Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnline 59-10 (2025) i–xv

IFAC PapersOnline
CONFERENCE PAPER ARCHIVE

International Federation of Automatic Control

11th IFAC Conference on Manufacturing Modelling, Management and Control MIM 2025

Trondheim, Norway, June 30 – July 03, 2025

PROCEEDINGS

Edited by
Fabio Sgarbossa, *Norwegian University of Science and Technology, NO*
Sotirios Panagou, *Norwegian University of Science and Technology, NO*
Erlend Alfnes, *Norwegian University of Science and Technology, NO*
Alexandre Dolgui, *IMT Atlantique, FR*
Dmitry Ivanov, *Berlin School of Economics and Law, DE*
Daria Battini, *University of Padova, IT*

ELSEVIER

IFAC Proceedings Volumes (IFAC-PapersOnline) — ISSN 2405-8963

IFAC PapersOnline — ISSN 2405-8963

Published by:
International Federation of Automatic Control (IFAC)
Hosting by Elsevier Ltd.

Available online at

www.sciencedirect.com

Publication date
July 2025

Copyright conditions

11th IFAC Conference on Manufacturing Modelling, Management and Control
MIM 2025

Sponsored by

International Federation of Automatic Control (IFAC)
- Management and Control in Manufacturing and Logistics, TC 5.2.

Co-Sponsored by

International Federation of Automatic Control (IFAC)
- TC 1.3. Discrete Event and Hybrid Systems
- TC 3.2. Computational Intelligence in Control
- TC 5.1. Manufacturing Plant Control
- TC 7.4. Transportation Systems
- TC 9.1. Economic, Business, and Financial Systems

Supporting organizations and sponsors

NTNU | Faculty of Engineering
Department of Mechanical and Industrial Engineering

NTNU | Production Management Research Group
- LOGISTICS 4.0 LAB -

Springer

Taylor & Francis
Taylor & Francis Group

nfea

TRONDHEIM KOMMUNE
Tråanten tjïelte

hexaly

FutureLOG
Funded by The Research Council of Norway

International Programme Committee

Alexandre Dolgui, FR (Advisory Chair)
Dmitry Ivanov, DE (IPC Chair)
Daria Battini, IT (IPC Vice-Chair)
Oleg Y. Gusikhin, US (IPC Vice-Chair from Industry)

El-Houssaine Aghezzaf, BE
Erlend Alfnes, NO
Lionel Amodéo, FR
Bjørn Andersen, NO
Fazel Ansari, AT
Simone Arena, IT
Julia Arlinghaus, DE
Ronald Askin, US
Zied Babai, FR
Hossein Baharmand, NO
Natalia Bakhtadze, RU
Eric Ballot, FR
Zbigniew Banaszak, PO
Olga Battaïa, FR
Daria Battini, IT
Lyes Benyoucef, FR
Bopaya Bidanda, US
Alexandra Brintrup, UK
Martina Calzavara, IT
Sergio Cavalieri, IT
Felix T.S. Chan, HK
Weiwei Chen, UK
Tsan-Ming, UK
Yuval Cohen, Israel
Isabel Demongodin, FR
Xavier Delorme, FR
Yasser Dessouky, US
Stephen Disney, UK
Alexandre Dolgui, FR
Banu Ekren, UK
Martin Fabian, SE
Alexander Fay, DE
Serena Finco, IT
Samuel Fosso, FR
Giuseppe Fragapane, NO
Michael Freitag, DE
Stanley Gershwin, US
Christoph Glock, DE
Stephen C. Graves, US
Eric Grosse, DE
Robert Grubbström, SE
Angappa Gunasekaran, US
Surendra M. Gupta, US
Oleg Gusikhin, US
Hichem Haddou, FR
George Huang, HK
Lars Magnus, NO
Benoit Iung, FR
Dmitry Ivanov, DE
Jayanth Jayaram, US
Esko Juuso, FI
Manju Kamath, US
Abdelhakim Khatab, FR
Dimitris Kiritsis, CH
Matthias Klumpp, DE
Lenny Koh, UK
Ratnesh Kumar, US
Andrew Kusiak, US
Tone Lerher, SI
Andrei Lobov, FI
Marco Macchi, IT
Andrea Matta, IT
Semyon M. Meerkov, US
Manuel Meyer, DE
Stefan Minner, DE
Laszlo Monostori, HU
Benoit Montreuil, US
Trindade M. Alice Moreira, IT
Enzo Morosini Frazzon, BR
Dimitris Mourtzis, GR
Josefa Mula, ES
Giovanni Mummolo, IT
Rakesh Nagi, US
Shimon Y. Nof, US
José F. Oliveira, PT
Antonio Padovano, IT
Sotirios Panagou, NO
Hervé Panetto, FR
Alessandro Persona, IT
Erwin Pesch, DE
Michael L. Pinedo, US
Roberto Pinto, IT
David Porter, US
Jörg Raisch, DE
Tobias Reggelin, DE
Geir Ringen, NO
Debjit Roy, IN
Ivan Russo, IT
Joseph Sarkis, US
Tadeusz Sawik, PO
Suresh Sethi, FR
Daniel Silva, US
David Simchi-Levi, US
Alice Smith, US
Boris Sokolov, RU
Kathryn Stecke, US
Marco Taisch, IT
Sri Talluri, US
Chris Tang, US
Ou Tang, SE
Lixin Tang, CN
R. Tavakkoli-Moghaddam, IR
Matthias Thurer, CN
Manoj Tiwari, IN
Tulio Tolio, IT
Kaihara Toshiya, JP
Francois Vernadat, FR
Susana Vieira, BR
Agostino Villa, IT
Francesco Viti, LU
Thomas Volling, DE
Fei-Yue Wang, CN
Xiao Wang, CN
Torgeir Welo, NO
Frank Werner, DE
Dash Wu, CA
Alice Yalaoui, FR
Farouk Yalaoui, FR
Candace Yano, US
Marek Zaremba, CA
Ilenia Zennaro, IT
Guoqing Zhang, CA
Yrjö Majanne, FI

National Organizing Committee

Sotirios Panagou, NO (NOC Co-Chair)
Erlend Alfnes, NO (NOC Co-Chair)
Geir Ringen, NO (NOC Vice-Chair from Industry)

Fabio Sgarbossa, NO (General Chair)
Eric Grosse, DE (Social Media and Website Committee)
Sotirios Panagou, NO (Social Media and Website Committee)
Enes Demiralay, NO (Social Media and Website Committee)
Giulia Fede, NO (Social Media and Website Committee)

Erlend Alfnes, NO
Hossein Arshad, NO
Giulia Fede, NO
Sobhan M. Darmian, NO
Enes Demiralay, NO
Yüksel D. Demiralay, TR
Niloofar Jafari, NO
Ayah Mustafa, NO
Uyen Ngo, NO
Anna Olsen, NO
Sotirios Panagou, NO
Geir Ringen, NO
Fabio Sgarbossa, NO
Sinan Smith, NO
Kasuni V. Weerasinghe, NO
Amir Zare, NO

From NTNU conference:
Monica Amundsen, NO
Anna Cassigneul, NO

Technical Associate Editors

Erlend Alfnes, NO
Simone Arena, IT
Olga Battaïa, FR
Daria Battini, IT
Martina Calzavara, IT
Xavier Delorme, FR
Alexandre Dolgui, FR
Enzo Morosini Frazzon, BR
Eric Grosse, DE
Dmitry Ivanov, DE
Sotirios Panagou, NO
Roberto Pinto, IT
Fabio Sgarbossa, NO

Doctoral Workshop Committee

Hind Bril El Haouzi, FR (Co-Chair from TC 5.1)
Daria Battini, IT (Co-Chair from TC 5.2)
Hossein Arshad, NO (National organizer)

Mentors

Amin Abdous, FR
Simone Arena, IT
Hossein Arshad, NO
Daria Battini, IT
Martina Calzavara, IT
Xavier Delorme, FR
Krzysztof Ejsmont, PL
Hind Bril El Haouzi, FR
Serena Finco, IT
Chiara Franciosi, IT
Eric Grosse, GE
Matthias Klumpp, IT
Giulio Mangano, IT
Roberto Pinto, IT
Foivos Psarommatis, CH
Daniel Silva, US

FOREWORD

The 11th IFAC Conference on Manufacturing Modelling, Management and Control (MIM 2025) was held in Trondheim, Norway, from 30th June to 3rd July. This year's edition is particularly special as we gather under the powerful and timely motto: "Be the Impact! Make a Better World."

Industrial and academic worlds around manufacturing and logistics are facing every day new challenges but also rapid changes in technology developments and business models, like Generative AI, smart robotization & automation, digitalization and data-analytics, advanced simulation, industry 4.0 and 5.0, circular economy, shared economy, and many others, which can help decision makers, practitioners, researchers to find solutions to those challenges.

