between the age of respondents and the incidence of foot deformity.
2. Alternative hypothesis (H1): There is a statistically significant correlation between the age of respondents and the occurrence of foot deformity.

Table 5. Empirical data on the effect of age on having foot deformities.

Age	I do not have	I do not know	I have	Total
18–35 years	43	40	46	129
36–65 years	63	37	32	132
total	106	77	78	261

For the data in Table 5, the next characteristics were calculated using Formulas (2–4) and the Excel function (=chi.test):

- The chi-square statistic is $\chi^2 = 6.4$
- Probability is $p = 0.0413855431$
- The degrees of freedom are $df = 2$
- Cramer Factor is $Vc = 0.15622029$

The analysis of obtained probabilities allows us to reject the null hypothesis, indicating a statistically significant relationship between respondents’ age and the occurrence of foot deformities. However, the Cramer Factor Vc suggests a low correlation strength, signifying a weak relationship between age and foot deformities. While the data confirms a significant correlation, it’s important to note that the influence of age on foot deformities is moderate, indicating a noteworthy but not exceptionally strong connection.

Research Question #3: Is there a statistically significant relationship between the characteristics of customised footwear, such as appearance, lead time and cost, and the gender of respondents?

The survey focused on respondents' preferences for appearance, lead time, and cost of customized footwear. Gender served as the independent variable, while preferences for appearance, lead time, and cost were the dependent variables. Calculations were performed separately for each feature category, including only positive and negative responses, while neutral responses were excluded from the study.

1. Impact of Preference for the Appearance of Customised Footwear.

For the data in Table 6, the following characteristics were calculated using formulas (2,3,5) and the Excel function (=chi.test):

- The chi-square statistic is $\chi^2 = 11.6$
- Probability is $p = 0.000676735$
- Factor $\phi = 0.218$

Table 6. Empirical data on the effect of customized footwear design versus gender.

Feature	Woman		Man		Total	% total
	n	%	n	%		
Appearance has an impact	170	83%	20	57%	190	79%
Appearance has no impact	36	17%	15	43%	51	21%
Total	206	85%	35	15%	241	100%

Detailed analysis reveals a significant difference in preferences for the appearance of customized footwear between genders ($p = 0.0006$). Women exhibit a higher impact of these preferences on purchasing decisions compared to men. Specifically, 83% of women (170 respondents) noted that preferences influence their purchases, while 57% of men (20 respondents) reported the same.

The value of the chi-square statistic of 11.6 indicates the statistical significance of this relationship. In addition, the phi ϕ coefficient of 0.218 suggests a moderate strength of the relationship between respondents' gender and shoe appearance preferences.

2. Impact of Preference for the Waiting Time of Customized Footwear.

For the data in Table 7, using Formulas (2), (3), (5) and the Excel function (=chi.test), the following characteristics were calculated:

- The chi-square statistic is $\chi^2 = 0.1$
- Probability is $p = 0.7667$
- The coefficient $\phi = 0.02$

Table 7. Empirical data on the impact of waiting time for customized shoes vs. gender.

Feature	Woman		Man		Total	% total
	n	%	n	%		
Time has an impact	146	94%	23	92%	169	93%
Time has no impact	10	6%	2	8%	12	7%
Total	146	94%	23	92%	169	93%

Both women (94%) and men (92%) recognize the influence of waiting time on decisions about customized footwear. With small percentage differences, there is no significant disparity between the sexes. In conclusion, the data does not provide sufficient evidence for a relationship between respondents' gender and the impact of waiting time on decisions about customized footwear. Percentage analysis in the table shows that 94% of women and 92% of men recognize that waiting time influences their decisions on customized footwear.

3. The Impact of Preference for the Cost of Customized Footwear.

For the data in Table 8, using formulas (2,3,5) and the Excel function (=chi.test), the following characteristics were calculated:

- The chi-square statistic is $\chi^2 = 3.1$
- Probability is $p = 0.0787$
- The coefficient $\phi = 0.12$

Table 8. Empirical data on the impact of cost of customized shoes vs. gender.

Feature	Woman		Man		Total	% total
	n	%	n	%		
Cost has an impact	146	52%	23	32%	169	93%
Cost has no impact	10	48%	2	68%	12	7%
total	180	89%	25	11%	181	100%

The chi-square statistic $\chi^2 = 3.1$ suggests moderate statistical significance, indicating a relationship between respondents' gender and the impact of cost on purchasing decisions for customized footwear. The p-value ($p = 0.0787$) is slightly below the traditional significance level of 0.05, signifying a 92.13% confidence in the observed relationship. The phi correlation coefficient ($\phi = 0.12$) reveals a small but significant connection between gender and cost influence. Analysis shows that 52% of women consider cost crucial, compared to 32% of men, indicating a tendency among women to prioritize cost considerations.

6 Conclusions

This study delves into the interplay between consumer awareness and footwear customization in Industry 4.0. Survey results show correlations between social factors (gender, age, education, residence) and consumer awareness, impacting preferences. Women and city residents have higher awareness, while higher education and employment associate with heightened awareness. Younger respondents (18–35 years) show greater awareness than older counterparts (36–65 years).

A substantial percentage (68%) lack familiarity with “Industry 4.0,” highlighting the need for educational initiatives. Product personalization (83%) and customization (77%) enjoy high recognition, indicating growing interest. A robust understanding (92%) of “Consumer Awareness” suggests consumers grasp the significance of purchasing choices.

In customization preferences, women show a significantly higher inclination for appearance influencing footwear decisions. Waiting time does not significantly differ between genders, and there is a moderate relationship between gender and cost considerations.

No committed relationship was found between education level and opting for custom-made footwear. However, age correlates with foot deformities, and gender associates with appearance and cost considerations in purchasing customized footwear.

These findings offer valuable insights into consumer decisions, guiding future marketing strategies and product development. Tailoring efforts based on demographics, like gender and age, enhances footwear customization campaign efficacy. Recognizing the importance of educational initiatives, especially in Industry 4.0 awareness, aligns with the evolving footwear industry landscape.

To enhance understanding of consumer awareness, preferences, and the evolving footwear industry in Industry 4.0, further research will focus on exploring educational interventions for increased awareness, considering diverse communication channels and formats. Analyzing demographic factors’ detailed influence, examining intersectionality like the interplay of gender and age in shaping consumer choices.

Investigating the direct impact of Industry 4.0 technologies (e.g., 3D printing, collaborative robotics) on the footwear industry. Conducting comparative studies across regions and countries to discern variations in consumer awareness and customization preferences.




References

1. ARC Market and Opinion: Shopping online: How Poles buy clothes and shoes during the pandemic? (2021)
2. Gracz, L., Ostrowska, I.: Young Buyers on E-Shopping. Placet, Warsaw (2014)
3. Jaciow, M., Wolny, R.: The Polish e-consumer: Typology, Behavior. Helion, Gliwice (2011)
4. Gorzelany-Dziadkowiec, M.: Changes in consumer behavior in times of COVID-19. *Probl. Econ. Law* **5**, 1–15 (2020)
5. Maciejewski, G.: Consumers’ preferences about purchasing places of consumer goods and services. *Stud. Ekon.* **302**, 7–17 (2016)

6. Rahman, O.: Online consumer choice: footwear design and visual presentation. *JTATM* **10**(4), 1–19 (2018)
7. Branthwaite, H., Chockalingam, N.: Everyday footwear: an overview of ill-fitting footwear and associated pain and pathology. *Foot* **39**, 11–14 (2019)
8. Poland in Numbers. <https://stat.gov.pl/polska-w-liczbach-2022>. Accessed 09 Sept 2023
9. Mider, D.: Quantitative Data Analysis for Political Scientists. ACAD, Warszawa (2013)
10. King, B., Minium, E.: Statistics for Psychologists and Educators. PWN, Warszawa (2009)
11. Feet IN 4.0. <https://erasmus-plus.ec.europa.eu/projects>. Accessed 09 Sept 2023
12. Maslow, A.: A theory of human motivation. *Psychol. Rev.* **50**(4), 370–396 (1943)
13. Schiffman, L.G., Kanuk, L.L.: Consumer Behavior. Pearson (2010)
14. Solomon, M.R.: Consumer Behavior: Buying, Having, and Being. Pearson (2017)
15. Schwab, K.: The Fourth Industrial Revolution. Crown Business (2017)
16. Dziadkiewicz, A.: Personalization vs. customization. *Marketing* **15**(1), 98–108 (2017)
17. Zhang, J., Wedel, M.: The Effectiveness of Customized Promotions in Online and Offline Stores. University of Maryland, Baltimore (2007)
18. Woźny, D.: Impact of psychological determinants on the purchasing behaviors of young durable goods buyers. *WSZiB* **38**, 86–98 (2015)
19. Ciechomski, W.: Mass customization as a form of market communication with consumers. *PNUE Wrocław* **414**, 77–90 (2015)
20. Kucharska, B.: Trends in consumer behavior as a determinant of retail innovation. *UE Katowice* **187**, 220–228 (2014)
21. The Conscious Consumer. <https://www.accenture.com>. Accessed 09 Sept 2023
22. Bretyn, A.: Analysis and evaluation of selected aspects of consumer awareness on the example of young consumers. *Sci. Notebook US* **10**, 59–68 (2015)
23. Duda, A.: Problemy Komfortu i Bezpieczeństwa Użytkowania Obuwia. *Akademia Ekonomiczna W Krakowie* **685**, 5–18 (2005)



The Impact of KAIZEN on the Operational Performance of Multinational Manufacturing Companies Through the Degree of Maturity. A Mixed Study in Mexico

Manuel F. Suárez-Barraza¹  , Jesús A. Chávez-Pineda²,
Dailin A. Ramírez Altamirano³ , and María Isabel Huerta-Carvajal¹

¹ University of the Americas, Puebla, Mexico
manuel.suarez@udlap.mx

² Autonomous University of Chihuahua, Chihuahua, Mexico

³ National Polytechnic Institute, Mexico City, Mexico

Abstract. Kaizen or change for the better continues to be a term that needs much to be explored in the industrial environment and in the academic arena. Understanding its implementation, especially in multinational manufacturing companies (EMMs), is vital to avoid errors and confusion. On the other hand, the EMMs that apply it must explore the degree of maturity or sustainability of the implementation of Kaizen techniques to achieve positive results in their operational performance. Therefore, the general objective of this study is: to analyze the impact of Kaizen techniques through the degree of maturity on operational performance in multinational manufacturing companies (EMM). A mixed methodology (qualitative and quantitative) to analyze the implementation of the Kaizen EMM, the quantitative result, speaking, indicates the most implemented techniques, and how those EMMs that have a greater degree of maturity and implementation present better results in their operational performance.

Keywords: Kaizen · degree of maturity · operational performance · Kaizen techniques · degree of conformation · multinational manufacturing companies (EMM)

1 Introduction

In recent years, different empirical studies continue to point out the importance of Kaizen in 21st century organizations and, of course, in the academic world [1, 2]. Last year (2022), at least fifteen academic papers were presented online at the Production Operation Management Conference (POMs) 2022 that was held in virtual format from Nara Japan. On the other hand, Masaaki Imai, the man who made the term Kaizen “famous” in the mid-eighties, published his new book in 2021 “Strategic KAIZEN™” (Strategic Kaizen), where he develops the idea of Kaizen in a new global operational management through Total Flow Management. The primary focus of the book is to reduce the traditional

emphasis on volume and velocity, and replace it with a more effective approach of: flow assessment, timing, and leveling, focusing Kaizen on reducing process waste by guiding work to a value stream of each of the company's processes [4]. Similarly, in 2018 a special issue of Kaizen was published in the magazine academic TQM Journal of Editorial Emerald led by the first author, where 11 articles were published and 7 were rejected, making a grand total of 18 articles that were submitted to this special issue. Each author contributed certain theoretical elements that helped to further clarify the definition and characteristics of Kaizen [5].

The actuality of Kaizen in the 21st century is demonstrated in the interest of academics and organizations in studying the subject. Organizations have always indicated that various efforts to implement this management approach, Kaizen, over the years have not been sustained over time and have little impact on their operational performance when this occurs [5, 6]. On the other hand, it seems that the implementation of Kaizen is more focused on environments of multinational manufacturing companies (EMM) derived from the managerial and strategic influence of their corporations with respect to the management techniques they apply. Therefore, the results of the implementation of the Kaizen efforts in recent years indicate, from a practical vision of the companies, that the Kaizen has not had a sufficient impact on the operational performance of the processes themselves, they have not grown or matured in the implementation of the techniques, nor have they managed to sustain the effort for at least three years, representing great inhibitors of Kaizen in its implementation in EMM [8, 9]. In this way, the degree of maturity of the implementation of Kaizen techniques and tools is highly related to the application over time, that is, the sustainability of the improvement effort in the company [8, 10]. Therefore, it is essential to understand what is happening in companies, particularly in EMMs when they implement Kaizen with their techniques and tools with respect to their degree of maturity to demonstrate its impact on operational performance in the 21st century environment.

The Kaizen literature over the last few years has focused specifically on looking at the effectiveness of Kaizen events [11, 12], its implementation outside of Japan [13–15] even studying it as a possible business and personal philosophy [16, 17, 56]. Little if any research has studied the impact of Kaizen on operational performance through its degree of maturity or sustainability of the improvement effort. Therefore, this last element represents our academic gap (“research gap”) that has generated the motivation for the study on the part of the authors. In this way, the objective of the research is: “to analyze the impact of Kaizen techniques through the degree of maturity in the operational performance in multinational manufacturing companies (EMM)”. The research questions that support the study are the following:

- Q1.- How is Kaizen implemented in multinational manufacturing companies (EMM)?
- Q2.- What is the degree of conformation in the degree of maturity according to the conceptual scheme of Kaizen multinational manufacturing companies (EMM)?
- Q3.- What is the degree of implementation of Kaizen techniques in multinational manufacturing companies (EMM)?
- Q4.- Do Kaizen techniques with a high degree of implementation improve operational performance in multinational manufacturing companies (EMM)?

- Q5.- Is the degree of maturity in the implementation of Kaizen techniques related to greater operating performance in multinational manufacturing companies (EMM)?

Finally, the work is structured in four sections. A literature review covering the theoretical aspects of the Kaizen definition, guiding principles, main features, techniques and tools. Said section, allows to find the conceptual scheme (theoretical framework) of the investigation. Similarly, a section was added that studies the degree of maturity and sustainability of Kaizen and continuous improvement, as well as the operational performance section. In the middle section of the article, the quantitative research model derived from the analysis of the literature review is shown and the mixed methodology (qualitative and quantitative) is explained, to close with the section on statistical quantitative results, and the discussion and conclusions. Final, based on the research questions.

2 Literature Review

2.1 A Kaizen. Definition, Characteristics, Guiding Principles, Main Characteristics, Techniques and Tools

KAIZEN is an ancestral Japanese concept, probably originating from the practices of ZEN Buddhism, Japanese Shintoism, and the Bushido samurai code [3, 12, 57]. However, the term became “famous” in the managerial world environment when Masaaki Imai [22]. He published his book: “KAIZEN, the key to the Japanese competitive advantage”. Since that time, many western organizations began to practice kaizen as a continuous improvement approach in their operational processes. For Imai [22 p. 23] defines it as: “a means to continuously improve personal life, home life, social life and work life. In the work area, KAIZEN means continuous improvement for each of the company’s employees (managers and workers alike), at all times of work”. Its roots can probably be traced back to the 13th and 14th century in medieval samurai Japan [7, 12]. For Newitt [38], it is defined as the derivation of two Japanese ideograms (Kanjis): KAI (改) – change and ZEN (善) – virtuous, benevolent, to improve; that combined indicated: “change to improve” or “the principle of continuous improvement” [30 p. 28]. In this regard, the Japan Human Relations Association [4 p. 4] points out that, for the Japanese, the word KAIZEN is assumed as a symbol of the problems and struggles of every day, and the way in which people (employees) face all of it. Probably characterized by the Japanese work culture, immersed in the philosophies of Buddhism, Confucianism, Taoism and Shintoism [24, 35]. For this reason, KAIZEN has also been seen as an ethical force (internally found in oneself) of each worker, who is capable of solving problems on a day-to-day basis, fully convinced and voluntarily [50]. Therefore, reaffirming what was previously indicated, KAIZEN begins to be visualized then, as a “philosophy of life”, in which personal, family, social spheres and of course the work aspect can be covered [31]. Due to this tendency to understand KAIZEN as a harmonizing principle of the environment with the values of each individual, other authors even establish its origin in the confusionist philosophy, which establishes a deep respect and harmony for the environment, through a balance between the individual and nature [33, 34] For what is seen, as a principle or “individual spirit” of Cooperation and Improvement [42, 45]

which quickly unfolds generating a positive impact in society [33 p. 197]. According to the literature [23, 24, 29, 45, 49] there are at least four main characteristics that simplify Kaizen in the business environment:

Kaizen is a cyclical approach that tends towards simplicity and simplicity in its application through small incremental and gradual improvements.

- The improvement in the Kaizen is carried out in the processes and in the work methods with the objective of eliminating the Muda, solving problems and identifying new areas of opportunity. His focus is on processes to ensure the result.
- Employee participation is total, through work teams called KAIZEN (group KAIZEN) and improvement proposal systems (Kaizen Teian or individual).
- For problem solving, the PDCA-Plan-Do-Check-Act cycle (Plan, Do, Verify and Actual) is used as an approximation as a methodology for solving operational problems.

Once the specific characteristics of Kaizen have been presented, it is necessary to explain its theoretical scheme that was first presented in the literature in the 2011 publication in the INNOVAR magazine by Suárez-Barraza and Miguel-Dávila [48] in the Fig. 1 shows the theoretical scheme of Kaizen with its guiding principles, techniques and tools. Each of its theoretical elements is explained below:

- The guiding principles are: “a series of practices that provide an understanding or orientation allowing a bridge between knowledge and practical action, in order to generate changes in the company” [16].
- Techniques are: “a collection of problem-solving improvement activities governed by a set of common philosophical principles that have problem-solving as their goal” [16].
- The tools are: “any simple improvement task linked to a technique, that supports decision making or facilitates data analysis” [16 p. 38].

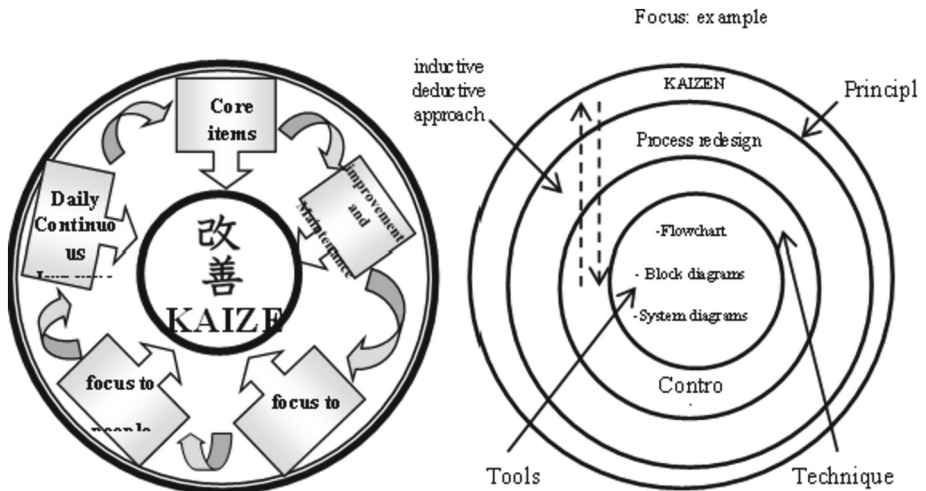


Fig. 1. Conceptual scheme of KAIZEN. Taken from the article: Suárez-Barraza, M. F. and Miguel-Dávila, J. [41], “Implementation of KAIZEN in Mexico: an exploratory study of a Japanese managerial approach in the Latin American context” (p. 24) which has as previous Copyright and intellectual property of the author, registration number 02005.12191047000001 of the book *The KAIZEN: the philosophy of continuous improvement and incremental innovation behind total quality management* (2007) Panorama editorial.

2.2 Sustainability and Degree of Maturity in the Implementation of Kaizen Techniques

As indicated in the introduction, the degree of maturity and sustainability of the improvement effort are critical to the long-term success of Kaizen. Despite the fact that Kaizen has spread worldwide, this managerial approach has presented difficulties and inhibitors in the sustained implementation in Western companies and/or outside Japan [13, 14, 40, 47]. For this reason, it is necessary to address the development of Kaizen practices towards a degree of maturity that leads to long-term sustainability.

The degree of maturity has been addressed by various authors who have conceptualized and studied this evolution of continuous improvement or Kaizen, generally focused on different evolutionary stages or sustainability paths at the time that Kaizen is implemented. Among them are the works of Bateman and David [47], Bateman [50], Suárez-Barraza and Ramis-Pujol [8], Garza-Reyes et al., [18].

The models of sustainability and degree of maturity allow mitigating to a greater or lesser extent the difficulties and/or inhibitors that may arise in the implementation of Kaizen techniques. According to the literature, the models of sustainability and degree of maturity serve to define directions of the Kaizen effort, prioritize opportunities for improvement or problems to be solved, and of course, guide possible cultural changes that may occur during the application. In this way, the models of sustainability and degrees of maturity allow us to observe the evolutionary stages that work as visual guides for change, which can be useful in the company's transformation process [53, 56]. Garza-Reyes et al., (2002) found these factors for Kaizen events [18].

By having structured and standardized models of sustainability and degree of maturity, it is ensured that the implementation of Kaizen improves the operational performance of companies [10]. For example, Suárez-Barraza and Ramis-Pujol [8] indicate that the degree of maturity of Kaizen is reached in the analyzed case study when the path of sustainability or institutionalization stage is reached (standardization of management practices in the organization). This had an impact on the sustainability of the Kaizen practices in the Spanish Town Halls that carried it out, positively impacting their processes and public services. Along the same lines, [34] points out that the implementation of innovative Kaizen techniques causes a reduction in costs in the operating processes of the companies studied, that is, when the Kaizen techniques reach a high degree of maturity and sustainability in their implementation the impact on operational performance is much greater. Berhe [9], for his part, points out in a recent study in Ethiopian companies that the practice of Kaizen in said chemical companies is supported by a structured implementation framework (following a conceptual scheme of guiding principles), the complete practice of the promoters of the Kaizen (as support from senior management and middle managers), and the eradication of inhibitors, all of them allow improving operational performance by achieving quantitative (financial and non-financial) and qualitative results in terms of workers' quality of life.. Finally, the implementation of Kaizen is crucial in optimizing operational performance in manufacturing companies in Malaysia. Every one of these investigations argues that the implementation of Kaizen techniques with a high degree of sustainability and maturity causes a positive impact on the operational performance of the company.

Finally, specifically for this research, the degree of maturity of Kaizen is defined as: *the combination of the degree of conformation according to the conceptual scheme of Kaizen (see Fig. 1 and Table 2) and the degree of implementation of KAIZEN when the techniques are institutionalized or standardized in the EMM management system.* In particular, the degree of conformation refers to how widely the implementation of the guiding principles of Kaizen have been disseminated when applied in the various areas of the company, that is, how many departments or areas of the EMM have managed to implement integral to this philosophy of continuous improvement. Thus, the degree of conformation is divided into the implementation of the technique as integral and partial. Comprehensive conformation occurs when the Kaizen techniques prescribed in the conceptual scheme (see Fig. 1 and Table 2) are fully and comprehensively adopted following the five guiding principles of Kaizen. While the degree of partial conformation occurs when only some techniques have been implemented in isolation, without following the guiding principles of Kaizen. Finally, the other component of the degree of maturity, that is, the degree of implementation of Kaizen refers to how meticulous and disciplined the implementation of Kaizen techniques is in EMM [37]. In simple terms, follow all the methodological steps of the Kaizen technique for its implementation to be successful.

2.3 Operational Performance

Companies constantly have to be better every day to stay competitive in a globalized and changing world. This situation leads industries to seek improvements in operational performance that meet the goals set year after year. At the business level, performance is the results obtained by the company after executing its operational processes in a

certain time. One of the performance indicators that is considered relevant is operational performance since the expected results in the economic, social and environmental part of the company's products and services depend on it. Kong and Rajendra [45] mention that operational performance measurements are important because operating profits in the form of cost reductions can later be used in competitive pricing. Being the operational performance defined as the performance resulting from the daily operations of the company in the productive and administrative area [38, 39].

According to Mizuno [35] operational performance has been related to the vital competitive priorities of the company such as: quality (Quality-Q), cost (Cost-C), delivery (Delivery-D) and volume (volume-V). Nawanir et al. [36], indicates that operational performance is made up of a set of multiple dimensions such as customer satisfaction with respect to product quality and its delivery in a timely manner. For their part, Ghosh [28], Shah and Ward [43], indicate that this operational performance presents the following dimensions: right-first-time quality (RTY), delivery time, manufacturing cycle time, cost reduction, scrap (MUDA in Japanese), and accidents. For Abdallah et al. [2], and Dos Santos and Tontini [26] operational performance consists of introducing new products to the market with respect to quality, cost, delivery, flexibility and speed. Within the dimensions of operational performance, the variables of quality, delivery, and costs are considered, which represent the competitive priorities related to manufacturing and have a positive influence on productivity.

For this reason, operational performance is defined in this research as: *“the set of operational indicators that encompass the dimensions of customer satisfaction with respect to quality and delivery times; the yield of good to the first of finished product (RTY); scrap and rework; manufacturing cycle time; unit manufacturing costs; the delivery time to the client and the number of cases per cluster”*.

2.4 Research Model

Based on the conceptual scheme and all the previous literature review, the following research model is proposed that analyzes the relationship between Kaizen techniques and operational performance through the degree of KAIZEN maturity in EMMs in Mexico. Below, Fig. 2 shows the established relationships schematized in the research model.

The research methodology used to test the proposed model is shown below.

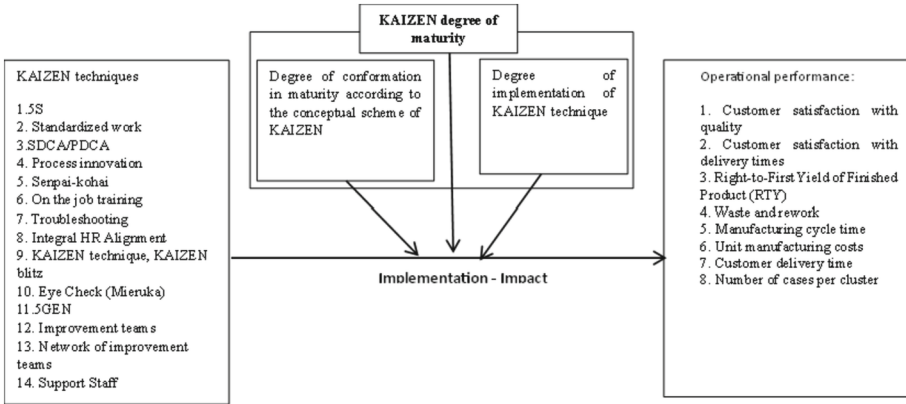


Fig. 2. Research model. Authors own design.

3 Research Methodology

According to the conceptual scheme, the literature and the research model, it was decided to carry out a mixed research methodology [46, 47]. In mixed methods there is a combination of qualitative and quantitative data collection techniques that complement each other and help to solve the limitations of each of them. In addition, the phenomena or problems in social sciences and administration (management) are complex and complicated, so they need a combination of multiple methods that cancel or limit the disadvantages of each one of them when applying them all together [46]. Therefore, the literature has a consensus that different types of methods when applying the research strengthen the study in question [46].

In this way, within the mixed research methodology, it was decided to use a sequential exploratory design of the derivative (DEPLOX) type. The selection of this approach was due to the fact that the essential focus was to carry out an initial exploration of the problem statement through a qualitative approach [46] so that once the data analysis phase was closed, specific patterns emerged. a proposed model of emerging research from the qualitative phase to later generalize it in a quantitative sample [47]. This design allowed starting from the base of the qualitative results obtained from semi-structured in-depth interviews applied to continue with the design, collection and analysis of quantitative data from surveys.

3.1 Qualitative Research: Semi-structured In-Depth Interviews

According to the derivative DEPLOX design, the first phase of the research was qualitative because it consisted of exploring how Kaizen is implemented in EMMs, specifically to understand the application of both the guiding principles and its techniques and tools. The selection of the candidates was made with the database of the EMMs located on the *LinkedIn* platform. Being the population, 512 plants with accessible candidates via this social network. Later in the complementary study this database was vital for the development of the quantitative phase. While for the selection of the actors to be interviewed

it was carried out through theoretical sampling [51]. Those people who had positions related to Kaizen who had stood out in seminars, certifications, contests, and exhibitions on the subject at the national level were selected. A total of 13 EMM candidates were contacted via email and via the LinkedIn social network. Of said total, only nine of them could be interviewed due to agenda issues and confidentiality criteria. The interviews were in-depth semi-structured with a duration of 42 min on average. All the interviews were recorded with the permission of the participants and transcribed one day after they were carried out.

Data analysis was carried out after carrying out the aforementioned transcription in a data processor (Microsoft Office Word). During the data transcription process, fillers, redundancies and repeated words were eliminated without affecting the content of the interview. Once the nine interviews had been transcribed, content analysis was used to generate categories and codes in order to find: what was understood by Kaizen?, how was Kaizen applied in EMM?, what techniques and tools were used? implemented? How were they implemented, in isolation (alone) or using the guiding principles? The result was a series of codes that helped to confirm and redesign what was indicated in the literature in the conceptual scheme of Kaizen, each of the codes were developed in a deductive way, from the most general or the most particular, and for this the color coding using MAXQDA2022 software. After the analysis of the qualitative data through the codes, we advanced to the next phase of the mixed investigation of the derivative exploratory sequence process to fully design the quantitative measurement instrument.

3.2 Quantitative Investigation. Quantitative Measuring Instrument

On the other hand, with the quantitative research, the measurement instrument was designed in three sections comprised of the variables to be studied known as: Kaizen techniques, degree of maturity of Kaizen implementation and operational performance. The following explains how the variables were addressed:

- Kaizen techniques included as an independent variable based on the conceptual scheme presented in Fig. 1 and Table 2 described in the literature. For these 14 Kaizen techniques, the same Likert perceptual scale was used with the following options: 1) 0% of the plant, 2) Between 1% and 25% of the plant, 3) Between 26% and 50% of the plant, 4) Between 51% and 75% of the plant and 5) More than 75% of the plant.
- The degree of Kaizen maturity, as an intervening variable between Kaizen techniques and operational performance, is addressed by the degree of conformation according to the Kaizen conceptual scheme (Fig. 2) and the degree of implementation of each Kaizen technique implemented in the EMMs.
- Operational performance as a dependent variable is made up of customer satisfaction, quality right the first time, waste and rework, cycle time, manufacturing costs and delivery times as can be seen in Table 1.

Table 1. Description of the items used to measure operational performance.

Item	Likert Scale Used	Sources
Customer satisfaction with product quality	1) Never, 2) Almost never, 3) Often, 4) Most of the time, 5) Always	Rahman and Bullock, [41]; Nawanir et al., [36]
Customer satisfaction with delivery time		Rahman and Bullock, [41]; Nawanir et al., [36]
Right First Time Quality of Finished Product (RTY)	1) No improvement, 2) Improvement between 1% and 10%, 3) Improvement between 11% and 20%, 4) Improvement between 21% and 50%, 5) Improvement between 51% and 75% and 6) More than 75%	Shah and Ward, [43]; Ghosh, [28]
Waste and rework Manufacturing cycle time Unit manufacturing cost	1) No reduction, 2) Reduction between 1% and 10%, 3) Reduction between 11% and 20%, 4) Reduction between 21% and 50%, 5) Reduction between 51% and 75% % and 6) More than 75% reduction	Shah and Ward, [43]; Chen, [16]; Nawanir et al., [36]

Source: Authors design

The questionnaire was carried out through the specialized platform SURVIO on the internet. Table 6 shows the verification of the internal consistency and reliability of the data by means of Cronbach’s alpha for the fourteen items that make up the Kaizen techniques model was 0.939 and 0.878 for the seven items of the performance variable. Operational. In both cases higher than 0.7 is necessary to verify the internal consistency and reliability of the questionnaire.