Whatever trend we are living, we at NTNU – Production Management Research Group & Logistics 4.0 Lab believe that our activities should benefit society as a whole!!! Creative, Critical, Constructive and Respectful are values which guide us towards our vision "Knowledge for a better world".

This is why the general theme of the 11th IFAC Conference on Manufacturing Modelling, Management and Control (IFAC MIM2025) at NTNU was "Research and Innovation on Manufacturing and Logistics for a better world".

The aim of this conference was to bring together researchers and practitioners to present and discuss emerging topics in modern and future manufacturing modelling, management, and control, following a rich tradition of previous IFAC conferences and symposia in manufacturing and logistics. Through its motto "Be the impact! Make a better world.", IFAC MIM2025 focused on the most innovative methods in manufacturing and logistics, with emphasis in how to generate impactful research and innovation for society, with interdisciplinary and innovative methods, cross-sectorial applications, inclusive approaches, engagement, and growth of younger researchers.

In addition to scientific sessions, there was the opportunity to attend keynote presentations, workshops, and panel debates.

We are grateful to the International Program Committee, Technical Associate Editors, National Organizing Committee and the more than 800 reviewers for the excellent work done to put together the following program and guarantee the quality of papers submitted and research presented. Some numbers related to IFAC MIM2025:

- Number of submissions: 793 from 53 countries
- Number of session proposals: 81
- Number of authors: 2034 from 53 countries
- Number of reviewers: 800 reviewers for more than 2000 reviews received
- Presentations (papers and extended abstracts) in program: 574 (all on site)
- Acceptance rate: 72%
- Number of sessions in program: 119
- Number of participants: 707 from 51 countries (the conference was only fully physical, so no digital participation was allowed)

The main sponsor, IFAC Technical Committee 5.2 "Management and Control in Manufacturing and Logistics" supported the promotion and organization with its:

Chair:

- Prof. Dr. Fabio Sgarbossa (NTNU, Norway)

Vice-Chairs:

- Prof. Dr. habil. Dr. Dmitry Ivanov, ScD (Berlin School of Economics and Law, Germany)
- Prof. Dr. Alexandre Dolgui, Ph.D., Dr. habil. (IMT Atlantique, France)
- Prof. Dr. Natalia Bakhtadze, ScD (Institute of Control Sciences, Russia)
- Prof. Dr. Farouk, Yalaoui, Ph.D., Dr. habil. (University of Technology of Troyes, France)

Vice-Chair for Education:

- Prof. Dr. Daria Battini (University of Padua, Italy),

Vice-Chair for Publication:

- Prof. Dr. Enzo Morosini Frazzon (Federal University of Santa Catarina, Brazil),

Vice-Chair for Industry:

- Dr. Oleg Gusikhin (Ford, USA),

Vice-Chair for Social Media:

- Jun.-Prof. Dr. Eric Grosse (Saarland University, Germany)

More than 110 members from about 30 countries have been creating a vibrant and collaborative environment. The following working groups organized more than 30 sessions:

- WG1 Digital Supply Network Engineering and Management
  Chairs: Prof. Alexandre Dolgui and Prof. Dmitry Ivanov
- WG2 Advanced multi-criteria applications in manufacturing and logistics
  Chairs: Prof. Lyes Benyoucef, Dr. Aguirre Hernan and Prof. Farouk Yalaoui
- WG3 Design and modelling of flexible and reconfigurable manufacturing systems
- Chairs: Dr. Olga Battaia, Dr. Xavier Delorme, Dr. Rita Gamberini and Prof. Manoj Kumar Tiwari
- WG5 Challenges and opportunities in applying Additive Manufacturing in Supply Chains
  Chairs: Associate Prof. Mirco Peron, Dr. Nils Knofius, Associate Prof. Francesco Lolli, Prof. Fabio Sgarbossa, Prof. Tsan-Ming Choi
- WG6 Intelligent methods and systems supporting supply chain decision making
  Chairs: Prof. Michael Freitag, Prof. Enzo Morosini Frazzon, and Prof. Raphaël Oger
- WG7 Human factors and ergonomics in industrial and logistic system design and management
  Chairs: Prof. Daria Battini, Prof. Fabio Sgarbossa, Prof. Christoph Glock, Prof. Eric Grosse, Prof. Martina Calzavara
- WG8 Smart, Reliable and Sustainable Manufacturing-Distribution Systems
  Chairs: Dr. Abdelhakim Khatab, Prof. Lyes Benyoucef, Prof. Claver Diallo, Prof. El Houssaine Aghezzaf, Prof. Uday Venkatadri
- WG9 Digital Twins in Manufacturing and Logistics Systems
  Chairs: Dr. Serena Finco, Prof. Mirco Peron, Prof. Audrey Derrien, Prof. Olga Battaïa, Prof. Xavier Delorme, Prof. Daria Battini
- WG10 Smart intralogistics for warehousing and material handling in manufacturing and distribution systems
  Chairs: Prof. Martina Calzavara, Prof. Eric Grosse, Dr. Dominic Loske, Prof. Elena Tappia, Prof. Ilenia Zennaro

The local organizer, the Production Management Research Group at Department of Mechanical and Industrial Engineering, is a team of about 20 professors and researchers focusing on the design and planning of production and logistics systems, seen as integrated systems of people, materials and products, information, equipment, and energy and environmental resources.
The research group develops specialized knowledge, applying mixed methodology, combining qualitative and quantitative methods, from action research and case studies to statistical analysis and operations research. Focus is put on multidisciplinary approach, joining skills, principles and methods of engineering, management, and computer science.
Research is done in close cooperation with industrial and international networks, funded by funding bodies, as EU commission and Research Council of Norway. The current portfolio is composed of more than 5 active research projects, for about 2.5 million euro. The results of these projects are published in relevant journals, such as International Journal of Production Research, Production Planning and Control, International Journal of Production Economics, European Journal of Operational Research, Journal of Intelligent Manufacturing, International Journal of Operations and Production Management. Members of the research group are actively involved in editorial boards of relevant journals (IJPR, IJPE, JIM, and others) as well as active and managing roles in international societies (IFIP, IFAC, MHI, and others).
The Production Management Research Group is responsible of the Logistics 4.0 lab, the Norway's first logistics laboratory that merges digital technologies with traditional production and logistics systems, enabling researchers, practitioners, engineers, pioneers, students, and other enthusiasts to come together and collaborate on common ground.

Key highlights of the conference

The conference started with the 2nd Doctoral Workshop on "Advances in Manufacturing and Logistics management and control problems" on the 30th June. The workshop was proposed by TC 5.1 and TC 5.2 in collaboration with the CC 5 and IFAC MIM2025. The participation to this new initiative leveraged synergies between the experienced and the young researchers in our community, within a context that facilitated research and knowledge exchanges. The goal for TC 5.1 and TC 5.2 was to create an open environment through which it was possible to promote insights, discussions, and guidance. 43 PhD candidates and 12 mentors participated to the workshop. It began with the opening remarks from Prof. Fabio Sgarbossa and Dr. Hossein Arshad. Then the morning continued with Prof. Daria Battini discussing the strengths and challenges of the PhD journey, and Prof. Hind Bril El Haouzi addressing ethics in publishing. Afterwards, Dr. Abdous Mohammed Amine and Dr. Foivos Psarommatis shared personal insights from their PhD experiences. A networking lunch provided time for informal connections. In the afternoon, participants joined parallel incubator sessions with peers and mentors. The day concluded with final reflections from the workshop chairs.

From July 1st to 3rd, the conference brought together a vibrant community of researchers and professionals for a fully in-person event. Over the course of three days, 574 papers (518) and extended abstracts (56) were presented across 119 sessions, showcasing a wide range of innovative work and insights. The conference welcomed more than 700 participants from 51 countries, fostering rich international exchange and collaboration. Notably, the event was held exclusively on-site, with no digital participation options, emphasizing the value of face-to-face interaction and networking.

Exceptional keynote talks were included in the program (in order of presentation):

Pascal Van Hentenryck *(A. Russell Chandler III Chair Professor at H. Milton Stewart School of Industrial and Systems Engineering – Georgia Tech)*

AI For Engineering and Societal Impact

The fusion of AI with optimization and control has the potential to deliver outcomes that are beyond the realm of these technologies when applied independently on complex engineering applications. This talk reviews the theoretical foundations underlying this fusion, including the concepts of primal and dual optimization proxies, predict then optimize, self-supervised learning, and deep multi-stage policies. The presentation also highlights these methodological developments in a variety of engineering areas, with a focus on supply chains and manufacturing.

Laura Albert *(Professor of Industrial and Systems Engineering at University of Wisconsin-Madison)*

Industrial Engineering with Impact: Shaping a Better Future

Industrial engineering plays a pivotal role in solving some of our most complex challenges and boosting the global economy. In this keynote, we will embark on a journey to explore the boundless possibilities of industrial engineering, manufacturing, and logistics as well as the latest trends shaping the future of the field. Advancing industrial engineering and operations research through societally relevant applications has been a central theme of Dr. Laura Albert's academic research career. In this talk, she will overview her research that studies how to design and operate public sector systems in applications ranging from public safety, critical infrastructure protection, and election resilience. Using stories from her research, she will offer insight into identifying problems worthy of study, overcoming modeling challenges, creating data-driven modeling frameworks, and influencing policy. Attendees will gain insights into how academic research in engineering can translate into tangible benefits for society and make a positive impact on our world.

Nikolay Osadchiy *(Associate Professor of Information Systems and Operations Management at Emory University Goizueta Business School)*

Making More Resilient Manufacturing Networks

We show how the network perspective can be used to understand and mitigate risks faced by manufacturers and their partners. We will discuss three key research areas: the propagation of idiosyncratic shocks and the bullwhip effect in supply networks, correlated shocks and systematic risks in networks, and the role of community structure in shock propagation. We will discuss implications for supplier and customer diversification strategies and the financial performance of firms.

Alexandra Brintrup *(Professor of Digital Manufacturing and Head of Supply Chain AI Lab at University of Cambridge)*
Beyond mere efficiency: Artificial Intelligence for better Supply Chains
Artificial Intelligence (AI) and its impact on Supply Chains (SC) has become a popular topic prone to hype, hope and fear. Will AI help us “make supply chains better” or will we just use it to do what we have always been doing – just more efficiently? In this talk we will delve into “unorthodox” supply chain AI research, including digital supply chain surveillance, collective model building, and agent-based automation. We will discuss how AI, if developed and adopted in the right way, has the potential to help prevent a range of endemic supply chain issues, from modern slavery to emergence of bullwhip effects. We will conceptualise SC-AI through the lens of a human-mimicking Intelligent Agent to discuss how practitioners could collaborate with AI agents – and what risk factors should researchers pay attention to in the coming years.

Weiwei Chen *(Professor in Department of Supply Chain Management at Rutgers University)*
Shaping Better Service Systems through Data-Driven Optimization
Over the past few decades, the global economy has experienced rapid growth in the service sector, which now plays a crucial role across diverse industries such as retail, healthcare, and manufacturing. Unlike traditional optimization problems that rely on predefined information and fixed parameters—whether deterministic or based on well-defined distributions—optimizing service systems in real-world scenarios often involves ill-defined parameters, requires robust predictive models, and is influenced by endogenous factors and the optimization outcomes themselves. In this talk, we will delve into these complexities in optimizing the design and operations of various service systems, including e-commerce platforms, recommender systems, and bike-sharing systems. We will demonstrate how harnessing vast amounts of data and employing advanced analytical methods can significantly improve the design and operational efficiency of service systems.

Jen Pazour *(Professor of Industrial and Systems Engineering at Rensselaer Polytechnic Institute)*
Resource Exchange Platforms: from warehouses to non-profits
Underutilized resources exist all around us. When at a stoplight, notice the empty seats and cargo spaces in the vehicles around you. Think about the monolithic distribution centers that are a mismatch for most businesses’ seasonal and fluctuating space and throughput requirements. To harness these and other underutilized resources, organizations need to think differently about how resources are acquired, managed, and allocated to fulfill requests. We will provide an overview of research into the design of resource exchange platforms to harness underutilized resources. By accessing resources with lower marginal costs, supplemental resources can be deployed when and where they are needed. Promising use cases include on-demand warehousing platforms, and SWAP, a platform that enables resource sharing among nonprofits.

Oleg Gusikhin *(Senior Director, Supply Chain Analytics at Ford Global Data Insight & Analytics)*
Impacting Supply Chain Excellence through Digital Innovation and Analytics
In recent years global supply chains faced unprecedented challenges. In addressing these challenges, the criticality of digitalization and data-driven approaches came to the forefront of the attention of supply chain theory and practice. The presentation overviews Ford’s supply chain digital transformation journey from individual data-driven decision support to supply chain digital twin. The presentation highlights the need for the integration of data, models, and AI/ML technology to provide end-to-end supply chain visibility and optimization, sourcing decision support, and supply chain stress test along the product lifecycle.

Alexandre Dolgui *(Professor of Industrial and Systems Engineering, IMT Atlantique)*
Manufacturing modelling, management and control: History of the conference and IFAC Technical Committee 5.2
This presentation offers a comprehensive historical overview of the IFAC MIM (Manufacturing Modelling, Management and Control) conference series and the evolution of IFAC Technical Committee 5.2. It traces the origins of MIM from its first workshop in 1997 through its transformation into a triennial conference since 2013, highlighting key milestones, organizing chairs, and participant statistics. The talk also explores the relationship between MIM and INCOM conferences, the scope of research topics over time. Emphasis is placed on the integration of industrial engineering,

operations research, and systems management to address challenges in manufacturing and logistics.

The conference program included also several innovative sessions, workshops, competitions and industrial tours and laboratory visits:

Session: Meet the editors

This inspiring session brough together several esteemed editors participating in the conference to share their insights and perspectives on two important topics: AI & Ethics and How to Be a Great Researcher. The session presented a unique opportunity to hear directly from editorial leaders and gain valuable insights that can shape your future academic journey. Moderate by Alexandre Dolgui, International Journal of Production Research and Dmitry Ivanov, International Journal of Integrated Supply Management, the editors Stefan Minner, International Journal of Production Economics; Andrea Matta, Flexible Services and Manufacturing Journal; Paolo Gaiardelli, Production Planning and Control; Suresh Sethi, Production and Operations Management; and Eric Grosse, Operations Management Research, discussed and interacted with the audience providing excellent and visionary insights

Night session: Sunset of the Human-Only Era: A New Dawn for Human-AI Industry

An evening dialogue on the evolution of roles, intelligence, and trust in the future of Human-AI co-driven manufacturing and logistics.

In the frame of two EU projects, NTNU-Production Management Research Team is currently working on, X-Hulog4.0 https://x-hulog4.eu/ and SkillAIbility https://skillaibility.eu/, a night session was organized on a very relevant topic for our research community and the whole society: Human and AI! The session lasted more then 45-minute and it was very open with highly interactive discussion. There was no formal distinction between panelists and audience; instead, moderators facilitated a dynamic exchange among all participants. Everyone’s contribution was vital to the success of the conversation and to fostering a stimulating, forward-thinking dialogue. The session aimed to encourage critical and visionary idea-sharing. The session was followed by a “Greetings the sunset” at the roof of the venue since sunset was at 23.32 that day.

Special session: Guns n’ Roses concert and special speech on logistics for big events

The night of the gala dinner, Trondheim hosted Guns n’ Roses concert. Participants of IFAC MIM2025 could attend the concert and shared their moments with the remaining participants during the gala dinner. The day after the concert, IFAC MIM2025 participants had the opportunity to attend a special speech about logistics and operations in big events by the organizer of the concert:

From Bruce Springsteen to Robbie Williams to Metallica to Guns N’ Roses: The Granasen Concert Saga

by **Stein Vanebo** *(Trondheim Stage)*

It all started in 2016. Live Nation decided, let’s go! So, in 2016, Granåsen in Trondheim, Norway, hosted its first major concert featuring Bruce Springsteen. This event marked the beginning of Granåsen’s transformation into a premier event venue, attracting world-renowned artists like Guns N’ Roses in July 2025. The journey from Springsteen to Guns N’ Roses is filled with fascinating stories and behind-the-scenes anecdotes that you won’t find in the newspapers. Organizing large-scale concerts at Granåsen involves meticulous planning and coordination, from managing shuttle buses to accommodating the crew’s unique needs. Hosting Guns N’ Roses in 2025 is akin to organizing a massive event, with over 2,000 personnel involved. This session delved into the logistics, challenges, and memorable moments that have shaped Granåsen’s concert legacy, offering insights that go beyond the headlines.

Workshop: Share Your Science. Be the Impact.

Julius Wesche *(Innovation Systems Researcher at the NTNU)*

This 60-minute session, featuring a 30-minute keynote followed by a 30-minute interactive workshop, highlighted the importance of social media in science communication and career development. Julius addressed the key reasons why researchers should embrace social media: first, to make their research more accessible and impactful by connecting with industry professionals who can apply their findings; and second, to start building a professional network outside of academia. This network can be invaluable for those considering a transition to industry, opening up opportunities and connections that might otherwise be difficult to establish. In the workshop portion, participants engaged in a step-by-step process to create their own science communication strategy. By the end of the session, attendees had a personalized plan to effectively share their research on social media and start building a network that supports their long-term career aspirations, whether in academia or industry.

Workshop: Be YOUR Impact! Making a Better Researcher through Mental Fitness!
Elizabeth Sturdy *(Sturdy Coaching)*
Ready to be the proactive leader of your life and stress? Participants joined Elizabeth Sturdy to get the tools they need to understand, and interrupt stuck and negative thought patterns in yourself and others, as well as practical tools to deal proactively with stress and build resilience as a researcher.