The constructs of the present investigation were based on an extensive review of the literature and a detailed evaluation by professionals and academics with adequate knowledge and experience in Kaizen carried out previously in qualitative research. For this reason, the items used were pre-tested in previous empirical research and qualitative research, which were adapted to ensure the validity and reliability of the instrument. The original language of the items was Spanish, the instrument was previously tested through a pilot test in 3 EMMs to verify its comprehension, before applying it extensively to the selected sample [52].

3.3 Population and Sample

The study population were EMM located in the United Mexican States (Mexico country). The database was taken from a selection of EMM candidates located on the LinkedIn

platform. Being the population, 512 plants with accessible candidates via *LinkedIn*. The analysis unit was composed of selected EMMs which had representatives with managerial and engineering positions with knowledge and certifications related to Kaizen. Each of these representatives were subjects taken for the questionnaire sample.

3.4 Sampling Technique and Data Collection Method

Formula 1. Sample size for finite populations

$$n_{Total} = \frac{512 * 1,96^2 * 0,6 * 0,4}{0,05^2 * (512 - 1) + 1,96^2 * 0,6 * 0,4} \approx 214$$

Where:

n = Sample size sought

Z = Statistical parameter that depends on the confidence level = Z value normal curve = 1.96 (95% confidence)

p = probability of success = 0.6

q = probability of failure = 1 - p = 0.4

N = Population size

E = Sampling error = 5%

The type of sampling was probabilistic. The sample size was calculated for finite populations under the assumption that 60% (p) of the respondents consider Kaizen relevant or very relevant to improve operational efficiency and 40% (q) consider it irrelevant, little irrelevant or indecisive. The calculated sample size was 214 EMM. For the data collection, the *LinkedIn recruiter* service was used for the selection of candidates, as well as he sent the surveys by this means and via email.

Finally, the valid and collected surveys were from 226 EMM distributed in the following states of Mexico: Aguascalientes, Baja California Norte, Baja California Sur, Coahuila, Chihuahua, Guanajuato, Querétaro, Nuevo León, Puebla, San Luis Potosí, Sonora, Tamaulipas and Zacatecas.

3.5 Data Analysis

In Table 2 the significance is equal to 0.000 of the Kolmogorov-Smirnov test for with Lilliefors correction for each of the Kaizen techniques, which indicates that the data does not follow a normal distribution.

In Table 3, the significance is equal to 0.000 in the Kolmogorov-Smirnov test with Lilliefors correction for each of the items analyzed in the dependent variable of operational performance, which indicates that the data of these items do not follow a normal distribution.

To obtain the data for the degree of conformation variable, the EMM was classified as integral if it met the following condition: Having a degree of implementation greater than 1% in each and every one of the techniques prescribed in the conceptual scheme (Fig. 2). If the plant did not meet this condition, it was classified as partial. For the degree of implementation variable, the MMEs were classified into a high degree of implementation (deep) and a low degree of implementation (superficial) by means of

Table 2. Kolmogorov-Smirnov normality test for KAIZEN techniques with Lilliefors correction. Source: by own

KAIZEN techniques	N	MEDIA	SD
The 5s technique has been implemented in:	226	4.1429	1.06566
The standardized work technique has been implemented in:	226	3.8950	1.20892
The SDCA and PDCA cycle has been implemented in:	226	3.7325	1.21786
The training system (On job training) has been implemented in:	226	3.6272	1.34935
At the plant, the visual control methodology (mieruka) has been implemented in:	226	3.4748	1.30457
The KAIZEN or KAIZEN blitz technique has been implemented in:	226	3.4430	1.37674
Improvement teams have been implemented (KAIZEN teams, quality circles, KAIZEN project teams) in:	226	3.3246	1.34718
Process innovation methodologies have been implemented in:	226	3.2368	1.19693
The problem-solving technique (improvement kata, A3) has been implemented in:	226	3.2281	1.37335
A network of improvement teams have been implemented in the plant in:	226	3.0789	1.34816
A support staff team for KAIZEN has been implemented in:	226	3.0746	1.38865
The HR department has a comprehensive alignment or development plan, which has both been implemented:	226	3.0132	1.32572
The 5GEN technique has been implemented in:	226	2.8553	1.40519
The technique of SENPAI (master) KOHAI (apprentice) has been implemented in:	226	2.1535	1.29660

Table 3. Kolmogorov-Smirnov normality test for operating performance with Lilliefors correction

Items	N	Media	SD	sig.	
Customers are satisfied with the overall quality of our products	226	3.89	0.73	0.00	
Customers are satisfied with our delivery times	226	3.75	0.92	0.00	
What has been the behavior of the following indicators in the last 3 years?	Right-to-First Yield of Finished Product (RTY)	226	4.36	1.48	0.00
	Waste and rework	226	3.47	1.44	0.00
	Manufacturing cycle time	226	3.39	1.54	0.00
	Unit manufacturing costs	226	3.13	1.53	0.00
	Customer delivery time	226	3.06	1.61	0.00

a k-means cluster analysis. This technique was selected for its ease of understanding

and implementation, which allows analysis of larger data sets, recognition of response patterns, and can be used to analyze categorical data [53]. The degree of maturity of the EMM was identified as high if it met the following condition: a degree of comprehensive conformation (high integration of all KAIZEN techniques implemented using the five guiding principles of the conceptual scheme, Fig. 1) and a deep degree of implementation. of Kaizen techniques (refers to how widespread the techniques are following the guiding principles of Kaizen throughout the EMM).

4 Results

4.1 Descriptive Data Analysis

Next, a descriptive analysis of the data is carried out and the results of the degree of conformation in maturity are presented according to the conceptual scheme of Kaizen, the research model and the degree of implementation of Kaizen techniques.

4.1.1 Descriptive Analysis of the Independent Variable, Degree of Maturity in the Implementation of KAIZEN Techniques

4.1.1.1 Descriptive Analysis of the Degree of Conformation of the KAIZEN Techniques

To answer the research question Q1) What is the degree of compliance according to the conceptual scheme of Kaizen in multinational manufacturing companies (EMM)? The number of EMM with a high degree of conformation in the implementation of KAIZEN techniques was identified according to the conceptual scheme (see Fig. 1). 34.8% (79) of the EMMs presented a comprehensive implementation of the conceptual scheme (see Fig. 1), while 65.2% (147) presented a partial implementation. In other words, the proportion of multinational companies that have adopted the conceptual scheme in a comprehensive manner is lower.

4.1.1.2 Descriptive Analysis of the Degree of Implementation of Kaizen Techniques

To answer the research question Q2) What is the degree of implementation of KAIZEN techniques in multinational manufacturing companies (EMM)? Two strategies were applied to analyze the results. The first one was to order the frequencies from highest to lowest according to the average implementation. The second strategy consisted of a k-means cluster analysis to classify the EMMs according to their degree of implementation of KAIZEN techniques, this classification was divided into high implementation (deep and sustained application) and low implementation (superficial and little sustained application). The corresponding results of the two indicated strategies that continues explaining. The results of the first strategy are observed in Table 4 in which the Kaizen techniques were ordered according to degree of implementation. The Kaizen technique most used by the EMM studied is the 5's. While the least used Kaizen technique in the EMM was that of SENPAI (master) KOHAI (apprentice). Table 4 is shown below:

Table 4. Descriptive statistics of Kaizen techniques.

KAIZEN techniques	N	MEDIA	SD
The 5s technique has been implemented in:	226	4.1429	1.06566
The standardized work technique has been implemented in:	226	3.8950	1.20892
The SDCA and PDCA cycle has been implemented in:	226	3.7325	1.21786
The training system (On job training) has been implemented in:	226	3.6272	1.34935
At the plant, the visual control methodology (mieruka) has been implemented in:	226	3.4748	1.30457
The KAIZEN or KAIZEN blitz technique has been implemented in:	226	3.4430	1.37674
Improvement teams have been implemented (KAIZEN teams, quality circles, KAIZEN project teams) in:	226	3.3246	1.34718
Process innovation methodologies have been implemented in:	226	3.2368	1.19693
The problem-solving technique (improvement kata, A3) has been implemented in:	226	3.2281	1.37335
A network of improvement teams have been implemented in the plant in:	226	3.0789	1.34816
A support staff team for KAIZEN has been implemented in:	226	3.0746	1.38865
The HR department has a comprehensive alignment or development plan, which has both been implemented:	226	3.0132	1.32572
The 5GEN technique has been implemented in:	226	2.8553	1.40519
The technique of SENPAI (master) KOHAI (apprentice) has been implemented in:	226	2.1535	1.29660
Valid N (per list)	226		

The second strategy shows that the Kaizen techniques of the conceptual scheme (see Fig. 1 and Table 5) were classified into a high degree of implementation (deep) and a low degree of implementation (superficial). As shown in Table 5, the techniques with a higher degree of implementation in a greater number of EMMs (number in parentheses) can be ordered as follows: Process innovation (161), 5S (160), KAIZEN event (156), standardized work (155), problem solving (146), training (On the Job training) (134), SDCA/PDCA Cycle (132), visual control (mieruka) (115), improvement teams (98), support staff (88), improvement team network (86), 5 Gen and HR comprehensive lineup (81) and finally the senpai-kohai technique (40). Table 5 explains the results of the second strategy.

Table 5. Cluster analysis for KAIZEN techniques

Cluster analysis Items	Clusters			
	High Implementation (Deep)		Low implementation (Superficial)	
	Cluster centers	EMM number	Cluster centers	EMM number
5S	4.76	160	2.64	66
Standardized work	4.64	155	2.34	71
SDCA/PDCA	4.64	132	2.45	93
Process innovation	3.84	161	1.77	64
Senpai-kohai	4.45	40	1.65	185
On the job training	4.64	134	2.16	91
Troubleshooting	4.08	146	1.65	79
Comprehensive HR Allignment	4.56	81	2.15	144
KAIZEN technique, KAIZEN blitz	4.22	156	1.67	69
Eye Chesk(Mieruka)	4.59	115	2.29	111
5GEN	4.51	81	1.94	144
Improvement teams	4.69	98	2:28	127
Improvement Teams Network	4.58	86	2.17	139
Support staff	4.60	88	2.09	137

4.1.2 Descriptive Analysis of the Dependent Variable, Operational Performance

Table 6 shows how those EMMs with high operating performance (99) and those with low operating performance (127) were classified using the K-means technique.

Table 6. Cluster analysis for operational performance

Items		Clusters	
		High operating performance	Low operating performance
Customers are satisfied with the overall quality of our products		4.15	3.71
Customers are satisfied with our delivery times		4.13	3.46
What has been the behavior of the following indicators in the last 3 years ?	Right-to-First Yield of Finished Product (RTY)	5.20	3.70
	Waste and rework	4.66	2.54
	Manufacturing cycle time	4.81	2.28
	Unit manufacturing costs	4.48	2.09
	Customer delivery time	4.40	2.01
	Number of cases per cluster	99	127

4.2 Correlational Analysis Between Kaizen Techniques and Operational Performance

For correlational analysis it is divided into two parts. The first part serves to study the relationship between Kaizen techniques individually and operational performance. The second part makes it possible to analyze the relationship between the degree of maturity of KAIZEN techniques and operational performance. The results are shown below.

4.2.1 Correlational Analysis Between Kaizen Techniques Individually and Operational Performance

To answer the research question P3) Do Kaizen techniques with a high degree of implementation improve operational performance in EMMs? The individual relationship of each of the Kaizen techniques and performance was analyzed through a contingency table. Calculating the value of χ^2 (from Pearson), its significance, the odds ratio and its confidence interval. The results for each of the Kaizen techniques are shown in Table 7.

According to the results shown in Table 7, all Kaizen techniques are associated with better operational performance. For example, for the 5's technique, the χ^2 (from Pearson) is 14.494 with a significance value $p = 0.000$, which is less than $\alpha = 0.05$, this indicates that the 5's technique is significant with respect to operating performance. Additionally, the *odds ratio* for the 5's technique was analyzed, which is 3.369 with a 95% CI of (1.771, 6.406), this indicates that the reason between high performance vs. a low performance is 3,369 times greater for the EMM that carried out a high degree of implementation of the 5's technique with respect to those that have a low degree of implementation of this technique, the same happens with each and every one of the

Table 7. Relationship between Kaizen techniques and operational performance

Practice	x2 (de Pearson)	Significance	Odds Ratio	Confidence interval (CI) 95%
5S	14.494	0.00	3.369	(1.771,6.406)
Standardized work	19.026	0.00	3.963	(2.090,7.515)
SDCA/PDCA	32.554	0.00	4.441	(2.972,9.961)
Process innovation	17.769	0.00	3.994	(2.047,7.795)
Senpai-kohai	25.558	0.00	7.045	(3.070,16.168)
On the job training	21.744	0.00	3.874	(2.162,6.942)
Troubleshooting	27.863	0.00	5.188	(2.738,9.828)
Comprehesive HR Allignment	26.390	0.00	4.400	(2.461,7.867)
KAIZEN technique, KAIZEN blitz	17.494	0.00	3.766	(1.983,7.153)
Eye Chesk(Mieruka)	30.592	0.00	4.783	(2.705,8.458)
5GEN	35.719	0.00	5.768	(3.175,10.480)
Improvement teams	26.153	0.00	4.189	(2.390,7.344)
Improvement Teams Network	19.949	0.00	3.525	(2.007,6.192)
Support staff	20.075	0.00	3.523	(2.010,6.174)

practices presented in Table 7, in this case it stands out that the senpai-kohai technique is the one with the highest odds ratio.

5 Discussion and Final Conclusions

Once this research has been completed using the mixed research methodology, it is possible to conclude following the first research question of the study: How is Kaizen implemented in multinational manufacturing companies (EMM)? The answer is that the Kaizen in EMM is still “alive”, implemented and applied on a regular basis. As the Kaizen Manager of an interviewed EMM points out: “*We have been applying Kaizen for several years, and it is maintained day by day, because we do Kaizen events, at least two or three a year... we use Kaizen as a means to carry out our Total Productive Maintenance projects, which is known here as Unified Problem Solving (SUP), so it has always been with us (Ent-06-Kaizen-Research-2022–2023)*”. This result confirms what has been stated in the literature about implementing Kaizen in EMMs in environments that are not Japanese, in the sense that the managerial approach continues to be implemented and used throughout the world [13, 14, 57]. And in Mexico it was no exception. However, when the results of both quantitative and qualitative mixed research are observed, it is possible to conclude the following elements:

- 1) Kaizen continues to be applied in Mexican EMMs. However, it is understood in isolation and generally implemented with one or two of its techniques, the most common being the Kaizen or Kaizen Blitz event.
- 2) On the other hand, there is little clarity of the term Kaizen when applying EMM, it is confused with six sigma project effort, total productive maintenance, and even lean thinking.
- 3) According to the quantitative study, only 34.8% of the EMMs studied presented a comprehensive implementation using the guiding principles of the conceptual scheme (79 EMMs), while 65.2% (147 EMMs) implemented it partially, in isolation by techniques or tools, and/or mixed with other continuous improvement approaches with six sigma, total productive maintenance and/or lean thinking (Lean Thinking). Which answers research question 2: What is the degree of conformation in the degree of maturity according to the conceptual scheme of Kaizen multinational manufacturing companies (EMM)? Each and every one of the conclusions confirms the results published in the articles published in the 2018 Kaizen special issue of the TQM Journal, noting that kaizen remains a difficult term to define, to outline and even to implement effectively. Comprehensive following an established conceptual framework when taken out of the Japanese context [5, 6, 56, 54, 55]. Therefore, confusions, partial implementations, errors and failures remain in the studied EMMs.