Data Challenge competition
Participants of the conference could also participate to the 2nd Supply Chain and Logistics Data Challenge. The competition engaged participants in solving real-world logistics problems across three segments: Delivery Delay Prediction, Complex Network Analysis, and the Multi-Depot Capacitated Vehicle Routing Problem (VRP). Participants built predictive models, analyzed supply network vulnerabilities, and optimized routing strategies. The challenge launched on May 30, 2025, with datasets released in June and final submissions due by July 2. Winners were announced on July 3 during the conference. The organizing team included Dr. Liming Xu and Prof. Alexandra Brintrup (University of Cambridge), Dr. George Baryannis (University of Huddersfield), Prof. Dmitry Ivanov (Berlin School of Economics and Law), Prof. Fabio Sgarbossa and Dr. Hossein Arshad (Norwegian University of Science and Technology).

Industrial Tours and special workshop at Logistics 4.0 Lab
After the conference, on the 4th July, IFAC MIM2025 organized 4 industrial tours and one special workshop.
Four manufacturing companies in Trondheim and the surrounding region invited IFAC MIM2025 participants to visit their facilities on Friday, July 4:
- Siemens Energy
- Orkel AS
- Aker Solutions Verdal
- Sandvik Coromant Trondheim

Logistics 4.0 Lab was venue for the Special Workshop on Human-Robot Collaboration in Logistics where participants could visit the lab and see the ongoing research, which focuses on human-centric design in human-robot systems in warehousing. The work was part of the "Excellence in Human-Centered Logistics 4.0" (X-HuLog4.0) project.

Awards
IFAC MIM 2025 awarded several presented research contributions, encouraging the quality and relevance of innovative solutions in manufacturing, logistics, and control systems, while recognizing excellence in methodology, impact, and interdisciplinary collaboration. Several juries were appointed to guarantee a transparent process: each composed of academic and industry experts who independently evaluated the submissions based on predefined criteria such as originality, methodological rigor, practical relevance, and clarity of presentation:
- Commended Paper Award – Jury: MIM organizers and IPC chairs
- Best Paper Award – Jury: Eric Grosse (President), Alice Smith, Matthias Klumpp, Alexandra Lagorio
- Young Author Award – Jury: Enzo Morosini Frazzon (President), Simone Arena, Justyna Patalas-Maliszewska
- Best Application Award – Jury: Dmitry Ivanov (President), Alexandre Dolgui
- Data Challenge – Jury: Data Challenge organizers

Recipients of commended paper award:

- De Lombaert, Thomas; Braekers, Kris; De Koster, René B.M.; Ramaekers, Katrien. *Sustained Success or Fading Spark? Long-term Assessment of Participatory Order Assignments in a Warehouse Environment*
- Mai, Yen; Callefi, Mario Henrique; Grzona, Pierre; Riedel, Ralph; Thürer, Matthias. *Redefining Supply Chains with Additive Manufacturing: Insights from Network Modelling*
- Giacomelli, Marco; Rijal, Arpan; Pilati, Francesco; Roodbergen, Kees Jan. *Improving well-being and efficiency in order picking*
- Streibel, Lasse; Albers, Stefanie; Schluetter, Tino; Dorsel, Justus H.; Jordan, Patrick; Lindholm, Niklas; Zaeh, Michael. *Integrating Real-Time Data into Digital Twins for Reactive Disassembly Planning*
- Zheng, Ting; Glock, Christoph; Neumann, W. Patrick. *Human robot collaboration in warehousing operations: a sociotechnical analysis*
- KARIMI, Tourandokht; Thevenin, Simon; Haddou Benderbal, Hichem. *Workforce Management and Resource Selection with Fairness*
- Schoepf, Stefan; Foster, Jack; Brintrup, Alexandra *Machine unlearning in supply chains*
- Duran, Ege; Ozturk, Cemalettin; O'Sullivan, Barry *Scheduling Service Oriented Manufacturing Systems*
- Fede, Giulia; Sgarbossa, Fabio; Silva, Daniel; Collina, Giulia *A model-based approach to hydrogen supply scenarios for decarbonizing the glass melting process*
- Hosseini, Amir; Otto, Alena; Schiffer, Maximilian *Integrated material handling and machine scheduling with shared buffers*
- Mancusi, Francesco; Neumann, W. Patrick; Pierri, Francesco; Fruggiero, Fabio. *The Embodied Cognition paradigm: a novel approach to advancing Human-Robot Collaboration research*
- Klumpp, Matthias; Glock, Christoph. *Supply Chain Disruptions and Manufacturing Strategies: The Case of Exceptional Positive Demand Events*
- Alaeddini, Morteza; Mallek, Sabrine; Hönigsberg, Sarah *Uncovering Research Trends: A Textual Analysis of AI Applications in Circular Economy under an Industry 5.0 Paradigm*
- Lagorio, Alexandra; Piffari, Claudia; Cimini, Chiara. *Developing warehouse management skills through Learning Factories: a use case*
- Weerasinghe, Kasuni Vimasha; Sgarbossa, Fabio. *Performance & Economic Evaluation of Puzzle-based Movable Rack Systems*
- Füchtenhans, Marc; Katiraee, Niloofar; Dobbs, Debra; Glock, Christoph. *Considering aging workforce characteristics in production scheduling: literature review and novel job shop modelling approach*
- Zhao, Qian; Coruzzolo, Antonio Maria; Balugani, Elia; Gamberini, Rita; Lolli, Francesco. *A Novel Three-Way Decision Framework for Classifying Spare Parts Between Additive and Conventional Manufacturing*
- Demiralay, Enes; Sgarbossa, Fabio; Silva, Daniel; Razavi, Nima. *A Decision Support System for Identifying Cost-Effective Additive Manufacturing Process Option Considering Quality of Printed Parts*
- Fiedler, Jannick; Löwhagen, Nils; Netland, Torbjørn. *ASSYBOT: A Chatbot for Selecting Augmenting Assembly Technologies*
- Safari Dehnavi, Zahra; Brenter, Bernd Alexander; Karbasi, Atieh; Kostolani, David; Kassem, Khaled; Schlund, Sebastian. *Virtual Assembly Companion: A Study of Interactive Instructional Systems in Assembly*
- Noman, Abdullah Al; Zitnikov, Anton; Patwary, Firoj Ahmmed; Heuermann, Aaron; Thoben, Klaus-Dieter. *Explaining Manufacturing Anomalies: Transformer-Based Detection with xAI for Imbalanced Process Data*
- Swift, Andrew; Afshari, Hamid; Diallo, Claver. *Reliability-Based Design Optimization for Green Hydrogen Production Network*
- Berendes, Katharina. *Paradox Mindsets: A Pathway to Align Resilience and Efficiency in Supply Chain Management*
- Marchesano, Maria Grazia; Mattera, Giulio; Guizzi, Guido; Santillo, Liberatina Carmela; Converso, Giuseppe. *Explainable Deep Reinforcement Learning Enhancing Industrial Maintenance*

- Zenezini, Giovanni; Lagorio, Alexandra; Mangano, Giulio; Pinto, Roberto; Rafele, Carlo. *Implementing Digital Twins in Supply Chain Management: A Maturity Model*
- Nguyen, Phu; Ivanov, Dmitry. *A Two-Layer Digital Twin for Implementing Simultaneous Resilience Strategies in Electronics Manufacturing*
- Delorme, Xavier. *Some thoughts on the reliability of Reconfigurable Manufacturing Systems*
- Ivanov, Dmitry. *From digital twins to supply chain ecosystems*
- Psarommatis, Foivos; Kalb, Irina; Andronidis, Thodoris; Panagou, Sotirios; May, Gokan. *The Role of Digitalization and Human Aspects in the Use of Digital Product Passport for Sustainable Upcycling (De)Construction Waste*
- Matta, Andrea; Frigerio, Nicla. *Enhancing Circular Economy Efficiency through Digital Twins*
- Martignago, Michele; Katiraee, Niloofar; Calzavara, Martina; Battini, Daria. *Investigating labor shortages and automation opportunities in logistics: a simulation case study*

Finalists Best Paper Award:

- De Lombaert, Thomas; Braekers, Kris; De Koster, René B.M.; Ramaekers, Katrien. *Sustained Success or Fading Spark? Long-term Assessment of Participatory Order Assignments in a Warehouse Environment*
- Safari Dehnavi, Zahra; Brenter, Bernd Alexander; Karbasi, Atieh; Kostolani, David; Kassem, Khaled; Schlund, Sebastian. *Virtual Assembly Companion: A Study of Interactive Instructional Systems in Assembly*

Best Paper Award:

- Schoepf, Stefan; Foster, Jack; Brintrup, Alexandra. *Machine unlearning in supply chains*

Finalists Young Author Award:

- Alessandro Peris. *Cobot Integration for Large Parts Picking in Assembly*
- Giulia Fede. *A Model-Based Approach to Hydrogen Supply Scenarios for Decarbonizing the Glass Melting Process*
- Thomas De Lombaert. *Sustained Success or Fading Spark? Long-Term Assessment of Participatory Order Assignments in a Warehouse Environment*
- Zahra Safari Dehnavi. *Virtual Assembly Companion: Investigating Multimedia-Instruction Provision in Assembly*

Recipient of the Young Author Award

Phu Nguyen. *A Two-Layer Digital Twin for Implementing Simultaneous Resilience Strategies in Electronics Manufacturing*

Recipient of the Best Application Paper Award

- Fede, Giulia; Sgarbossa, Fabio; Silva, Daniel; Collina, Giulia. *A model-based approach to hydrogen supply scenarios for decarbonizing the glass melting process*

Data Challenge Award

- *Delivery Delay Prediction*

Winner in Best Performance: Pizza4All by Andrea Ferrari

Winner in Innovation: Supply Chain Research Group by Srinidhi Karthikeyan, Dimitrios Karagiannis, Manjo Babu, Sube Singh, Alok Choudhary

- *Multi-Depot Capacitated VRP*

Winner in Best Performance: SZTAKI EMI by András Kovács and Ádám Szaller

- *Complex Network Analysis*

Winner in Innovativeness and Creativity: MaxiNik by Maxi Udenio and Nikolay Osadchiy

In addition to IFAC journals, other 6 journals will select papers for publishing extended versions: Computers & Industrial Engineering, Flexible Services and Manufacturing, International Journal of Production Research, International Journal of Integrated Supply Management, Operations Management Research, Production Planning and Control.

During the conference TC 5.2 annual meeting selected which candidate to support for the next IFAC MIM2028 which will be held at University of Padova, Italy.

Editors

Fabio Sgarbossa, Norwegian University of Science and Technology, NO
Sotirios Panagou, Norwegian University of Science and Technology, NO
Erlend Alfnes, Norwegian University of Science and Technology, NO
Alexandre Dolgui, IMT Atlantique, FR
Dmitry Ivanov, Berlin School of Economics and Law, DE
Daria Battini, University of Padova, IT

Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 59-10 (2025) 1516–1521

Implementing Digital Twins in Supply Chain Management: A Maturity Model ⋆

Giovanni Zenezini* Alexandra Lagorio Giulio Mangano* Roberto Pinto** Carlo Rafele***

* *Deparment of Management and Production Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, Torino 10129 Italy (e-mail: giovanni.zenezini@polito.it, giulio.mangano@polito.it, carlo.rafele@polito.it).*

** *Department of Management, Information and Production Engineering, University of Bergamo, Viale Marconi 5, 24044 Dalmine BG, Italy. (e-mail: alexandra.lagorio@unibg.it, roberto.pinto@unibg.it)*

Abstract: Integrating Digital Twins (DTs) within supply chain management offers transformative potential for optimizing operations, enhancing decision-making, and fostering resilience. However, existing literature often lacks practical insights into assessing their maturity. This paper addresses these gaps by proposing a comprehensive Maturity Model (MM) tailored for supply chain DT development. The proposed MM is applied to real-world case studies, highlighting its utility in evaluating DT readiness and guiding implementation. Key challenges, including modeling capabilities, data and system integration, and stakeholders' collaboration, are discussed alongside strategies for overcoming them. This research provides practitioners with actionable insights for building robust DT architectures, enabling organizations to leverage the full potential of digital transformation while ensuring scalability and sustainability.

Keywords: Digital Twin, Supply Chain Management, Maturity Model, Data Integration, Real-Time Decision-Making, Digital Transformation.

1. INTRODUCTION

A digital twin (DT) can be defined as a "virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning, and reasoning to help decision-making" (Le and Fan, 2024). DT are predominantly used for designing, modelling, visualizing, testing, and implementing new ideas without disrupting the current process. The application of Digital Twin technology extends beyond conceptual frameworks to practical implementations, particularly in supply chain management, where it is possible to integrate sensors and other data handling technologies (e.g., Internet-of-Things) to several critical phases of supply chains (e.g., orders arrival timestamps, shipping tracking), generating insights into the performance of a physical supply chain, identifying potential issues or bottlenecks (Wang et al. 2022), supporting risk mitigation (Le and Fan, 2024) and including some benefits such as the optimization and improvement of customer service and traceability, costs reduction, and profits increasing (Lugaresi and Jemai, 2023).

Based on this premise, this research aims to address critical gaps in the study and application of Digital Twins in supply chain management (DTSCM). Despite growing interest, the literature predominantly focuses on developing DTSCM frameworks or their implementation, with limited exploration on evaluating the level of integration among stakeholders, data sources and systems and the main strategies towards the implementation of a full DT. Additionally, decision-makers face difficulties in understanding how a DT can be applied to their specific needs. A lack of performance assessment of the DTSCM levels of maturity then renders the integration of DT technologies into supply chains an actual challenge and hinders their practical adoption.

This study aims to analyze supply chain DTs through a Maturity Model to evaluate their stage of implementation. The objective is to offer businesses a decision support framework to assess the necessity of DT adoption, identify suitable technologies, and optimize their integration for sector-specific applications. Specifically, this research seeks to address the following questions::

RQ1. How can a Maturity Model be designed and implemented to evaluate the readiness and effectiveness of Digital Twins in supply chain environments?

RQ2. What are the key challenges that must be addressed to achieve higher levels of maturity in the implementation of DTSCM?

The structure of the paper will consist in a literature review section (Section 2) followed by a methodology section highlighting the approach towards the DTSCM maturity model development as well as its dimensions and

⋆ Project funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 – Call for tender No. 341 of 15/03/2022 of Italian Ministry of University and Research funded by the European Union – NextGenerationEU.

10.1016/j.ifacol.2025.09.255

levels (Section 3). Then, the final MM based on existing use cases will be presented in Section 4. Finally discussions and conclusion sections will close the paper (Sections 5 and 6).

2. LITERATURE REVIEW

2.1 Implementation process of Digital Twins in the Supply Chain

The DTSCM implementation steps are closely related to its architecture, which is often composed of hierarchical layers. Layers categorize and structure the functional aspects of a supply chain, while hierarchy levels organize and simplify the complexity within each layer, enabling modularity and scalability (Le and Fan, 2024). Le and Fan (2024) propose an holistic approach with three closely interrelated layers of the DT, namely physical, digital and communication layers. Freese and Ludwig (2024) organize the DTSCM development across five layers: i) a data layer; ii) a technology layer to capture, process and display data; iii) an application layer comprising the scope the DTSCM in terms of purpose (e.g. monitoring and control) and KPIs; iv) a workflow logic layer containing the processes in which the digital twin is integrated and finally v) a structural model layer depicting the structure of the supply chain within the DTSCM, including actors and physical assets. This architecture is fundamentally grounded in SCM theory and application and thus provides a significant development in terms of implementation steps and maturity levels in the context of DTSCM. A six-layer architecture for a manufacturing DT is also proposed by Redelinghuys et al. (2020). Additional layers are presented in this paper, namely local and cloud repositories and a "Data-to-Information Conversion Level", or IoT Gateway. This architecture is specifically developed to work with open communication protocols and thus provide a suitable way to integrate with existing legacy systems and supports the implementation of the DTSCM in operational terms. The DTSC implementation literature acknowledges that during the DTSCM implementation certain elements must be given significant consideration. Robust infrastructure, data connectivity, and skilled personnel are prerequisites for creating and operating DTs (Patil et al., 2024). Beyond data connectivity, effective data management is a fundamental pillar for the successful implementation of Digital Twins, as the quality and reliability of information directly impact the accuracy of monitoring, simulations, and decision-making (Lanzini et al., 2024). In their use case application, Redelinghuys et al. (2020) mentions latencies between layers as well as significant lags when updating values in the cloud server database as operational hurdles that affect the ability to emulate fast-changing process parameters in real-time. Using readily available technologies and services, such as cloud-based database services, may reduce the expertise required to develop a digital twin (Redelinghuys et al., 2020). It is worth mentioning in fact that organizational challenges arise when implementing a DT in such systems, and thus organizational leadership can support the DT implementation by promoting a culture of innovation and facilitating cross-functional collaboration to ensure the seamless integration of DTT into operational processes (Patil et al., 2024).

2.2 Maturity Models

In general terms, the concept of maturity can be defined as the state of being perfect, complete and ready or more specifically, as a measure to evaluate the resources used by an organization (Kucińska-Landwójtowicz et al., 2024). A Maturity Model (MM) is a tool that can be used to evaluate specific domains against a benchmark (Santana Tapia et al. 2008). It helps to identify technological or organizational potentials to improve desired outcomes (Uhlenkamp et al., 2022). Typically, maturity models define a series of levels or stages, each representing a higher degree of sophistication, efficiency, and optimization (Warnecke et al., 2019). A MM typically has three common components. First, a set of levels describing the development of a process. Every level is sequential with a hierarchical progression, ranging from the most basic degree to the best practices. To determine the maturity level, an evaluation is carried out considering several criteria that are divided into categories. The criteria are the second component and the categories (called attributes) are the third component of a MM (Guerra et al., 2024). MM have been applied to evaluate supply chain risks in different industry fields and to companies of different size to stimulate the development of capabilities required to advance from one stage to another (Dellana et al., 2022). Regarding the maturity levels of DT, the literature has introduced it based on the sophistication of the implemented DT, outlining the progressive levels of DT development (Hu et al., 2023). In the development of Digital Twin model, Liu et al. (2024) present a Digital Twin Maturity Model (DTMM), identifying five different steps related to the DT maturity. This model describes the conceptual domain, capabilities and developmental progression of DT, integrating the every objectives with the capabilities and the technologies. In the specific context of DTSCM, maturity levels are briefly mentioned in Freese and Ludwig (2024). At a low maturity level, only basic descriptive functions are achievable. At the diagnostic maturity level, it becomes possible to derive insights and diagnoses from historical data. The predictive maturity level facilitates the forecasting of potential future issues. The prescriptive maturity level, representing the highest stage, enables the digital twin to proactively predict, intervene, and autonomously influence the physical entity. At this advanced level, the integration of actuators, in addition to sensors, is essential. This study is, to the best of the authors' knowledge, the first attempt at evaluating the DTSCM from a MM standpoint.

3. METHODOLOGY

For this research, the steps for the development of a maturity model proposed by Becker et al. (2009) have been used. In particular, the different steps have been revised by the authors according to the research workflow shown in Figure 1.

The problem definition phase have been already reported in Section 2.1 in which the different gaps in implementing DT for supply chain have been discussed and the main objectives and challenges have been proposed. Section 2.2 has reported the comparison of existing maturity models discussing also the common dimensions and common scoring method adopted. Section 4 will present the result of

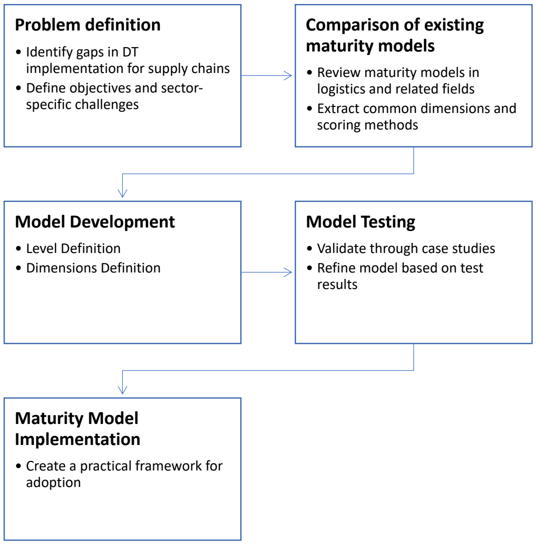

Fig. 1. Research Workflow

the model development in terms of level, dimensions and criteria. In particular the model proposed by Uhlenkamp et al. (2022) has been taken as a reference because it is the second model with the highest number of citations in the scientific literature on maturity models for digital twins. The most cited maturity model for digital twin is the one by Delgado and Oyedele (2021). However, this MM seems to be useful only in the case of built environment and less generalizable, while both Becker et al. (2009) and Uhlenkamp et al. (2022) are more generic and follow a dimensions definition based on the Human-Technology-Organization (HTO) framework that is also very common in maturity models related to Industry 4.0 assessment (Elibal and Özceylan, 2022). The supply chain customization of the model started from the analysis of the 31 dimensions stated by the Uhlenkamp et al. (2022) and their possible relation with the main elements of the supply chain domain.

After the development phase, the maturity model has been tested using case studies from literature, industry practices and use cases where the authors are involved. In particular, the DTSCM has been tested by retrieving information from highly cited papers from the following query launched on the SCOPUS database: TITLE-ABS-KEY (”Digital Twin” AND ”supply chain”). Only scientific papers with real DTSCM implementations were considered in the analysis.

4. MATURITY MODEL FOR DTSCM

According with the MM for supply chain risk management proposed by Guerra et al. (2024), a Maturity Model is composed of two elements: levels of maturity (Section 4.1), dimensions or attributes (Section 4.2) and criteria to differentiate between the levels (Section 4.3).

4.1 Levels

Levels are the maturity stages that the dimension assumes (Gastaldi et al., 2018). As highlighted in Section 2.2, four maturity levels of DTSCM are briefly introduced in Patil et al. (2024) but not well defined in terms of dimensions

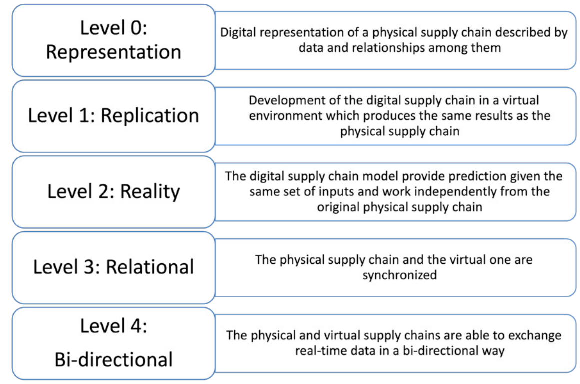

Fig. 2. Maturity Model Levels

Macro-Dimensions	Dimensions	Definition	Reference
Human	Learning capabilities	The ability of personnel to acquire, process, and apply knowledge and skills for implementing and managing DT.	Patil et al. (2024); Le and Fan (2024)
	Stakeholder collaboration	Cross-functional and inter-organizational teamwork enabling smooth adoption of DT technologies in supply chains.	Huang et al. (2024); Ivanov et al. (2019)
	Skills development	Continuous training programs for enhancing competencies in data-driven decision-making and DT management.	Freese and Ludwig (2024); Lanzini et al. (2024)
Technology	Traceability tools	Technologies that enable tracking and tracing of assets and information across the supply chain.	Ivanov et al. (2019); Redelinghuys et al. (2020)
	Digital processes	Automated and streamlined workflows supported by digital technologies.	Le and Fan (2024); Freese and Ludwig (2024)
	Modeling and computing capabilities	Different levels of capabilities to process the incoming information as well as simulation and data analytics methods	Uhlenkamp et al. (2022); Stadtfeld et al. (2024)
	Data and System Integration	Proficiency in deploying and integrating data from different sources, digital tools, platforms, and software for DT.	Lanzini et al. (2024); Liu et al. (2024)
	Update data frequency	Regular intervals at which real-time data is captured and synchronized across DT SC layers.	Redelinghuys et al. (2020); Frazzon et al. (2021)
	Cybersecurity strategies implemented	Measures ensuring the security, integrity, and confidentiality of data in DT-enabled supply chains.	Patil et al. (2024); Haraguchi et al. (2024)
Organization	Supply chain echelon definition	Clear identification and structuring of supply chain layers for effective DT deployment.	Becker et al. (2009); Uhlenkamp et al. (2022)
	Communication procedures among SC actors	Defined protocols for information exchange and coordination within the supply chain.	Lanzini et al. (2024); Freese and Ludwig (2024)
	Modularity of different echelon management	Flexible and scalable management systems enabling modular DT adoption.	Redelinghuys et al. (2020); Uhlenkamp et al. (2022)

Fig. 3. Maturity Model Dimensions

and assessment system. For this research instead the chosen maturity levels are based on the simulation and digital twin capability levels proposed by Wooley et al. (2023), which are then adapted to the supply chain context.

Figure 2 depicts the five maturity levels of digital twin (DT) implementation in supply chain management, progressing from basic digital representation (*Level 0: Representation*) to fully integrated bidirectional systems (*Level 4: Bi-directional*), going through a DT with prediction capabilities that hinge on the same set of inputs while working independently from the original physical supply chain (*Level 2: Reality*).

4.2 Dimensions

A dimension represents the characteristic of an organisation/process or the capability that is measured; Therefore, while maturity models can be one-dimensional, they are more commonly multi-dimensional, providing a structured assessment of a company's capabilities across different domains, each of which can be evaluated independently across scaled maturity stages(Wendler, 2012). Figure 3 contains the results of the dimensions and their definition.