On the other hand, to answer research question 3: What is the degree of implementation of KAIZEN techniques in multinational manufacturing companies (EMM)? Taking the results of the mixed research, it is possible to conclude that the most widely implemented KAIZEN technique is the 5's, since it is the one with the highest average degree of implementation, while the Senpai-Kohai technique shows the lowest degree of implementation of the entire study (See Table 4). In this way, the techniques that were most applied in the EMMs were also analyzed (see Table 5), once again it was confirmed that the 5's together with process innovation are the techniques with the highest degree of implementation in a greater number of EMMs, while again the Senpai-Kohai relationship technique was the least. This conclusion is interesting because, according to the EMM studied, it indicates that the 5's are "easy" to understand and implement and that is why they are applied regularly, which confirms the work of Suárez-Barraza and Ramis-Pujol, [45] and Ishijima et al., [41]. However, when it comes to more in-depth techniques related to learning, coaching and educating people (workers), how the Senpai-Kohai technique costs a lot of work, because first you have to know them, then understand them and finally implement them within of the EMM administration system. Without the application of the teacher (Senpai)-apprentice (Kohai) relationship, it is very difficult to generate a spiral of knowledge and continuous learning in the employees of the EMMs that seek to generate a continuous cycle of continuous improvement [6, 17, 56]. Finally, the last conclusion of the study that seeks to understand the relationship of Kaizen techniques with a high degree of implementation to improve the operational performance of EMMs, it can therefore be indicated that each and every one of the Kaizen techniques studied are positively associated with better operating performance. While the odds ratio indicates that the EMMs that present a high degree of performance is 26,122 times higher for the EMMs that present a high degree of maturity (sustainability over time) with Kaizen techniques, with respect to those that

present a low degree of maturity. In this way, it is possible to conclude that the EMMs that implement Kaizen techniques following the guiding principles with a high degree of maturity (conformation-implementation) have a greater possibility of having a better operational performance than those that do not. There is empirical evidence that indeed the degree of maturity of the conceptual scheme presented in this research is associated with greater operational performance in the EMMs analyzed. The main limitation of the study is that the study focused only on EMM, and with managers, middle managers and employees focused on manufacturing, in Mexico specifically, and only in the geographical area where there is a high concentration of EMM, leaving out others. Regions of the country with fledgling EMM companies. Despite using mixed research, there may be a bias with employees familiar with the term “KAIZEN”, so it will be necessary to ask other employees of the organization who are unaware of the concept both qualitatively and quantitatively. For future studies, the relationships of the variables of the research model should be deepened using the method of structural equations. In addition, to extend the study to multinational service organizations that apply Kaizen. Finally, it is recommended in future research to make comparisons between countries to observe that the conclusions issued in this research have greater external validity and reach similar conclusions.

References

1. Álvarez-García, J., Durán-Sánchez, A., del Río-Rama, M.d.l.C.: Systematic bibliometric analysis on Kaizen in scientific journals. *TQM J.* **30**(4), 356–370 (2018). <https://doi.org/10.1108/TQM-12-2017-0171>
2. Anil, A.P., K.P., S.: TQM practices and its performance effects – an integrated model. *Int. J. Quality Reliab. Manag.* **36**(8), 1318–1344 (2019). <https://doi.org/10.1108/IJQRM-10-2018-0266>
3. Aoki, K.: Transferring Japanese KAIZEN activities to overseas plants in China. *Int. J. Oper. Prod. Manag.* **28**(6), 518–539 (2008). <https://doi.org/10.1108/01443570810875340>
4. Asociación de Relaciones Humanas del Japón KAIZEN Teian. *Desarrollo de Sistemas Para la Mejora Continua a Través de las Propuestas de los Empleados*. Productivity Press, Portland, Oregon (1992)
5. Berhe, H.H.: Application of Kaizen philosophy for enhancing manufacturing industries’ performance: exploratory study of Ethiopian chemical industries. *Int. J. Quality Reliab. Manag.* **39**(1), 204–235 (2022). <https://doi.org/10.1108/IJQRM-09-2020-0328>
6. Bessant, J., Caffyn, S., et al.: Rediscovering continuous improvement. *Technovation* **14**(1), 17–29 (1994). [https://doi.org/10.1016/0166-4972\(94\)90067-1](https://doi.org/10.1016/0166-4972(94)90067-1)
7. Brunet, A.P.: New: KAIZEN in Japan: an empirical study. *Int. J. Oper. Product. Manag.* **23**(12), 1426–1446 (2003). <https://doi.org/10.1108/01443570310506704>
8. Carnerud, D., Jaca, C., Bäckström, I.: Kaizen and continuous improvement—trends and patterns over 30 years. *TQM J.* **30**(4), 371–390 (2018)
9. Chen, Z.: The relationships among JIT, TQM and production operations performance. *Process Manag. J.* **21**(5), 1015–1039 (2015). <https://doi.org/10.1108/BPMJ-09-2014-0084>
10. Cheser, R.: The effect of Japanese KAIZEN on employee motivation in US manufacturing. *Process Manag. J.* **6**(3), 197–217 (1998). <https://doi.org/10.1108/eb028884>
11. Chua, C.: *Leadernomics*. <https://leadernomics.com/business/act-dont-just-react>. Accessed 10 Sept

12. Chung, C.H.: The Kaizen Wheel – an integrated philosophical foundation for total continuous improvement. *TQM J.* **30**(4), 409–424 (2018). <https://doi.org/10.1108/TQM-03-2018-0029>
13. Creswell, J.W.: *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*, 3rd edn. Sage Publications, Thousand Oaks (2009)
14. Creswell, J., Plano Clark, V.: *Designing and Conducting Mixed Methods Research*. Sage, Thousand Oaks (2007)
15. Da Silva, R.: *Teorías de la Administración*. Thomson Reuters, New York (2003)
16. Dean, J.W., Bowen, D.E.: Management theory and total quality: improving research and practice through theory development. *Acad. Manag. Rev.* **19**(3), 392–418 (1994). <https://doi.org/10.2307/258933>
17. dos Santos, B.G., Tontini, G.: Developing an instrument to measure lean manufacturing maturity and its relationship with operational performance. *Total Qual. Manag. Bus. Excell.* **29**(9–10), 977–995 (2018). <https://doi.org/10.1080/14783363.2018.1486537>
18. Garza-Reyes, J.A., et al.: Deploying Kaizen events in the manufacturing industry: an investigation into managerial factors. *Product. Plan. Control* **33**(5), 427–449 (2022)
19. Gondhalekar, S., Subash Babu, A., Godrej, N.B.: Towards TQM using KAIZEN process dynamics: a case study. *Int. J. Quality Reliab. Manag.* **12**(9), 192–209 (1995). <https://doi.org/10.1108/02656719510101286>
20. Gonzalez Aleu, F., Van Aken, E., Cross, J., Glover, W.: Continuous improvement project within Kaizen: critical success factors in hospitals. *TQM J.* **30**(4), 335–355 (2018)
21. Greene, J.C., Caracelli, V.J.: Defining and describing the paradigm issue in mixed-method evaluation. In: Greene, J.C., Caracelli, V.J. (eds.) *Advances in Mixed Method Evaluation: The Challenges and Benefits of Integrating Diverse Paradigms*, vol. 74, pp. 5–17. San Francisco, Jossey-Bass (1997)
22. Imai, M.: *KAIZEN: The Key to Japan’s Competitive Success*. McGraw-Hill, New York (1986)
23. Imai, M.: *KAIZEN: Genba Kaizen*. McGraw-Hill, New York (1997)
24. Imai, M.: *Strategic KAIZEN™: Using Flow, Synchronization, and Levelling [FSL™] Assessment to Measure and Strengthen Operational Performance*. McGraw-Hill, New York (2021)
25. Inman, R.A., Sale, R.S., Green, K.W., Jr., Whitten, D.: Agile manufacturing: relation to JIT, operational performance and firm performance. *J. Oper. Manag.* **29**(4), 343–355 (2011). <https://doi.org/10.1016/j.jom.2010.06.001>
26. Ishijima, H., Miyamoto, N., Masaule, F., John, R.: Improvements to healthcare waste management at regional referral hospitals in Tanzania using the KAIZEN approach. *TQM J.* **34**(5), 939–956 (2022). <https://doi.org/10.1108/TQM-10-2020-0254>
27. Kong, S.M., Rajendran, M.: The moderating effect of KAIZEN culture on the relationship between innovation and operational performance. In: *Proceedings of the 8th International Conference on Entrepreneurship and Business Management, Advances in Economics, Business and Management Research*. ICEBM 2019 UNTAR (2019). <https://doi.org/10.2991/aebmr.k.200626.003>
28. Krajewsky, L., Ritzman, L., Malhotra, M.: *Administración de Operaciones*. 8th edn. Pearson Educación, México, D.F. (2008)
29. Liker, J.K.: *The Toyota Way: 14 Management Principles from the World’s Greatest Manufacturer*. McGraw-Hill, New York (2004)
30. Lillrank, P., Kano, N.: *Continuous Improvement-Quality Control Circles in Japanese Industry*. University of Michigan, Ann Ar Bor (1989)
31. Lindberg, P., Berger, A.: Continuous improvement: design, organization and management. *Int. J. Technol. Manag.* **14**, 86 (1997)
32. Maasouman, M.A., Demirli, K.: Development of a lean maturity model for operational level planning. *Int. J. Adv. Manuf. Technol.* **83**(5–8), 1171–1188 (2015). <https://doi.org/10.1007/s00170-015-7513-4>

33. Macpherson, W.G., Lockhart, J.C., Kavan, H., Iaquinto, A.L.: KAIZEN: a Japanese philosophy and system for business excellence. *J. Bus. Strateg.* **36**(5), 3–9 (2015). <https://doi.org/10.1108/JBS-07-2014-0083>
34. McQuater, R.E., Scurr, C.H., Dale, B.G., Hillman, P.G.: Using quality tools and techniques successfully. *TQM Mag.* **7**(6), 37–42 (1995). <https://doi.org/10.1108/09544789510103761>
35. Mizuno, S.: *Company Wide Quality Control*. Asian Productivity Organization, Tokyo (1988)
36. Nawanir, G., Teong, K.L., Othman, N.S.: Impact of lean practices on operations performance and business performance some evidence from Indonesian manufacturing companies. *J. Manuf. Technol. Manag.* **24**(7), 1019–1050 (2013). <https://doi.org/10.1108/JMTM-03-2012-0027>
37. Nesensohn, C., Bryde, D., Ochieng, E., Fearon, D.: Maturity and maturity models in lean construction. *Construct. Econ. Build.* **14**, 45–59 (2014). <https://doi.org/10.5130/CEB.v14i1.3641>
38. Newitt, D.J.: Beyond BPR, TQM - managing through processes: is kaizen enough? In: *IEE Colloquium on Beyond TQM and Re-Engineering - Managing Through Process*, 3/1 (1996). <https://doi.org/10.1049/ic:19960785>
39. Ohno, T.: *Toyota Production System: Beyond Large-Scale Production*. Productivity Press, New York (1988)
40. Oliver, N., Wilkinson, B.: *The Japanization of British Industry: New Developments in the 1990s*. 2nd edn. Blackwell, Oxford (1992)
41. Rahman, S.U., Bullock, P.: Soft TQM, Hard TQM, and organizational performance relationships: an empirical investigation. *Int. J. Manag. Sci.* **33**, 73–83 (2005). <https://doi.org/10.1016/j.omega.2004.03.008>
42. Sawada, N.: The KAIZEN in Toyota production system, CHU-SAN-REN quality control course. *Nagoya* **3**, 1–38 (1995)
43. Shah, R., Ward, P.: Lean manufacturing: context, practice bundles, and performance. *J. Oper. Manag.* **21**, 129–149 (2003). [https://doi.org/10.1016/S0272-6963\(02\)00108-0](https://doi.org/10.1016/S0272-6963(02)00108-0)
44. Singh, J., Singh, H.: *Kaizen Philosophy: A Review of Literature*. Kaizen Philosophy: A Review of Literature. The ICFAI University Press (2009). <http://docshare01.docshare.tips/files/22400/224003268.pdf>
45. Suárez-Barraza, M.F.: *El KAIZEN: la filosofía de Mejora Continua e Innovación Incremental detrás de la Administración por Calidad Total*. Panorama, México (2007)
46. Suárez-Barraza, M.F., Ramis-Pujol, J.: Implementation of Lean-Kaizen in the human resource service process: a case study in a Mexican public service organisation. *J. Manuf. Technol. Manag.* **21**(3), 388–410 (2010). <https://doi.org/10.1108/17410381011024359>
47. Suárez-Barraza, M.F., Ramis-Pujol, J., Kerbache, L.: Thoughts on kaizen and its evolution: three different perspectives and guiding principles. *Int. J. Lean Six Sigma* **2**(4), 288–308 (2011). <https://doi.org/10.1108/20401461111189407>
48. Suárez-Barraza, M.F., Miguel-Dávila, J.Á.: Implementación del KAIZEN en México: un estudio exploratorio de una aproximación gerencial japonesa en el contexto latinoamericano. *Innovar* **21**(41), 19–38 (2011)
49. Suárez Barraza, M.F., Rodríguez González, F.G., Miguel Dávila, J.-A.: Introduction to the special issue on Kaizen: an ancient operation innovation strategy for organizations of the XXI century. *TQM J.* **30**(4), 250–254 (2018). <https://doi.org/10.1108/TQM-06-2018-180>
50. Styhre, A.: KAIZEN, ethics, and care of the operations: management after empowerment. *J. Manag. Stud.* **38**, 795–810 (2001). <https://doi.org/10.1111/1467-6486.00259>

51. Suárez-Barraza, M.F. Ramis-Pujol, J.: Caminos de Sostenibilidad de la Mejora Continua de Procesos en la Administración Pública: Comparativa de Ayuntamientos Españoles. GCG GEORGETOWN UNIVERSITY – UNIVERSIA **2**(2), 1988–7116 (2008)
52. Tejada, A.S.: Mejoras de Lean Manufacturing en los sistemas productivos. *Ciencia y Sociedad*, vol. XXXVI, n. 2, abril-junio, 2011, pp. 276–310. Instituto Tecnológico de Santo Domingo, Santo Domingo, República Dominicana (2011)
53. Van Aken, E.M., Farris, J.A., Glover, W.J., Letens, G.: A framework for designing, managing, and improving Kaizen event programs. *Int. J. Product. Perform. Manag.* **59**(7), 641–667 (2010)
54. Vonk, J.: Process improvement in business permits through KAIZEN. *Innovations Manage.*, 33–34 (2005)
55. Womack, J., Jones, D.: *Lean Thinking: Banish Waste and Create Wealth in Your Corporation*. Rawson Associates, New York (1996). <https://doi.org/10.1038/sj.jors.2600967>
56. Womack, J.P., Jones, D.T., Roos, D.: *The Machine that Changed the World: Based on the Massachusetts Institute of Technology*. Rawson Associates, New York (1990)
57. Yokozawa, K., Steenhuis, H.-J.: The influence of national level factors on international kaizen transfer: an exploratory study in The Netherlands. *J. Manuf. Technol. Manag.* **24**(7), 1051–1075 (2013). <https://doi.org/10.1108/JMTM-05-2011-0046>



Applying Kaizen (Incremental Innovation) in a Mexican Handcrafted Talavera Company: A Case Study Approach

Manuel F. Suárez-Barraza¹ , José Ángel Miguel-Davila² ,
and María Isabel Huerta-Carvajal¹

¹ University of the Americas, Puebla, Mexico

manuel.suarez@udlap.mx

² University of Leon, Leon, Spain

Abstract. Innovation in organizations is a management approach that helps achieve high standards of competitiveness in today's markets, in addition to the financial and economic success so sought after in the 21st century. Many organizations today are committed to making efforts of some kind of innovation; call it product innovation, process innovation or even business model innovation. In Mexico and the rest of Ibero America, some craft organizations have begun to make efforts of some kind of incremental one, also known by its Japanese name "Kaizen". This paper presents a case study methodology based on an artisanal company that manufactures "Talavera" products in Puebla Mexico. The company applied incremental innovation in some of its artisanal processes to significantly improve its operations by reducing MUDA (waste) and errors in manual processes.

Keywords: Kaizen · Incremental Innovation · Case Study Handcraft · Talavera

1 Introduction

1.1 An Introduction

Innovation in organizations is a management approach that helps achieve high standards of competitiveness in today's markets, in addition to the financial and economic success so sought after in the 21st century [8]. Many organizations today are committed to making efforts of some kind of innovation, call it product innovation, process innovation or even business model innovation; all this in order to improve both its operations and the national and international competitiveness of its products [9, 21]. In Mexico and the rest of Latin America, some craft organizations have begun to make efforts of some kind of innovation [24, 29]. One of those kinds of innovation is the incremental one, also known by its Japanese name "Kaizen" [25]. Studying the implementation of incremental innovation or Kaizen in artisan organizations is a strong empirical need that needs to be done for the field of innovation management [10, 12]. Innovation of any kind in craft organizations refers to the ability they have to bring unique processes and products to the customer and the market [21]. Hence, the importance of investigating incremental innovation in this type of company, which in Mexico and Latin America is practically nil. There is a research gap that can be covered in this research.