Macro-Dimensions	Dimensions	Level 0: Representation	Level 1: Replication	Level 2: Reality	Level 3: Relational	Level 4: Bi-directional
Human	Learning capabilities	Awareness of DT concepts	Basic knowledge acquisition	Application of DT in limited contexts	Advanced proficiency in DT integration	Mastery and innovation in DT application
	Stakeholder collaboration	Initial stakeholder mapping	Basic collaboration structures established	Advanced collaboration mechanisms	Dynamic collaboration among stakeholders	Fully integrated, real-time stakeholder sync
	Skills development	Ad-hoc skill-building initiatives	Training for specific DT-related tools	Specialized training programs	Comprehensive cross-functional training	Continuous skill innovation programs
Technology	Traceability tools	Minimal data tracking	Simple tracking systems implemented	Advanced traceability with limited integration	Fully integrated traceability systems	Real-time, predictive traceability systems
	Digital processes	Manual workflows digitized	Automated workflows with minimal complexity	Comprehensive digital processes implemented	Synchronization of digital and physical processes	Fully autonomous digital processes
	Modeling and computing capabilities	Basic UML description of SC classes and actors	Simulation models with prediction capabilities over few problems	Simulation-optimization digital models able to treat more KPIs and predict what-if scenarios	Multi-objective advanced data analytics problem solving models implemented	Multi-objective advanced data analytics problem solving models with reinforcement learning capabilities
	Data and System Integration	Limited integration with legacy softwares with few unstructured data sources	Basic platform integration using structured data from few sources	Advanced platform integration using structured data from multiple sources within the SC	Fully integrated DT systems using structured data from multiple sources within the SC and unstructured data from external sources	Self-optimizing digital ecosystem using structured data from multiple sources within the SC and structured data from external sources
	Frequency of data update	Infrequent updates	Periodic updates	Near real-time updates	Real-time updates achieved	Continuous real-time data flow
	Cybersecurity strategies implemented	Basic data protection measures	Initial cybersecurity policies applied	Comprehensive cybersecurity systems	Real-time cybersecurity monitoring	Adaptive and predictive cybersecurity
Organization	Supply chain echelon definition	Echelons loosely identified	Echelons structured for DT adoption	Defined roles and responsibilities	Seamless echelon synchronization	Dynamic echelon management
	SC level communication procedures	Minimal communication protocols	Initial communication structures	Advanced communication procedures	Fully transparent communication	Real-time adaptive communication frameworks
	Modularity of different echelon management	Minimal modularity	Basic modular structures defined	Modular DT components implemented	Modular systems fully operational	Adaptive modular management systems

Fig. 4. Definition of criteria for the dimensions and levels of the DTSCM MM

4.3 Criteria

In this subsection the main criteria identified from findings from the data collection are presented. A full definition of the criteria for all dimensions and levels which is shown in Figure 4 is out of scope of this paper.

Digital Twins (DTs) in supply chains are increasingly supported by *Traceability tools* at varying levels of maturity. Foundational systems require simple tracking from legacy systems like Warehouse Management Systems to replicate the physical object (Ferrari et al., 2023). Intermediate tools, as seen in Lee and Lee (2021), propose the use of IoT sensor data to create virtual assets, such as trucks and modules, although such systems are not yet fully implemented. Advanced levels focus on establishing IoT-enabled smart environments to collect and pre-filter real-time spatial–temporal data (Zhao et al., 2022). These systems utilize BLE tags paired with mobile resources (e.g., trolleys, forklifts, personnel) and deep neural networks to locate entities and ensure spatial–temporal consistency between physical and virtual assets.

Data and system integration play a crucial role in enabling Digital Twins (DTs) for supply chains by connecting internal and external systems, synchronizing data sources, and ensuring actionable insights. Renault integrates its own data with partner ERP systems and public access data, enhancing visibility across suppliers and logistics networks (Stadtfeld et al., 2024). Platforms like JD.COM's DTSC (Wang et al., 2022) synchronize physical supply chains and digital models using network configurations, procurement, transfer, and fulfillment systems, achieving high accuracy in monitoring key metrics. Integration frameworks further simplify communication; for instance, Park et al. (2021) leverage APIs and protocols like Simple Object Access Protocol (SOAP) for loosely coupled integration. More advanced systems such as the DT by General Electric Power adopt advanced data harmonization by consolidating five unconnected ERP systems and managing structured, semi-structured, and unstructured data in a unified data lake. Additionally, this DT integrates third-party data to monitor external influences, such as political and environmental factors (Stadtfeld et al., 2024). A DT by TetraPak also showcases the use of electronic data interchange (EDI) to combine GPS data, weather information, and partner carrier inputs, facilitating accurate, real-time decision-making (Stadtfeld et al., 2024).

Data and system integration are key enablers of *Stakeholder Collaboration* and *Communication Procedures*, promoting real-time communication and reducing inefficiencies. Using local databases may hinder the ability to foster collaboration but does not require significant effort in terms of data conversion and semantics harmonization. Siemens utilizes an Anylogic database as a central repository, updating and sharing input and output entities to facilitate seamless communication across internal systems (Stadtfeld et al., 2024). Marmolejo-Saucedo (2020) also uses local databases in their DT. Renault instead is able to alert all relevant parties in real time, ensuring that all stakeholders are kept informed of critical developments by using CC technologies (Stadtfeld et al., 2024). Similarly, Tetra Pak's integration efforts reduce bottlenecks and miscommunications, particularly in shipment management, improving the coordination between partners (Stadtfeld et al., 2024). Zhao et al. (2022) highlight the benefits of inviting upstream and downstream suppliers to collaborate directly in the industrial park, which not only fosters better communication but also helps reduce delivery costs.

Modeling and computing capabilities are fundamental to the effectiveness of Digital Twins (DTs) in supply chain operations, enabling dynamic simulation, optimization, and decision support. The first steps of a DT maturity involves basic UML depiction of the main SC classes and actors and discrete-event simulation models to represent basic SC processes as well as make prediction on a few subset of SC problems and KPIs (Ferrari et al., 2023; Lagorio et al., 2024). Marmolejo-Saucedo (2020) leverages simulation-optimization methods to generate more system-level KPIs. Zhao et al. (2022) emphasize the importance of algorithms like Dijkstra's for optimizing routes while considering constraints such as time windows and capacity. These capabilities enable DTs to deliver high accuracy in simulating physical supply chains, as seen in JD.COM's platform, which captures key metrics with 96% accuracy, and supports continuous optimization for real-time decision-making. In more complex supply chain models, Wang et al. (2022) demonstrate that optimization and simulation algorithms can be integrated to balance conflicting objectives, simulate different strategies, and evaluate solutions based on various performance indicators like inventory turnover, order fulfillment, and costs. Further advancement envision the use of advanced data analytics methods. Renault utilizes AI to enhance decision-making and predict risks with greater accuracy, improving outcomes for drivers, fleets, and cargo (Stadtfeld et al., 2024). General Electric Power also incorporates AI to refine its operational efficiency, while Siemens applies advanced simulation and data analytics to optimize fleet management, enabling adaptive, data-driven decisions (Stadtfeld et al., 2024).

Learning capabilities within Digital Twins (DT) in supply chain management are essential to continuously improve decision making and operational efficiency. Learning relies primarily on manual data input and basic descriptive analytics at lower maturity levels. In contrast, at advanced levels, DTs leverage AI-driven predictive models, deep learning techniques, and real-time data harmonization to refine operational strategies and improve adaptability. Organizations investing in DT development must also focus on skill building and knowledge transfer to bridge the gap between technological advancements and workforce capabilities, ensuring sustainable and scalable implementations (Srivastava et al., 2022).

Finally, *Digital Processes* are crucial for automating and streamlining operations, reducing reliance on manual tasks, and improving efficiency. Marmolejo-Saucedo (2020) highlights that data is often collected and uploaded by professionals through spreadsheets or other databases, which can be time-consuming and prone to error. General Electric Power has significantly enhanced its processes by eliminating numerous separate, manually maintained spreadsheets and dashboards, which previously took days to compile, thus speeding up decision-making and improving data accuracy (Stadtfeld et al., 2024). Additionally, this system supports automated scenario testing, enabling the company to evaluate different operational strategies without manual intervention.

5. DISCUSSIONS

5.1 Cross-case analysis

From the use cases analyzed it is clear that several DT dimensions are interrelated and should be driven forward together in order to reach higher levels of maturity of the DTSCM. For instance, advanced modeling methods (e.g., AI) depend on seamless, real-time data integration to support prescriptive decision-making. Data integration also enhances stakeholder collaboration and enable digital processes with automates workflows, reducing the time lag between insights and actions. At higher maturity levels then, DTs enable self-optimizing, autonomous supply chain ecosystems capable of responding dynamically to disruptions and opportunities.

These seemingly trivial results conceals key challenges that the proposed MM brings front and center and that did not receive much attention from scholars in the field of Digital Twins in SCM. For instance, even though having standardized communication protocols fostered by a trusted and aligned network of stakeholders will help overcome the barriers to achieving full data and system integration, open questions remain as to how cybersecurity issues are to be solved, and what are the levels of maturity connected with different cybersecurity strategies. The inherent reliance of DTs on online digital platforms with varying security levels (open, walled garden, and closed), as well as the vulnerability of older, resource-constrained field gateways, further underlines the necessity of robust cybersecurity strategies (Tao et al., 2018). Furthermore, to facilitate the DT advanced data processing and analyses capabilities, its implementation typically relies on cloud storage, where practitioners should take notice of the different level of security between open cloud (least secure), hybrid cloud (medium security), and private cloud (most secure) (Pärn et al., 2024). Finally, real-time data exchange and communications enabled by digital tools inherently amplify vulnerabilities, exposing DTs to potential cyber intrusions and malicious attacks (Pärn et al., 2024).