The purpose of this research is to describe the application of incremental innovation (Kaizen) in a Talavera crafting company in Puebla Mexico. The re-search question that arises is the following:

- RQ: How is Kaizen applied in craft organizations, specifically in a traditional Talavera crafting company?

This research is structured in four main parts. The first part sets out a conceptual framework based on two components. The first component explains what incremental innovation approach is. The second component describes the innovation approach in handicraft organizations. The second part presents the research methodology that sustains the study. The third part encompasses the application of incremental innovation in the case study. The fourth part ends the book chapter with the conclusions section.

2 Literature Review

2.1 Kaizen Philosophy (Incremental Innovation) in Handcrafted Companies

Merino Estrada [18] defines innovation as: “the use of employee creativity and scientific, technological and management knowledge to generate and/or introduce processes that increase the value offered to customers”. Innovation is, therefore, a guiding axis of the organization to make substantial changes systematized in both processes and products. In other words, these changes that employees produce systematically are managed to provide market value. [1] classifies innovation as 1) product and service innovation, 2) process innovation, 3) strategic position innovation and 4) paradigm innovation. From another perspective, Mintzberg and Westley [19] indicate that there are radical innovations, incremental innovations, focus innovations, isolated and piecemeal innovations. The incremental innovations according to these authors are those that produce small incremental changes over time. In Japan, this type of incremental innovation is known as Kaizen [25].

Kaizen is defined by Imai [15] as: “improvement or continuous improvement in social, family, personal and work life. In the workplace, Kaizen means a continuous improvement that involves everyone, managers and workers alike”. For Newitt [20], the definition of Kaizen is based on the fact that the word Kaizen is a derivation of two Japanese ideograms (Kanjis) that mean: KAI = (Change), ZEN = Good (to improve); in short, Continuous Improvement or Principle of Continuous Improvement [17]. Some techniques related to incremental innovation or Kaizen focused on small specific changes are the following according to Suárez-Barraza and Miguel-Dávila [27]:

1. *5'S*.- A technique of the first guiding principle of Kaizen that prepares employees in the values of organization, order, visual control, and operational discipline. The 5'S are Seiri (separate what is necessary from what is unnecessary), Seiton (visual organization), Seiso (corrective and preventive cleaning), Seiketsu (systematization of the three elements of the S), and Shituske (operational self-discipline).
2. *Standardization*.- A technique of the first guiding principle of Kaizen to create work guides and homogenize work processes.

3. *On-the-Job-Training*.- A technique of the fourth guiding principle of Kaizen that allows training and education in a specific technical subject in their work area.
4. *Improvement Kata or Toyota Kata*.- The methodology of the fifth guiding principle of Kaizen focused on solving operational problems [26].

There are also other innovation techniques focused on more radical approaches such as process redesign [28]. Some authors relate the incremental innovation of the Kaizen type with the radical innovation of the break-through type, resulting in the term “CONTINUOUS INNOVATION” [2, 11].

The Kaizen philosophy literature indicates that there are two types of approaches and time horizons in its implementation. The two types that are found is the permanent one, where the Kata-type problem-solving methodology of “permanent cut” improvement is used with Kaizen teams, which are applied as long as the company survives and grows. Find operating; or the “temporary cut” related to Kaizen events [32]. Regarding the topic of Kaizen events, the literature is very rich in demonstrating different critical success factors, such as: clearly defining event goals, scheduling extended follow-up activities, defining measures to track results, assigning roles for Kaizen event evaluation activities, and sharing lessons learned [9, 10]. Each and every one of these lessons learned from the time perspective at Kaizen events are vital in the implementation of Kaizen-type incremental innovation in any manufacturing industry.

According to the subject literature, the level of innovation in the craft industry depends on factors such as: value-adding, design uniqueness, new product development, cultural uniqueness, using advanced technology, experience of the owner, ability of owner to adapt to trends in market and quality of raw materials [21]. The main focus of artisans is in product innovation and with less importance in process and organizational innovation [13, 14]. According to Domínguez Hernández [5] the competitiveness of handicrafts is increased with the innovation and creativity of artisans and differentiation strategies. For these authors, artisans can look for better ways to do their work, optimizing times and costs to try to counteract the dynamism of technology in the craft world, including in its processes the stages of the painting and glazing of pieces, that is, innovating the processes incrementally.

Sánchez-Medina et al., [24] mention that incremental innovations in handicraft businesses can be presented in the form of environmental innovation, that is, treating raw and processed materials, equipment, and production processes with an environmental focus before the appearance of toxic substances in this type of operations. Finally, Harel et al. [12] indicate that incremental innovation can be presented more effectively when the Open Innovation approach is applied in small and medium enterprises. Finally, Kaizen-type incremental innovation requires, and needs committed operators with high concentration and manual dedication to their craft work, which is why the theoretical framework of Kaizen with mindfulness is vital to begin to observe more disciplined and constant with their standard of operation [33].

3 Methodology

The research methodology used for this book chapter was the Case Study [6; 31, 35]. This approach is particularly useful when the researcher needs to answer “how” and “why” questions [31, 35]. In this particular study, given the exploratory nature of it and to understand the application of Kaizen in an artisanal production organization such as the ones that produce Talavera in Puebla, the case study was selected as the optimal methodology for its application. This case study methodology is applied and is closely linked to the field of operations management [30, 34]. This case study is based on an organization located in the Mexican state of Puebla. It has many years in operation and boasts excellent experience in the artisanal manufacture of Puebla’s Talavera. Therefore, it was selected following the theoretical sample criteria [16]. The chose case study thus has great scope for contributing to a theoretical understanding and development. Pettigrew [22] notes that the importance of this kind of sample selection lies not in the number of cases but in an in-depth study of each case [22]. Accordingly, such a case should lead one to create robust theories given that the emerging propositions are linked to a wide range of the empirical evidence gathered [7]. The methods used to collect the case study data were the following:

(1) direct observation; (2) document analysis; and (3) semi-structured interviews [31].

For the direct observation method, the company was visited for 20 occasions in the period from January to March 2019. The objective of the process was to observe in a particular way how Kaizen techniques were applied in the TALAVERA-PUEBLA organization. In some cases, such as in the application of the 5’s techniques, photographs were taken before and after implementation. At the same time, the scarce documentation that the artisan company had about its operational processes was obtained to have technical support that would help us begin to write the first “draft” of the case study, validated for our book chapter. As an example, the documentation collected and that was used consists of certain processes formats and some technical manuals of machines such as ovens and painting. Finally, an interview protocol was designed, and a database was created that collected the results of their analysis [22]. The main interview and project guide contact were the Operations Manager of the Talavera-Puebla company. This person was the leader of the Kaizen implementation project. The 7 people responsible for each phase of the process were interviewed, with special emphasis on the phases of molds, lathes, enamel, glass, and paint. In total, 21 interviews were carried out with the area managers and certain key operators in the period indicated above. All interviews were semi-structured and were transcribed 48 hours after they were conducted. Everything that arose during the analysis was clarified with the contact person through the mail and by telephone. Our data analysis sought to both ensure the validity of the construct with multiple sources of evidence and carefully planned data gathering. We also sought to increase the external validity of the research by making multiple comparisons with other case studies [31].

4 Applying Incremental Innovation in Handicraft (Talavera) Mexican Company

4.1 Puebla's Talavera and the Organization's History

One morning in September 2018, the Director of the consulting area of our University contacted the researchers of this book chapter to explain a request from our University's President for a possible research-consulting project. The main purpose of this project was to support with our knowledge a group of "new entrepreneurs" who had acquired one of the "legendary" companies of the State of Puebla, Mexico; that from this moment on we will call it: "TALAVERA-PUEBLA". The Puebla businessmen sought to modernize and make the company more productive to take it to the competitive context of the 21st century. As one of the owners pointed out: *"Since we acquired the company, we have always kept in mind bringing the company's processes to the current reality of the 21st-century market, maintaining its tradition, but with modern, efficient and productive processes. That is our main purpose (E-001-TP-2019)"*. Puebla is a state of the Mexican Republic famous for its porcelain crafts, in particular, the art of Puebla's Talavera. Its origin probably dates back to Chinese production, due to its similarity to the "wan" bowls used in Japan to drink green tea or "osha". The similarity between the Hasami (波佐見焼 Hasami-Yaki) porcelain, to which this type of vases belongs to, to Puebla's Talavera is very close, hence the idea of its oriental origin. Some authors place the origin of Talavera or earthenware in China, where it began with the glazing of ceramics in the eighth and ninth centuries. At the end of the 12th century, potters from Muslim Spain took Chinese designs to the Iberian Peninsula via Mallorca. Once there, it spread throughout Europe under the definition of Mayólica. The Kingdom of Castile in Spain was the cradle of this type of craftwork, the artisans of Talavera de la Reina, populated by the kingdom, made it their own and gave it their seal and quality characteristics that govern it to this day. Of course, Chinese and Italian influences were incorporated in later years, but in that Spanish region, the true masters of this art were created.

Practically during the same period, the pre-Hispanic cultures of Mexico also entered the pottery techniques. However, they never evolved to the glaze and much less to the potter's wheel, although his skill was extraordinary. Different historical versions try to explain the arrival of majolica ceramics to Mexico, from the idea that the missionary friars themselves knew the technique until the arrival of Spanish artisans and potters who taught the craft and techniques of glazed ceramics to the inhabitants of the Mesoamerican cultures [4]. In this sense, during this colonization and migration of Spanish citizens to the new world there was also a significant number of lay potters who came to the new Spain from Seville and Talavera de la Reina during very early periods of the viceregal era. Some of them were notable in their contributions to the development of the characteristics particular to the Talavera of Puebla, one of them was Don Diego Gaytán, born in Talavera Spain [3]. By definition, Puebla's Talavera is conceptualized as a: *"type of majolica pottery typical of the State of Puebla, its distinctive base, is its ivory white vitreous finish. The authentic Talavera of Puebla only comes from that State, specifically from the towns of Atlixco, Cholula and Tecali, due to the quality of the mud found there and the tradition of its manufacture that goes back to the 16th century"* [23]. And its process continues in the state of Puebla of the Mexican Republic since the sixteenth, seventeenth, eighteenth and nineteenth centuries.

The company in the “TALAVERA-PUEBLA” case has its business history in these historical events of Puebla’s Talavera, and currently, this type of industry in Mexico’s Puebla is an internationally consolidated cluster in image, price, and market. However, it faces different operational challenges that were and still needs to be improved in companies with totally handmade processes. Therefore, the challenge presented by researchers-consultants was very great in the sense of combining tradition with modern administration and engineering techniques. However, the company exports its products to Europe, the United States, and even Oceania. Its production processes are handmade, that is, “handmade Talavera” and follow the traditions of probably the eighteenth and nineteenth centuries, is characterized by the fine clays found in the Puebla’s region, cooked with a lead and tin varnish at high temperatures Baking is still traditional. However, 20th-century ovens are used for cooking. The resulting enamel is yellow close to white, so the resulting enameled piece passes to the painting phase. At this stage, the piece is decorated with colors such as black, white, cobalt blue and king blue mainly. Other colors are used in other pieces such as yellow, green, red and sometimes hot pink. However, this process was still 100% handmade and the company presented the great challenge of innovating to face the new markets that were beginning to open for the product. The Production Manager indicated in this regard: *“The modernization and improvement focused on making the production process of the workshop efficient is a basic need for the new administration. Similarly, the great challenge we have is to ensure that personnel with a lot of technical and manual experience in the development of the pieces, think of innovation and improvement from a process efficiency approach. The reason is simple for many years working with an approach to work in artisanal production and by hand (E-002-TP-2019).”*

In summary, the company TALAVERA-PUEBLA presented four main challenges regarding operational innovation: 1) To reach a productive efficiency in the processes of artisanal production mainly focused on the products with customers of distribution stores that demand volume, by looking for the standardization of the work processes. 2) To improve the organization, order and visual control of certain workstations in the production process. 3) To motivate staff on issues of Kaizen (incremental innovation), problem-solving and MUDA (Japanese word for spending and waste) reduction to achieve greater commitment in their daily work. In other words, these changes that employees produce systematically are managed to provide market value.

4.2 Kaizen Kickoff at TALAVERA-PUEBLA

The first step was the realization of two meetings with the Management Team of the company TALAVERA-PUEBLA. The main purpose of these kickoff meetings was to build the map of the entire process of the organization to identify the traditional production process. The result is shown in the Fig. 1.

As can be seen from the figure, the process consists of nine phases that go from mud handling and the filter press to the final baking, the quality control, and the patch. Derived from the time restrictions of the application project, it was only possible to work on the Kaizen implementation in three threads that can be observed in red on the map. These processes were: 1) lathes-molds, 2) enamel-glaze, and 3) paint. Once the comprehensive process map of the production process was identified, the TALAVERA-PUEBLA Kaizen Management Team was created. It was formed by the Production

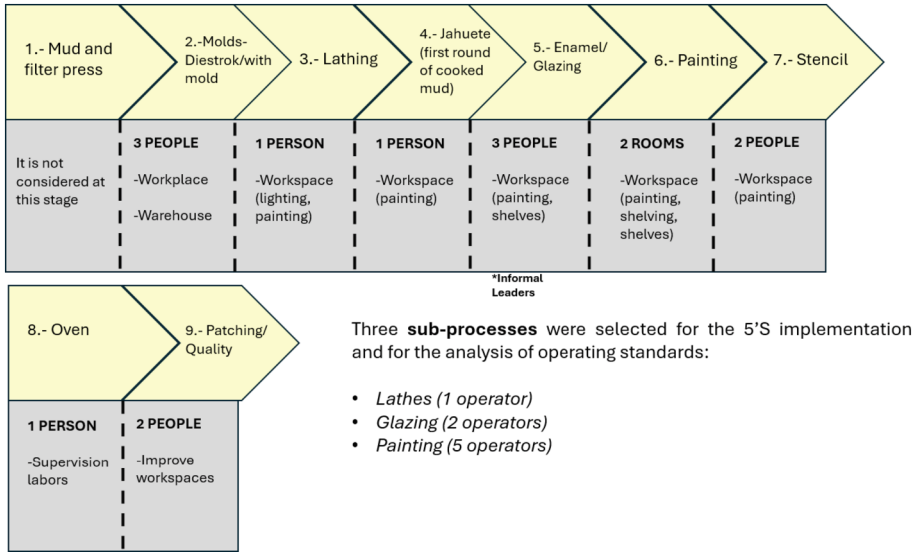


Fig. 1. Productive Process map of TALAVERA-PUEBLA. By authors.

Manager and the seven supervisors of virtually each of the nine phases of the project, in addition to the consultancy support of the three authors of this book chapter. The result of this new meeting was the determination of a work plan for the implementation of Kaizen in the company. Thus, the application of Kaizen in TALAVERA-PUEBLA began, based on at least four main techniques:

1. **ON-THE-JOB TRAINING:** Sensitize and train staff in the Kaizen philosophy and the techniques that are to be applied (5'S and standardization).
2. **ORGANIZATION, ORDER AND VISUAL CONTROL:** Application of the 5's technique in three subprocesses of the production phases (work areas).
3. **MICRO-PROCESS STANDARDIZATION:** Preparation of the operating standards sheets for the sub-processes of lathe-molds, glazing, and painting.

4.3 “On-the-Job Training” Technique

The training strategy focused on three 12-h training workshops each (one was about the Kaizen philosophy and two were regarding the 5'S technique). The central workshop focused on a 5-h training of the Kaizen philosophy to about 90 workers of TALAVERA-PUEBLA. In it, the concepts of Kaizen, process, improvement and of course, MUDA (waste) were explained. MUDA is any activity that consumes resources and does not add value to the process. Upon completion, the workers held a small exhibition where each of the groups that were formed explained the main MUDA of their workstations. The main reason for this is because all the training was done at the company's workstations. Some of the main results were the following:

- The need to improve work furniture (chairs, tables, shelves, among others) and the organization and distribution of workstations.
- The need to clearly understand the specific tasks of each process.

- The need to specifically understand workloads (schedules, work time of each employee, among others).
- The need to improve work and safety equipment for processes with high risk.