Furthermore, it is well known that tracing technologies (e.g. IoT, blockchain) play a significant role in overcoming the challenges of data harmonization, and computing capabilities enable advanced data analytics problem solving by the Digital Model of the DT. However, oftentimes there is a steep learning curve for the DT development and thus organizations should also invest in DT development skills and learning capabilities, in order to increase their overall level of maturity.

5.2 Theoretical and practical implications

In terms of theoretical implications, the novelty of this work lies in its first attempt at generalizing the levels of maturity of a DTSCM over multiple dimensions that go beyond the more traditional perspective of a DT as a technology. The definitions of the levels of maturity here proposed may help practitioners and scholars to take more informed decisions at the pre-adoption or pre-implementation stage, particularly in terms of the simulation software to use, which will affect the computing capabilities as well as dictate which skills to develop (Lanzini et al., 2024); the choice of the reference object, meaning which processes or actors of the SC are modeled by the DT, which will drive the path towards higher levels of data and system integration and stakeholders collaboration maturity (Huang et al., 2024; Uhlenkamp et al., 2022). Finally, this MM introduces a definition for the fully developed DTSCM, which can unlock the potential for a system-of-systems approach or better a DT of DTs approach, where multiple DTs are integrated to provide improvement beyond the single company SC. In this sense, creating frameworks that support data sharing within a data ecosystem, such as data spaces, is instrumental.

6. CONCLUSIONS

This paper presented a first attempt at a Maturity Model for Digital Twins in the supply chain management domain of application. The definition of levels and dimensions were taken from previous works on MM in Digital Twins and Supply Chain contexts, and a proposal for defining the criteria for all dimensions at all levels is also outlined in this work. The MM highlighted the strategies for transitioning towards higher level of maturity, focusing on few interrelated dimensions such as data and system integration and stakeholders collaboration. It also outlined some dimensions that could receive more attention in future research such as skills development and cybersecurity strategies. This study has several limitations. First, the maturity model has been tested only on few selected use cases and scientific papers. A proper evaluation of the maturity model will be the subject of future work and will involve extending the analysis to a more encompassing literature review and gaining insights from practitioners and real-life use cases. Second, only the development of the maturity model was included within the scope of this paper. The implementation phase will be developed in future research activities.

REFERENCES

Delgado, J.M.D. and Oyedele, L. (2021). Digital twins for the built environment: learning from conceptual and process models in manufacturing. *Advanced Engineering Informatics*, 49, 101332.

Dellana, S., Rowe, W.J., and Liao, Y. (2022). A scale for measuring organizational risk management maturity in the supply chain. *Benchmarking: An International Journal*, 29(3), 905–930.

Elibal, K. and Özceylan, E. (2022). Comparing industry 4.0 maturity models in the perspective of tqm principles using fuzzy mcdm methods. *Technological Forecasting and Social Change*, 175, 121379.

Ferrari, A., Carlin, A., Rafele, C., and Zenezini, G. (2023). A method for developing and validating simulation models for automated storage and retrieval system digital twins. *The International Journal of Advanced Manufacturing Technology*. doi:10.1007/s00170-023-12660-y.

Freese, F. and Ludwig, A. (2024). A conceptual framework for supply chain digital twins–development and evaluation. *International Journal of Logistics Research and Applications*, 1–23.

Gastaldi, L., Pietrosi, A., Lessanibahri, S., Paparella, M., Scaccianoce, A., Provenzale, G., Corso, M., and Gridelli, B. (2018). Measuring the maturity of business intelligence in healthcare: Supporting the development of a roadmap toward precision medicine within ismett hospital. *Technological Forecasting and Social Change*, 128, 84–103.

Guerra, J.H.L., Souza, F.B.d., Pires, S.R.I., and Sá, A.L.R.d. (2024). A maturity model for supply chain risk management. *Supply Chain Management: An International Journal*, 29(1), 114–136.

Hu, B., Guo, H., Tao, X., and Zhang, Y. (2023). Construction of digital twin system for cold chain logistics stereo warehouse. *IEEE Access*.

Huang, Y., Ghadge, A., and Yates, N. (2024). Implementation of digital twins in the food supply chain: a review and conceptual framework. *International Journal of Production Research*, 62(17), 6400–6426. doi:10.1080/00207543.2024.2305804.

Kucińska-Landwójtowicz, A., Czabak-Górska, I.D., Domingues, P., Sampaio, P., and Ferradaz de Carvalho, C. (2024). Organizational maturity models: the leading research fields and opportunities for further studies. *International Journal of Quality & Reliability Management*, 41(1), 60–83.

Lagorio, A., Mangano, G., Pinto, R., Rafele, C., and Zenezini, G. (2024). Empirical grounded simulation models for make-to-order (mto) supply chains: An application in the furniture industry. In *IFIP International Conference on Advances in Production Management Systems*, 78–91. Springer.

Lanzini, M., Ferretti, I., and Zanoni, S. (2024). Towards the Implementation and Integration of a Digital Twin in a Discrete Manufacturing Context. *Processes*, 12(11), 2384. doi:10.3390/pr12112384. URL `https://www.mdpi.com/2227-9717/12/11/2384`.

Le, T.V. and Fan, R. (2024). Digital twins for logistics and supply chain systems: Literature review, conceptual framework, research potential, and practical challenges. *Computers & Industrial Engineering*, 187, 109768. doi:10.1016/j.cie.2023.109768.

Liu, Y., Feng, J., Lu, J., and Zhou, S. (2024). A review of digital twin capabilities, technologies, and applications based on the maturity model. *Advanced Engineering Informatics*, 62, 102592.

Marmolejo-Saucedo, J.A. (2020). Design and development of digital twins: A case study in supply chains. *Mobile Networks and Applications*, 25, 2141–2160.

Park, K.T., Son, Y.H., and Noh, S.D. (2021). The architectural framework of a cyber physical logistics system for digital-twin-based supply chain control. *International Journal of Production Research*, 59(19), 5721–5742.

Pärn, E., Ghadiminia, N., de Soto, B.G., and Oti-Sarpong, K. (2024). A perfect storm: Digital twins, cybersecurity, and general contracting firms. *Developments in the Built Environment*, 18, 100466.

Patil, A., Srivastava, S., Paul, S.K., and Dwivedi, A. (2024). Digital twins' readiness and its impacts on supply chain transparency and sustainable performance. *Industrial Management & Data Systems*, 124(8), 2532–2566. doi:10.1108/IMDS-10-2023-0767.

Redelinghuys, A.J.H., Basson, A.H., and Kruger, K. (2020). A six-layer architecture for the digital twin: a manufacturing case study implementation. *Journal of Intelligent Manufacturing*, 31(6), 1383–1402. doi:10.1007/s10845-019-01516-6.

Srivastava, D.K., Kumar, V., Ekren, B.Y., Upadhyay, A., Tyagi, M., and Kumari, A. (2022). Adopting industry 4.0 by leveraging organisational factors. *Technological Forecasting and Social Change*, 176, 121439.

Stadtfeld, G.M., Lienemann, R., and Gruchmann, T. (2024). An analysis of digital twin technologies enhancing supply chain viability: empirical evidence from multiple cases. *Production Planning & Control*, 1–17.

Tao, F., Qi, Q., Liu, A., and Kusiak, A. (2018). Data-driven smart manufacturing. *Journal of Manufacturing Systems*, 48, 157–169. doi:https://doi.org/10.1016/j.jmsy.2018.01.006. Special Issue on Smart Manufacturing.

Uhlenkamp, J.F., Hauge, J.B., Broda, E., Lutjen, M., Freitag, M., and Thoben, K.D. (2022). Digital Twins: A Maturity Model for Their Classification and Evaluation. *IEEE Access*, 10, 69605–69635. doi:10.1109/ACCESS.2022.3186353.

Wang, L., Deng, T., Shen, Z.J.M., Hu, H., and Qi, Y. (2022). Digital twin-driven smart supply chain. *Frontiers of Engineering Management*, 9(1), 56–70. doi:10.1007/s42524-021-0186-9.

Warnecke, D., Wittstock, R., and Teuteberg, F. (2019). Benchmarking of european smart cities–a maturity model and web-based self-assessment tool. *Sustainability Accounting, Management and Policy Journal*, 10(4), 654–684.

Wendler, R. (2012). The maturity of maturity model research: A systematic mapping study. *Information and software technology*, 54(12), 1317–1339.

Wooley, A., Silva, D.F., and Bitencourt, J. (2023). When is a simulation a digital twin? a systematic literature review. *Manufacturing Letters*, 35, 940–951.

Zhao, Z., Zhang, M., Chen, J., Qu, T., and Huang, G.Q. (2022). Digital twin-enabled dynamic spatial-temporal knowledge graph for production logistics resource allocation. *Computers & Industrial Engineering*, 171, 108454.