Each MUDA presented by the teams coincides with the work plans of senior management for improving and modernizing TALAVERA-PUEBLA and with the diagnosis made by the Kaizen Management Team. Finally, three main benefits of performing the On-the-job-training technique were detected:

- 1) Employee awareness of the Kaizen philosophy of continuous improvement and the concept of MUDA (waste) in their work areas.
- 2) Making practical examples of the processes that each of the employees operate in their respective workstations.
- 3) Resolution of operational doubts and obtaining data from the MUDA analysis of employees to redirect the Work Plan of the Kaizen application.

4.4 Organization, Order and Visual Control

The second technique used was the implementation of the 5'S. The purpose of this technique was to sow into the employee simply and easily the “seed” of continuous improvement. In other words, the habit to improve. As indicated in the previous technique, two 5'S training workshops were held to explain the technique to employees in their work area. Specifically, the application of this elementary Kaizen technique was carried out with the first 3'S. In this way, Separate (SEIRI) the necessary from the unnecessary (material, waste, broken parts, tools, brushes, etc.), Visual Order (SEITON) the remaining material was organized, and the work areas were painted. Finally, the Cleaning (SEISO), corrective and preventive cleaning of the selected work areas was performed. As an example, we will look at some photographs of the implementation of SEIRI, as well as of SEITON and SEISO (Fig. 2).



Fig. 2. Example of application of SEITON (VISUAL ORDER) Case of TALAVERA-PUEBLA (Not real name).

As can be seen in the first photograph, the area where the mud is received was painted in the lathe workshop, that is, the raw material areas (clay to be processed) were painted yellow. Another example was in the area of painting where the shelf was painted where all kinds of pieces were placed. After SEITON, the shelf was painted green for the finished pieces, yellow for the pieces that require some other adjustment in the paint, and finally, red for the section of failed and rejected parts. Finally, another example of SEITON and SEISO is what happened in the area of glazing. Before 5's, the tables were messy, a bit dirty because of the nature of the work and lacked visual control. After cleaning in a corrective manner and with ordering the tables in mind, a green ribbon was placed that separates the glazing work section (yellow line) with the area of the finished pieces. This small improvement in the whole process helps the glazing area to have better control in their work and their daily operations (Fig. 3).

Before 5'S application



After 5'S application



Fig. 3. Application example of SEITON (Visual Order) and SEISO (Cleanliness) in the glazing area. Case of TALAVERA-PUEBLA (Not real name).

The 5'S provide the first steps for continuous improvement in the minds of workers. Kaizen is then consolidated with small efforts and changes during the improvement of the operation.

4.5 Micro-process Standardization

The last technique of Incremental Innovation that was applied in the Kaizen implementation process at TALAVERA-PUEBLA was the standardization of the micro-process. It is not a simple task derived from the fact that such an artisanal and manual work is difficult to translate into a homogeneous and stable work. To carry out the study of the work at the micro-process level required to be with the personnel that carried out the task of the processes to be able to elaborate the operation standards sheets of the lathes-molds, glazing and painting sub-processes.

The study to obtain the data of the operating standards was carried out as follows:

1. Design and adjust the template document for the operating standards of a handmade process.
2. Conduct the study in the work area to determine the sequence of work, that is, activities and areas sequentially.
3. Subsequently, obtain the cycle time of each activity for three samples.
4. Obtain the average cycle time needed to complete a piece in each lathe, glaze and paint process.
5. Consider the specifications determined by piece size and craft activities.
6. Perform time calculations to determine the specific cycle times of each process.

In the end, the three phases of 10 workstation processes were measured (Table 1).

Table 1. Results of the measurement of operational standards. Source: Own design from the data obtained. Data is close to reality, modified for the case study

No	Operator	Piece	Cycle time of a finished piece
1	Molding 1	Small dish 37 cm	11 min
2	Glazing 1	Flower vase model 701	13.2 min
3	Glazing 2	Salt shaker 8 pieces	22.6 min
4	Glazing 3	Large tureen	19.4 min
5	Painting 1	Bowl	50 min
6	Painting 2	Large flower base	1.38 h
7	Painting 3	Small tile pieces	1.30 min
8	Painting 4	Small teapot	6 min
9	Painting 5	Medium salad dish	10 min
10	Painting 6	Large flowerpot	58 min

As a result of this work, a special formula had to be developed to calculate the cycle time per work movement, that is, the molding of the clay of each plate, the brushing in a certain section, among other movements. An example of the modified molding standard to take care of the confidentiality of the data is shown in Table 2.

Table 2. Molding standard (just a partial example). Case of TALAVERA-PUEBLA (Not real name).

No	Activity/Task	1	2	3	Real Average Time [s]
1	Preparation for work				
2	Transport to pick up packages (balas)	64	58	62	61.33
3	Puts on apron	2	2.8	2.2	2.33
4	Picks up mud in specific zone	4	5	6	5.00
5	Place mud on kneading plate	2	4	6	4.00
6	Mud kneading				
7	Kneads mud	147	118	126	130.33
8	Adds or removes pieces to form the mud pieces	6	8	6	6.67
9	Transports piece to work area	4	3	4	3.67
10	Molding process	15	12	10	12.33
11	Sits down to start operation	2	1.8	2.2	2.00
12	Place mun on lathe	4.2	4.6	4.3	4.37
13	Puts water on hand to begin molding	2	1.8	2	1.93
14	Molds downwards to give shape to mud piece	136	142	138	138.67
15	Spins lathe with leg	5	3	3	3.67
16	Dish molding cycle	226	302	279	269.00
17	Uses thread for edge cutting	2	2.5	2.2	2.23
18	Uses ruler to measure diameter	3.2	3	3.6	3.27
19	Uses L-shaped ruler to deepen plate	6.2	7	6.8	6.67
20	Uses sponge for final finish	4.5	4	4.3	4.27
21	Moistens piece once again	3	3.4	2.8	3.07

One of the best-known potters of TALAVERA-PUEBLA and who is in charge of the molding section commented: “I am 42 years old, my dad is a potter, my grandfather was also a potter, I come from a potter’s family, so my dishes, as you can see, are made with passion and a lot of hard work. They are not perfect, but every day I do them, they come out well (E-008-TP-2019).”

While elaborating his operation standard and taking the time it takes to mold a plate, he pointed out the following: “Everything is completely manual, all handmade for the Talavera to be desirable because if it is Talavera, it has to be handmade. Now, I had never seen the importance of improving my work, with this of what is called “Kaizen” I have begun to see that perhaps I had always improved my workday by day without knowing it (E-005-TP-2019)”.

Finally, another employee in the area of painting, who from our point of view had an outstanding talent for making her pieces, indicated the following: *“I think we were missing something like that, we spent a lot of time in the workshop painting each piece, as you can see, I have already painted 25 small tiles today, but I can paint about 50 without failures. But I don’t know how long it takes me to paint each one if I can improve my work, even if they can pay me more to make things better every day (E-006-TP-2019).”*

5 Conclusions and Lessons Learned

When thinking about the operation of the handicraft industry, we always focus on the artisanal features, on the beauty of the products, and even more so when it is about the Talavera of the State of Puebla in Mexico. Therefore, thinking about product innovation is viable due to its aesthetic and artisanal character. However, applying innovation in the artisanal operating process is a complex and difficult task. Now, as a conclusion of this study, we will answer the question: *“How is incremental innovation type Kaizen applied in craft organizations, specifically in a traditional Talavera company?”* The answer, according to the evidence of the case study, is that it is possible to start an effort to implement the Kaizen-type Incremental Innovation to begin to improve the operational problems that may arise in the development of handicrafts. This conclusion confirms the literature that indicates that it is possible to apply certain elements of incremental innovation in the handicraft industry either in the form of open innovation or environmentally oriented [12, 13, 24]. Our study helps to indicate that under a gradual and systematic innovation model (applied with a methodology), the operational processes of an artisanal company can be innovated. A series of lessons learned emerged from the results found in the case study:

1. *There is a strong need to standardize the operational processes of artisanal companies to eliminate all those activities that do not add value to the process and to make them more productive. The fact that they are craft processes does not exempt them from operational efficiency and added value to the process and the product.*
2. *Technical training in the workplace (OJT) is essential to improve the quality of the work performed and the focus of workers at the time of their daily activities.*
3. *The use of techniques and tools focused on Incremental Innovation (Kaizen philosophy) is essential to begin to change the focus of a traditional craft methods company to an innovative organization focused on constant and continuous change as required by the 21st century.*
4. *When innovation is presented gradually with small improvements as indicated by Kaizen (Incremental Innovation), resistance to change by employees is much lower. Also, if accompanied by training and training, employees endorse all efforts to innovate their processes through improvement teams.*

Five managerial implications from this implementation case study confirm the Kaizen literature [9, 10, 11, 12, 13, 24, 31, 33]:

- The operational planning of the processes with a focus on incremental innovation has been key in this Kaizen project at the craft company, when we turn to see the genba (the real place in Japanese) and plan on operational processes, the results of

these projects change noticeably in the perspective of the degree of success of the implementation.

- The commitment of senior management is essential to initiate a Kaizen-type incremental innovation effort in a craft company.
- Middle managers also play an active role in expanding and applying Kaizen techniques; in this case study, all the support of the manufacturing manager with the employees was vital.
- The organization, order, cleanliness and of course, visual control in such a manual and artisanal process has helped workers achieve greater results in terms of productivity, production quantity, reduction of errors, and above all, intrinsic motivation towards their work.
- Workers through the application of these techniques begin to experience less work stress, because their concentration and ease at work becomes innate, and their work is that of true experts in the field what the Japanese call (*munnen musso*) “*Iwork without a mind.*”

Finally, as the authors of this research, we are aware that with a single case study, a single type of handicraft company and in a single specific country, it is not possible to generalize the results found. However, a theoretical contribution is feasible to observe derived from the richness of the results presented here.

References

1. Bessant, J.: High Involvement Innovation. John Wiley and Sons Ltd., Chichester West Success England (2003)
2. Boer, H., Gertsen, F.: From Continuous improvement to Continuous innovation: a (retro) perspective. *Int. J. Technol. Manag.* **26**(8), 805–827 (2003)
3. Connors, M.: Talavera poblana: the renaissance of a Mexican ceramic tradition. *Mag. Antiq.* **156**(6), 824–831 (1999)
4. Delgado, C.: Talavera en su casa. Reforma, Ciudad de México, p. 5 (1996)
5. Domínguez Hernández, M.L., Hernández Girón, J.D.I.P., Toledo López, A.: Competitividad y ambiente en sectores fragmentados: El caso de la artesanía en México. *Cuader. Administ.* **17**(27), 127–158 (2004)
6. Eisenhardt, K.: Building theory from case study. *Acad. Manag. Rev.* **14**(1), 57–74 (1989)
7. Eisenhardt, K.M., Graebner, M.E.: Theory building from cases: opportunities and challenges. *Acad. Manag. Rev.* **50**(1), 25–32 (2007)
8. Frater, J., Hawley, J.: A hand-crafted slow revolution: co-designing a new genre in the luxury world. *Fashion Style Popul. Cult.* **5**(3), 299–311 (2018)
9. Garza-Reyes, J.A., et al.: Deploying Kaizen events in the manufacturing industry: an investigation into managerial factors. *Product. Plan. Control* **33**(5), 427–449 (2022)
10. Gonzalez Aleu, F., Van Aken, E.M.: Systematic literature review of critical success factors for continuous improvement projects. *Int. J. Lean Six Sigma* **7**(3), 214–232 (2016)
11. Gonzalez-Aleu, F., Van Aken, E.M., Cross, J., Glover, W.J.: Continuous improvement project within Kaizen: critical success factors in hospitals. *TQM J.* **30**(4), 335–355 (2018)
12. Gomezelj, D.: The impact of entrepreneurial characteristics and organisational culture on innovativeness in tourism firms. *Int. Res. J.* **14**(1), 93–110 (2016)
13. Gupta, R., Murkherje, I.: Scope of cottage and small-scale industry in West Bengal in early 2000. In: SSRN Working Paper Series, pp. 10–16. California (2006)

14. Harrington, H.J.: Continuous versus breakthrough improvement: finding the right answer. *Bus. Process Re-eng. Manag. J.* **1**(3), 31–49 (1995)
15. Harel, R., Schwartz, D., Kaufman, D.: Open Innovation in small business in the industry and craft sectors. *Int. J. Innov. Manag.* **23**(4), 1–33 (2019)
16. Hernández Girón, J.D.I.P., Domínguez Hernández, M.L., Caballero Caballero, M.: Factores de innovación en negocios de artesanía de México. *Gestión Polít. Públ.* **26**(2), 353–379 (2007)
17. Hernández Girón, J.D.I.P., Domínguez Hernández, M.L., Caballero Caballero, M.: Factores de éxito en los negocios de artesanía en México. *Estudios Gerenciales* **23**(104), 77–99 (2007b)
18. Imai, M.: *Kaizen-The key to Japan's Competitive Success*. Random House York, New York (1986)
19. Lewis, J., Ritchie, J.: Generalising from qualitative research. In: *Qualitative Research Practice: A Guide for Social Science Students and Researchers*. Thousand Oaks, London (2003)
20. Lillrank, P. M., Kanō, N.: *Continuous Improvement: Quality Control Circles in Japanese Industry*. Thousand Oaks, Michigan (1989)
21. Merino-Estrada, V.: La dimensión necesariamente estratégica e innovadora del gobierno local. En: FEMP (eds.), *Gobierno y Administración Municipal Creativos*, Madrid, España (2007)
22. Mintzberg, H., Westley, F.: Cycles of organizational change. *Strateg. Manag. J.* **13**(1), 39–59 (1992)
23. Newitt, D.J.: Beyond BPR & TQM - Managing through processes: Is kaizen enough? Institution of Electric Engineers (eds.) *Industrial Engineering*, London (1996)
24. Naidu, S., Chand, A., Southgate, P.: Determinants of innovation in the handicraft industry of Fiji and Tonga: an empirical analysis from a tourism perspective. *J. Enterpr. Commun.: People Places Glob. Econ.* **8**(4), 318–330 (2014)
25. Pettigrew, A.M.: What is a processual analysis? *Scand. J. Manag.* **13**(4), 337–348 (1997)
26. Pomade, R.: Talavera – Mexico's earthly legacy from the City Of Angels, Mexconnect newsletter. Consultado el 16 de junio de 2012 (2006)
27. Sánchez-Medina, P., Corbett, J., Toledo-López, A.: Environmental innovation and sustainability in small handicraft business in Mexico. *Sustainability* **3**(1), 984–1002 (2011)
28. Suárez-Barraza, M.F.: El Kaizen: la filosofía de mejora continua e innovación incremental detrás de la administración por calidad total. *Panorama*, DF, México (2007)
29. Suárez-Barraza, M.F.: *La Kata de la mejora*. Ágora, Toluca, Estado de México (2010)
30. Suárez-Barraza, M.F., Miguel-Dávila, J.: Implementación del Kaizen en México: un estudio exploratorio de una aproximación gerencial japonesa en el contexto latinoamericano. *INNOVAR* **21**(42), 19–37 (2011)
31. Suárez-Barraza, M.F., Ramis-Pujol, J., Estrada-Robles, M.: Applying gemba-Kaizen in a multinational food Company: a process innovation framework. *Int. J. Quality Serv. Sci.* **4**(1), 27–50 (2012)
32. Suárez Barraza, M.F., Rodríguez González, F.G., Miguel Dávila, J.A.: Introduction to the special issue on Kaizen: an ancient operation innovation strategy for organizations of the XXI century. *TQM J.* **30**(4), 250–254 (2018)
33. Suárez-Barraza, M.F., Huerta-Carvajal, M.I.: Kaizen-mindfulness a twin continuous improvement approach at workplace: a qualitative exploratory study. *TQM J.* (2023). <https://doi.org/10.1108/TQM-07-2023-0226>
34. Voss, C., Tsikriktsis, N., Frohlich, M.: Case research in operations management. *Int. J. Oper. Prod. Manag.* **22**(2) 195–219 (2002)
35. Yin, R.: *Case Study Research, Design and Method*. Thousands Oaks, California Estado Unidos, Sage Publication (1994)



Success Factor Driven Adaptive Approach to Pro-ergonomic Project Management

Wiktoria Czernecka^(✉)  and Marcin Butlewski 

Poznan University of Technology, Poznan, Poland
wiktoria.czernecka@put.poznan.pl

Abstract. In the era of striving for sustainable production and organization of human work, projects with ergonomic objectives are being implemented in order to provide employees with the safest and most comfortable working conditions. The question of how to achieve a positive result from such projects is therefore being addressed. The research carried out and presented in this article analyzed the factors that contribute to the successful implementation of pro-ergonomic project management. These factors were assessed by experts in such projects and the results of these assessments were then analyzed using descriptive statistics and the convergence of expert opinions was examined using cluster analysis. The most important factors assessed by the experts were: “Ensuring full support of top management in the activities of the ergonomics” and “Effective involvement of employees in the analyzed workplaces in the implementation of pro-ergonomic projects (e.g. through surveys, interviews regarding the workplace)”. The results were used to develop a method for implementing pro-ergonomic projects in manufacturing companies, the assumptions of which can be adapted depending on the project input data and company capabilities. The results of study can be used in manufacturing companies in different industries interested in pro-ergonomic project management.

Keywords: project management · pro-ergonomic approach in project management · ergonomics in production · sustainable work organization

1 An Introduction

In recent years, there has been a noticeable connection between ergonomic aspects and the sustainable development of the company. Many researchers examine the relationship between the pursuit of a balanced and sustainable work system and the implementation of ergonomic principles [1]. It is indicated that focusing the activities undertaken on the human factor in the context of the work of employees (especially towards optimizing their physical, mental and social workload) also favors other aspects of the company’s operations, e.g. production, quality of offered products and services or image as an employer [2]. The implementation of ergonomic solutions in enterprises (also in the context of shaping a sustainable organization) may be achieved by establishing ergonomic goals in ongoing projects. Increasingly, their assumption is not only to achieve satisfactory

results in a timely manner and with established resources (budget), but also to meet the adopted criteria of sustainable development. These criteria may concern the social sphere of employees' functioning, the impact of the project on the work environment or the optimal use of resources [3, 4]. It can be noticed that all these indicated areas are closely related to ergonomics - the implementation of its assumptions favors the optimal organization of the sociotechnical work system in the enterprise [5].

With the development of projects with assumed ergonomic goals, the question arose of how to increase the chances of their successful implementation, primarily due to the many variables that may shape its course [6]. Another problem considered was the fact that the full potential of such projects is not being used (they have been carried out successfully, but the results are not entirely satisfactory), e.g. in terms of the use of resources or the optimal adjustment of workstations to the capabilities of employees [7]. Doubts also arose when determining which specialists should deal with the ergonomic part of the project [8] and at what stages of the project the implementation of ergonomic goals should be planned and checked [9]. It is also problematic to separate ergonomics from goals such as productivity, as the factors for achieving them may be the same [10]. Ergonomic criteria and goals can be a reason to change decisions on how to produce and ultimately eliminate humans from the working environment in a particular area [11]. Thus, continuing to proceed with the project as ergonomic becomes unjustified.

The above premises for considering pro-ergonomic projects in the context of sustainable development and the identified research gaps in this area led to the development of a concept for investigating the success factors of such projects, which was undertaken and presented in this article. Based on a literature review and practical experience, a list of pro-ergonomic project success factors was developed and evaluated by experts. Selected factors were then included in the developed, adaptive method for implementing pro-ergonomic projects. The method can be used to manage pro-ergonomic projects in various manufacturing companies (e.g. automotive, large-scale production, production of household appliances, production of textile products), but there is also potential for its development in other areas.

2 Pro-ergonomic Approach to Project Management in Manufacturing Companies in Context of Sustainable Work Environment

In the management of pro-ergonomic projects (e.g. reorganization of the workstation, improvement of the production line, construction and equipment of a new production hall, change of work organization), ergonomic aspects are taken into account at various stages of the project (especially in the area of planning and activities undertaken as part of the project implementation). Figure 1 shows the scope of possible supplementation of project's stages with an ergonomic context.

Taking into account the above-mentioned aspects in project planning and implementation resulted in the search for factors that contribute to conducting such projects with positive outcome. For this reason, as part of the research undertaken, a review of the literature on such factors was conducted (which was supplemented with conclusions from

The stage of the project	Ergonomic aspect of the project stage
Determining the feasibility of the project; recognizing the problem	Initial ergonomic analysis using appropriate assessment methods
Defining the project assumptions; establishing goals, scope and limitations	Indication of needs for the implementation of ergonomic activities in project; setting ergonomic goals
Functional analysis of the system; analysis of the status of the existing process covered by the project	Using the results of ergonomic analysis to assess the workload of employees and indicating directions for actions to reduce this workload
Designing solutions that will be implemented in the project	Taking into account the principles of ergonomics
Implementation of project results	Ergonomic reassessment with adapted methods
Evaluation of solutions implemented in the project; solving problems after implementation	Solution evaluation support in real conditions and employee training

Fig. 1. Ergonomic aspect in project management (based on: [9, 12]).

practical experience in production projects). The factors were identified in the following categories [6, 13–15]:

- project management in general (e.g. schedule, resources),
- requirements of project's stakeholders (e.g. requirements of workplace users),
- management of ergonomic activities (e.g. ergonomic assessments),
- organizational culture and safety in the organization (e.g. value assigned to ergonomic working conditions),
- external factors affecting the project (e.g. legal conditions).

Some of the identified factors refer to the aspect of sustainable development of the organization - especially in terms of taking into account the human factor in the course of the project (e.g. employee involvement in project activities). A broader qualification of the factors taken into account in the research will be presented later in the article.

3 Materials and Methods

The research was conducted using the method of analyzing experts' opinions and clustering analysis of experts' answers using a dendrogram (single link method).

3.1 Expert Opinion Study

In the conducted research, experts (employees of ergonomics units in manufacturing enterprises) assessed the importance of the 62 success factors of pro-ergonomic projects in successfully implementing such projects on a fivepoint scale (scale 1–5, where: 1 - Very low level of importance, 2 - Low level of importance, 3 - Medium level of importance, 4 - High level of importance, 5 - Very high level of importance). Eleven experts took part in the study, what is considered as sufficient for these type of studies. Due to the small number of ergonomics units operating in manufacturing enterprises in Poland, it was decided to partially use the assumptions of the expert Delphi method in the study, but without conducting a full study in this area in accordance with its assumptions (rejection of extreme answers from experts) [16]. The criteria for selection of experts were:

- employment in the ergonomics unit in a large (employing 250 or more employees) manufacturing company,
- a member of an officially established ergonomics unit operating in the audited enterprise,
- experience in implementing pro-ergonomic projects.

3.2 Cluster Analysis of Experts' Responses

In the analysis of the answers provided in the experts' opinion study, a cluster analysis of the answers was also carried out using a dendrogram (single link method) [17, 18]. According to the assumption of cluster analysis using the single-link method, there is no clearly defined boundary (link distance) according to which clusters (individual groups of studied objects) are created - the choice depends on the characteristics of the phenomenon being studied, as well as the experience of the person conducting the research. To build a dendrogram, an analysis of the convergence of experts' assessments was used using the average of the answers provided (indicated in Table 1).

The result of the analysis was the selection of the most important success factors of the pro-ergonomic project, which were used to develop the proposed methods of implementing such projects.

4 Results

4.1 Descriptive Statistics in Expert Opinion Research

The analysis of the research results began with the presentation of descriptive statistics. The arithmetic mean, minimum and maximum value and median were taken into account (data presented in Table 1).

In order to maintain the readability of the data presented in the article, the table above presents a reduced number of factors (31 out of 62) that were selected on the basis of the conducted research to be included in the developed method.

Table 1. Descriptive statistics of expert assessment results. Source: Authors' own elaboration

No.	Project success factor	Avr.	Min.	Max.	Me.
1	Detailed identification of the problem requiring solution and setting the purpose of the project - results of the preliminary analysis of the project area	4,00	2	5	4
2	Setting a schedule for the implementation of each project, detailing all planned tasks (assigned to responsible persons)	4,09	4	5	4
3	Defining clear rules and communication channels during project implementation - communication of the project progress and results	4,18	3	5	4
4	Selection of competent members of the ergonomics unit - establishing a committee that will implement ergonomic goals in the project	4,18	3	5	4
5	Recognizing the training needs of ergonomics unit members and providing this training (e.g. in ergonomic assessments)	4,09	3	5	4
6	Effective communication of the activities of the ergonomics unit in the company to all employees - ensuring that employee opinions are taken into account in the project	4,18	3	5	4
7	Establishing clear rules for communication between the ergonomics unit and the company's employees (e.g. dedicated form, assignment of shifts, email address)	4,27	3	5	4
8	Providing organizational support for the ergonomics unit in direct contacts with employees - supporting this contact through, for example, an appropriate work schedules	4,09	3	5	4
9	Establishing clear rules for the ergonomics unit to consider employee complaints regarding working conditions and complying with them	4,09	3	5	4
10	Establishing clear templates for reports, instructions and operating procedures of the ergonomics unit	4,36	3	5	4
11	Providing full organizational support for the ergonomics unit in the project - e.g. including reporting and monitoring the implementation of the goals presented by the unit	4,09	3	5	4
12	Providing members of the ergonomics unit with the opportunity to perform tasks within project by limiting other responsibilities	4,00	3	5	4
13	Ensuring full support of top management in the activities of the ergonomics - e.g. periodic reports, participation in the development of solutions for implementation	4,82	4	5	5
14	Determining the budget available to the ergonomics unit in the project	4,27	3	5	4

(continued)

Table 1. (continued)

No.	Project success factor	Avr.	Min.	Max.	Me.
15	Establishing monitorable criteria and indicators for assessing the activities of the ergonomics unit	4,18	3	5	4
16	Setting precisely defined ergonomic goals in projects related to the production sphere in the enterprise e.g. reduction of employee ailments, reduction of activities assessed as the most burdensome	3,91	3	5	4
17	Establishing a schedule for the implementation of each pro-ergonomic project and following it	4,09	3	5	4
18	Effective communication in the company of the implementation and results of pro-ergonomic projects (employees know about such activities)	4,18	3	5	4
19	Effective involvement of senior and lowerlevel employees in the implementation of pro-ergonomic projects (use of experience, exchange of views)	4,27	3	5	4
20	Effective involvement of employees in the analyzed workplaces in the implementation of pro-ergonomic projects (e.g. through surveys, interviews regarding the workplace)	4,64	3	5	5
21	Proposing ergonomic solutions, taking into account the specificity of the workplace and the possibility of implementation (e.g. testing prototypes)	4,00	3	5	4
22	Proposing ergonomic solutions taking into account only the resources allocated for the implementation of the pro-ergonomic project (e.g. budget, technical possibilities)	4,00	2	5	4
23	High level of awareness among top management about the importance of safe and ergonomic working conditions in the company	4,64	4	5	5
24	High level of awareness of lower level employees about the importance of safe and ergonomic working conditions in the company	4,45	3	5	5
25	Effective involvement of production employees in activities aimed at improving working conditions	4,36	4	5	4
26	Providing appropriate training in the field of occupational health and safety, including building employee awareness of the importance of ergonomic working conditions	4,36	3	5	4
27	The culture of cooperation between all employees of the company in the organization to ensure safe working conditions	3,91	3	5	4
28	Friendly atmosphere in the organization, openness to employees' ideas	4,18	3	5	4

(continued)

Table 1. (continued)

No.	Project success factor	Avr.	Min.	Max.	Me.
29	Taking into account the ergonomic factor each time in the analysis of accidents at work, near misses and health problems of employees	4,09	3	5	4
30	Ensuring effective communication within the company of activities aimed at improving working conditions (including shaping ergonomic workstations)	4,00	3	5	4
31	Prioritizing the safety of employees in the enterprise (safety as the highest value)	4,45	2	5	5

4.2 Dendrogram of Expert Opinion Cluster Analysis

The study conducted using experts' opinions was also supplemented with the Kendall and Smith analysis of the agreement between experts due to the fact that there were more than three experts and the possibility of presenting the scale of their assessments in an ordinal form. The obtained coefficient was $K = 0.246$, which proves the existence of expert agreement, but its degree can be considered insufficient [19, 20]. Therefore, in the procedure of selecting factors for developing the method, it was decided not to use only descriptive statistics of experts' assessments. The cluster analysis was also used (single-link method), which involves analyzing the statements presented in the research sheet in terms of the convergence of individual expert assessments. The results in the form of a dendrogram are presented in Fig. 2.

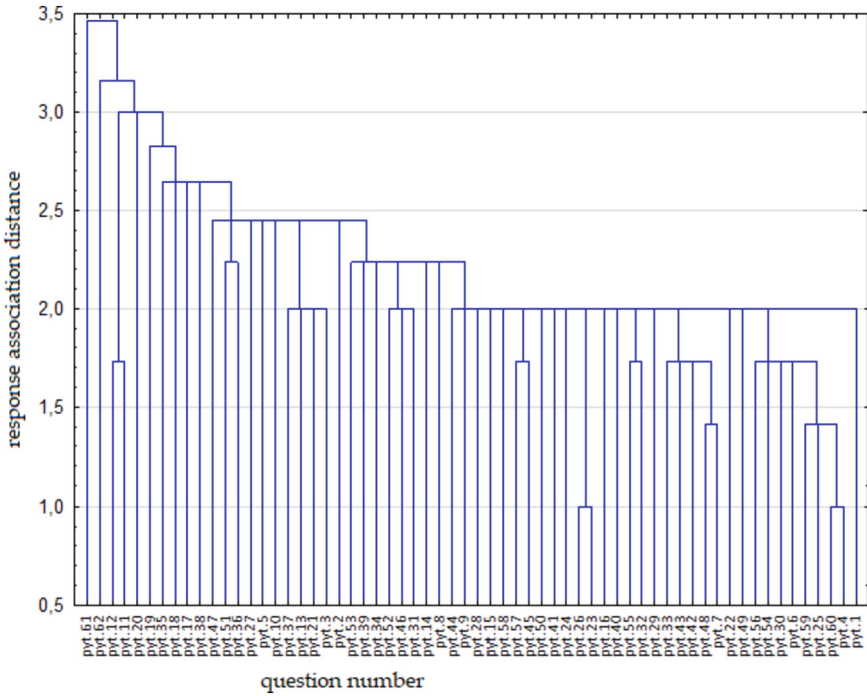


Fig. 2. Dendrogram of cluster analysis of expert responses. Source: Authors' own elaboration.

In order to select the most important factors for the success of pro-ergonomic projects in manufacturing enterprises according to experts, the bond distances between them were analyzed. According to the assumption of cluster analysis using the single-link method, there is no clearly defined boundary according to which clusters are created. Therefore, after analyzing the dendrogram presented in Fig. 2, it was decided to initially combine factors with a bond distance of 2 and smaller into groups (it can be observed that the most groups are formed there). The connections of factors into groups are shown in Table 2.

Table 2. Division into groups of factors in cluster analysis. Source: Authors' own elaboration

Factors adopted for the proposed method		Factors rejected in the proposed Method	
Group of factors according to cluster analysis	Factor number	Group of factors according to cluster analysis	Factor number
B	57	A	11
	45		12
C	26	E	33
	23		43
D	55	F	42
	32		48
G	56	J	7
	54		37
	30		13
	6		21
H	59	L	3
	25		44
I	60		9
	4		28
K	52		15
	46		58
	31		
M	50		
	41		
	24		
N	16		
	40		
O	22		
	49		

Based on cluster analysis, 24 factors were selected for the proposed method of implementing pro-ergonomic projects. Seven further factors (number: 1, 14, 29, 34, 39, 53, 62) that had a further bond distance were taken into account due to the high average rating of the experts. The final list of factors is presented in Table 1.

4.3 The Method of Implementing Pro-ergonomic Projects in Manufacturing Enterprises

Based on the research results, a method for implementing pro-ergonomic projects was developed. The method is applied by carrying out individual steps of defining, planning, monitoring and implementing the project results (in relation to the project course defined on the basis of the literature review in this field [21, 22]). Ergonomic aspects have been taken into account for the following parts of the projects [23, 24]:

- identification of the problem covered by the project,
- defining the assumptions and goals of the project,
- carrying out project activities and implementing new solutions,
- verification of the achievement of initial assumptions through project implementation.

The steps in applying the developed method are shown in Fig. 3. Due to the need to maintain the readability of the diagram, only the most important steps in the procedure were presented.

An additional aspect (beyond the standard project course) in the application of the method is the company's self-assessment of the level of shaping the success factors of the pro-ergonomic project in relation to the planned project (presented in Table 1) on a five-point scale (each factor was also assigned an average assessment of its importance by experts). The next step is to take actions aimed at shaping their desired level if it is necessary to take such actions, taking into account the nature of the project and the input data for its implementation. The method was supplemented with a set of recommendations regarding shaping the desired level of the factor (developed on the basis of a literature review and with the participation and consultation of experts participants of the ergonomics units).

After the implementation of activities aimed at increasing the level of success factors of a pro-ergonomic project in the enterprise or their level being accepted by the project team, the stage of analysis of ergonomic problems identified in the project planning phase begins, among others, by conducting ergonomic assessments using selected methods, as well as interviews with employees and observation of workplaces. It usually ends with the project team presenting a detailed report on the results obtained, which is then used to conceptualize solutions to the identified problems. It involves a review of designs available on the market (e.g. technical devices, methods of performing work), as well as identifying the need to design a new ergonomic solution, adapted to the analyzed workstations and processes. The next steps of the method include selecting solutions that will be implemented in the enterprise (taking into account its capabilities) and developing a detailed plan for this implementation. The next stage involves the implementation of the planned solutions (in some cases preceded by testing of prototypes) and initial familiarization of users with their use. Usually at this stage there are comments on necessary corrective actions provided by users, e.g. problems in functioning or inadequacy of the solution to the capabilities of employees. The method has adaptive features because there is a possibility of adapting the use of the method and its assumptions to the specificity of the enterprise and the adopted approach to project management. After implementing the solutions and making any possible corrections in their implementation, the project results

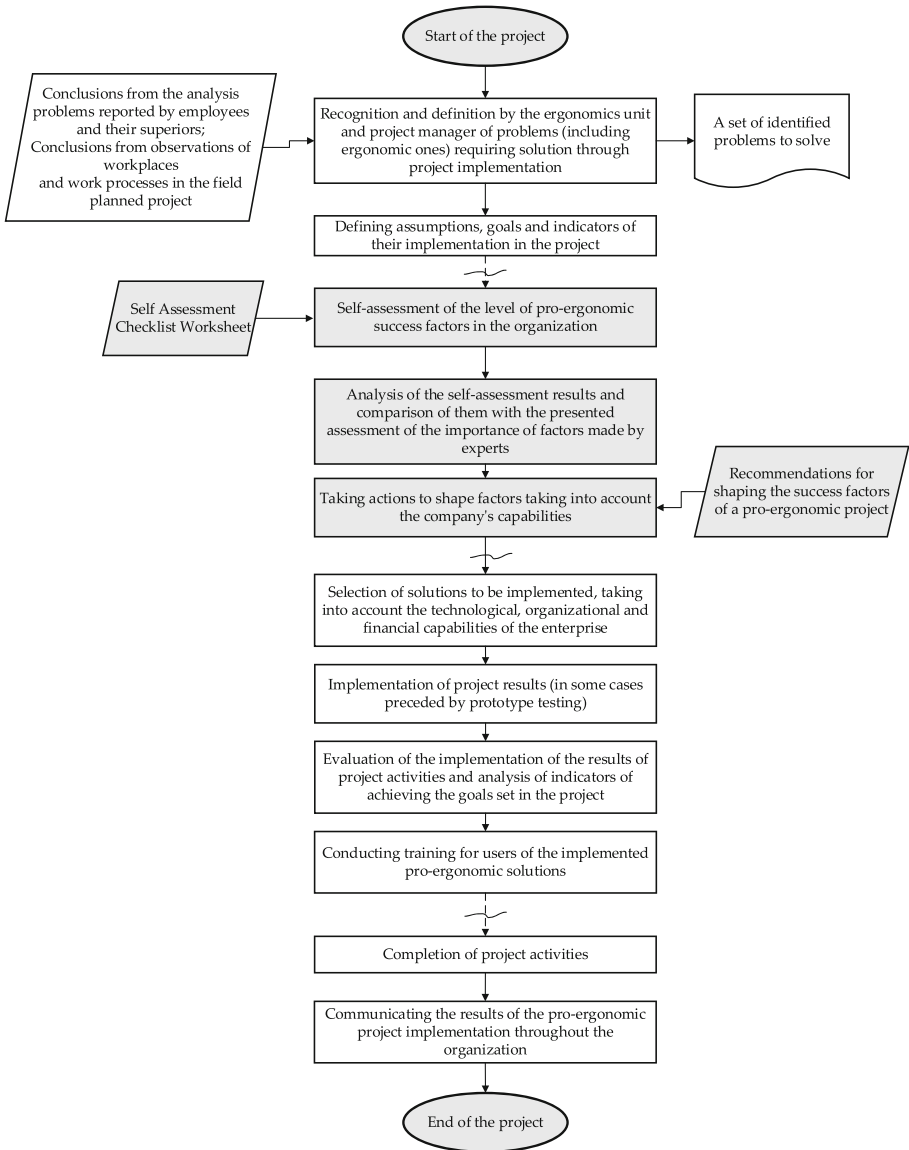


Fig. 3. Diagram of the method for implementing pro-ergonomic projects (own elaboration)

are evaluated and the degree of fulfillment of the objectives set in the planning phase is determined (if any discrepancies are noticed, corrective actions should be implemented to eliminate them).

5 Discussion

Conducting the research and developing the method led to organizing knowledge about pro-ergonomic projects and filling research gaps, as well as providing practical guidelines for their management. The use of a dendrogram to analyze the results of expert opinion study may seem questionable. It was used to complement the analysis of expert responses using descriptive statistics to more accurately assess the convergence of respondents' responses. There are no requirements as to the number of factors tested with this method, so it was possible to use it.

In the research undertaken, limitations in examining expert opinions may be indicated, e.g. related to incomplete completion of the research form or lack of understanding of the presented issues. The research eliminated this problem by appropriate selection of experts and direct explanation of the purpose and course of the study. Cluster analysis also has limitations, e.g. in the context of selecting the binding distances for analysis. In the research undertaken, this choice was made based on the analysis of the obtained graphic dendrogram.

The method was verified by applying all its steps on the example of a selected pro-ergonomic project implemented in a selected manufacturing company. Verification was carried out through participant observation in the project implementation process and contact with the project team (analysis of reports submitted by the team). It was noticed that the use of a checklist helps to organize activities related to the planning and preparation phases of the project, as well as to structure the tasks of the ergonomics unit in the project. Another conclusion identified by the project team was that they took actions that had not been taken in the company during the implementation of previous projects e.g.:

- involving senior and lower level employees in activities for ergonomics (employee participation in ergonomic assessments and conclusions based on them),
- increasing the awareness of top management in the area of ergonomics (providing short, weekly reports on the implementation of project goals),
- providing various channels of contact for the ergonomic unit with employees (e-mail, short messages about activity statuses, face-to-face meetings),
- communicating the results of the project implementation within the organization (current project status). The activities supported the implementation of the project due to increased awareness of its importance among employees and their involvement in individual stages of its implementation. According to the project team, shaping these factors resulted in considering the project from different points of view and allowed them to notice non-project aspects that may positively or negatively affect their results. In the development of the presented research, the method will be verified on a larger number of enterprises.

The method presented in the article can also be developed in the following directions: examining the application possibilities of the method in non-production enterprises, taking into account a larger number of success factors, simplifying the steps used to ensure greater universality and usability.

6 Conclusions

Striving to take ergonomic aspects into account in projects carried out in enterprises is not a new direction of research, but it requires supplementing with practical examples of how to manage such projects and factors influencing their course. The spread of such practices may support the effective management of human work in processes, but also provides opportunities for the development of a sustainable organization. Scientific research in this area may be difficult due to the multitude of processes taking place in modern organizations and the different levels of ergonomics represented in them. Nevertheless, these areas should be developed, especially considering the great importance of ergonomic working conditions (e.g. in the context of an aging society, automation and changes in the way work is organized and striving to maintain work-life balance).

References

1. Bolis, I., Albuquerque, T.A., Sigahi, C., et al.: Contribution of ergonomics and human factors to sustainable development: a systematic literature review. *Ergonomics* **66**(3), 303–321 (2023)
2. Rathore, B., Biswas, B., Gupta, R., et al.: A retrospective analysis of the evolution of ergonomics for environmental sustainability (2011–2021). *Ergonomics* **66**(6), 730–748 (2023)
3. Ebbesen, J., Hope, A.: Reimagining the iron triangle: embedding sustainability into project constrains. *PM World J.* **II**(III), 1–13 (2013)
4. Chawlaa, V.K., Chandab, A.K., Angraa, S.: The sustainable project management: a review and future possibilities. *J. Project Manag.* **3**, 157–170 (2018)
5. Bolis, I., Brunoro, C.M., Sznelwar, L.I.: Mapping the relationships between work and sustainability and the opportunities for ergonomic action. *Appl. Ergon.* **45**, 1225–1239 (2014)
6. Gauthier, F., Lagacé, D.: Critical success factors in the development and implementation of special purpose industrial tools: an ergonomic perspective. *Proc. Manuf.* **3**, 5639–5646 (2015)
7. Sultan-Taïeb, H., Parent-Lamarache, A., Gaillard, A., et al.: Economic evaluations of ergonomic interventions preventing work-related musculoskeletal disorders: a systematic review of organizational level interventions. *BMC Publ. Health* **17**, 1–13 (2017)
8. Dutier, J., Guennoc, F., Escouteloup, J.: The ergonomist: a full design actor. *Proc. Manuf.* **3**, 5830–5837 (2015)
9. Commissaris, D., Schoenmake, N., Beune, E., et al.: Applying principles of change management in ergonomic projects: a case study. *Human Fact. Ergon. Manuf.* **16**, 195–223 (2006)
10. Gajšek, B., Šinko, S., Kramberger, T., Butlewski, M., Özceylan, E., Đukić, G.: Towards productive and ergonomic order picking: multi-objective modeling approach. *Appl. Sci.* **11**(9), 4179 (2021)
11. Suszyński, M., Rogalewicz, M.: Selection of an industrial robot for assembly jobs using multicriteria decision making methods. *Manag. Prod. Eng. Rev.* **11**, 62–72 (2020)
12. Pikaar, R.: New challenges: ergonomics in engineering projects. In: Pikaar R. (eds.) *Meeting Diversity in Ergonomics*, p. 238. Koningsveld and Settels Elsevier Ltd. (2007)
13. Butlewski, M., Czernecka, W., Szczepaniak, A., et al.: Practical implications on ergonomic assessments resulting from EN-167102 ergonomics methods: a methodology for work analysis to support design. *Zeszyty Naukowe Małopolskiej Wyższej Szkoły Ekonomicznej w Tarnowie* **43**(3), 127–142 (2019)
14. da Conceição, C.A., Broberg, O., Francisco, D.: A six-step model to transform an ergonomic work analysis into design guidelines for engineering projects. *Work* **66**(3), 699–710 (2020)

15. Theberge, N., Granzow, K., Colec, D., et al.: Negotiating participation: understanding the “how” in an ergonomic change team. *Appl. Ergon.* **37**, 239–248 (2006)
16. Drumm, S., Bradley, C., Moriarty, F.: “More of an art than a science”? The development, design and mechanics of the Delphi Technique. *Res. Soc. Adm. Pharm.* **18**(1), 2230–2236 (2022)
17. Fleischmann, M.C.: Visualization and diagnostics for cluster analysis. *J. Open Source Softw.* **8**(89) (2023). <https://doi.org/10.21105/joss.05240>
18. Stanisław, A.: *Przystępny kurs statystyki z zastosowaniem STATISTICA PL na przykładach z medycyny*, vol. 3. *Analizy wielowymiarowe*, Wyd. StatSoft, Kraków (2007). [in polish]
19. Tahani, C.M.: A new weighted rank coefficient of concordance. *J. Appl. Statist.* 1–22 (2014)
20. Gorbaniuk, O.: Wykorzystywanie procedury sędziów kompetentnych w naukach społecznych i możliwości jej oceny psychometrycznej za pomocą narzędzi dostępnych w STATISTICA. *Zastosowanie statystyki i data mining w badaniach naukowych* [in polish]. (The use of the competent judges procedure in the social sciences and the possibilities of its psychometric evaluation with the tools available in STATISTICA. The use of statistics and data mining in scientific research.) Kraków, p. 520 (2016)
21. *A Guide to Project Management Body of Knowledge*, 4th edn. Project Management Institute, Newtown Square, Pennsylvania (2008)
22. Charvat, J.: *Project Management Methodologies*. Wiley, New Jersey (2003)
23. Alexandrova, M., Ivaniva Stankova, L.: Critical success factors of project management: empirical evidence from projects supported by EU programmes. In: 9th International ASECU Conference on “Systemic Economic Crisis: Current Issues and Perspectives”, Sofia, Bulgaria (2013)
24. Serrador, P.: The impact of planning on project success a literature review. *J. Mod. Project Manag.* 29–39 (2013)

Author Index

A

Ahmed, Tauseef 34
Ammar, Muhammad 34

B

Banaszak, Zbigniew 276
Bartkowiak, Tomasz 98
Bataleblu, Ali Asghar 125
Behúnová, Annamária 21
Berladir, Khrystyna 140, 328
Bocewicz, Grzegorz 276
Borreguero, Tamara 251
Borucka, Anna 239
Burduk, Anna 300
Butlewski, Marcin 395

C

Chávez-Pineda, Jesús A. 359
Czernecka, Wiktoria 395

D

Dąbrowski, Dariusz 98
Dąbrowski, Jan 98
Danilczuk, Wojciech 213
Davidrajah, Reggie 227
Diering, Magdalena 140
Dragomir, Diana 189
Duda, Jan 151
Duraismy, Rajesh 178

E

Emer, Asja 125

F

Fertsch, Marek 201

G

García-Castellano Gerbolés, Carlos 251
García-Sánchez, Álvaro 251
Gola, Arkadiusz 213

Golińska-Dawson, Paulina 276

Golser, Michaela 125

Grabowik, Cezary 342

H

Hovorun, Tetiana 328
Hrehová, Stella 60
Huerta-Carvajal, María Isabel 359, 381
Husár, Jozef 21, 60

I

Iakovets, Angelina 328
Ivanov, Vitalii 46, 328

K

Kabak, Kamil Erkan 189
Karwasz, Anna 165
Kaščák, Jakub 112
Khan, Rehan 34
Khan, Umair 34
Kłos, Sławomir 290
Knapčíková, Lucia 21, 60
Kochańska, Joanna 300
Kočiško, Marek 112
Krawczyk-Dembicka, Elżbieta 265
Krenczyk, Damian 227
Krishna, Ankur 178

L

Łampika, Łukasz 300
Łapczyńska, Dagmara 300
Lima, Ana 3
Lopes, Helena 3
Loska, Andrzej 84

M

Machado, Jose 3
Martiček, Matúš 21
Marujo, Pedro 3
Matt, Dominik T. 125

Miguel-Davila, José Ángel 381
Musiał, Kamil 300

N

Niesterowicz, Beata 74

O

Oleśków-Szłapka, Joanna 201
Oleszek, Sylwester 151
Ortega-Mier, Miguel 251

P

Paszkowski, Waldemar 84
Patalas-Maliszewska, Justyna 290
Patrejko, Krzysztof 239
Patrejko, Łukasz 239
Pizoń, Jakub 213
Polakowski, Konrad 239
PopiŃster, Florin 189

Q

Qureshi, Ariba 34

R

Ramirez Altamirano, Dailin A. 359
Rauch, Erwin 125

S

Santarek, Krzysztof 151, 313
Santos, André S. 46, 140
Silva, Hugo 46, 140
Skolud, Bożena 227
Sobowale, Adeniyi 3
Stachowiak, Agnieszka 201
Suárez-Barraza, Manuel F. 359, 381
Szwarc, Eryk 276

T

Tauberová, Rebeka 21
Terelak-Tymczyna, Agnieszka 74
Török, Jozef 112
Trojanowska, Justyna 3, 46, 328
Trojanowski, Piotr 60

U

Urban, Wiesław 265

V

Varela, Leonilde R. 46, 140
Vilanova Diego, Carmen de 251
Vodilka, Adrián 112

W

Waszkowski, Robert 84
Wawrzynowicz, Igor 165
Wieczorowski, Michał 34
Wierzchowski, Piotr 98
Wrześniowska, Karolina 342