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

Trondheim, Norway, June 30 – July 03, 2025

PROCEEDINGS

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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)

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- 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*
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- 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*
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Developing warehouse management skills through Learning Factories: a use case

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Abstract: The advancements in the manufacturing sector have necessitated the evolution of educational paradigms to address skills mismatches and enhance workforce adaptability. This paper explores the potential learning use cases related to the incorporation of automated warehouse stations into Learning Factories (LFs) to develop competencies for warehouse management within Industry 5.0 framework. It presents a structured methodology for aligning educational goals with industry demands, emphasizing technical, methodological, personal, and interpersonal skills. A detailed analysis of the skills required for warehouse managers was conducted using the ESCO database and scientific literature. These findings informed the development of a laboratory use case involving an automated warehouse station at the University of Bergamo's SLIM Lab. The study evaluates various warehouse management strategies, emphasizing the relationship between operational choices and key performance indicators (KPIs) like energy consumption, error rates, and processing times. Results highlight the effectiveness of LFs in fostering essential competencies while addressing limitations in current LF configurations, such as inconsistencies in data collection and KPI measurement. The proposed framework demonstrates potential for broader applications across diverse job profiles and LF setups, providing a robust foundation for advancing education and training in automated logistics systems. Future research aims to extend this framework to encompass additional job profiles and advanced LF technologies.

Keywords: Learning factory, automated warehouse, competences, skills.

1. INTRODUCTION

The manufacturing sector has recently experienced significant changes driven by the digitalization of production and logistics, technological advancements, and growing priorities such as sustainability, resilience, and human-centric design (Directorate-General for Research and Innovation, 2021). Factors like climate change, the COVID-19 pandemic, and geopolitical conflicts have accelerated these transitions, emphasizing the role of technology in enhancing efficiency, reducing costs, and improving both sustainability and workforce well-being. However, the rapid pace of these changes demands swift adaptation in both technology and workforce to avoid skills mismatches and inefficiencies. In particular, skill mismatch, defined as the gap between the skills demanded by companies and those possessed by workers, poses critical challenges (Brunello & Wruuck, 2021). This phenomenon affects innovation, technological adoption, and access to quality jobs. Skill mismatch happens because as technological progress is incremental, workers require ongoing skill updates through continuous learning and professional development, commonly referred to as lifelong learning and this is still not a common practice and requires a change in the education paradigms. These shifts have also impacted higher education, necessitating alignment with industry demands to equip students with relevant skills, thereby fostering Education 4.0 (Mourtzis et al., 2022). The Education 4.0 framework focuses on advanced manufacturing education that integrates cutting-edge technologies and makes the sector more appealing. In this context, Learning Factories (LFs) have emerged as a promising approach to teach manufacturing processes through a socio-technical, work-based learning environment. A learning factory is an adaptable learning environment that simulates real-world production processes, integrating technical and organizational aspects through hands-on, competency-based training, which may occur in physical or virtual settings, with learning facilitated via teaching, training, or research to drive both skill development and innovation (Abele et al., 2017). Since their introduction in 1994 (Lamancusa et al., 2008), LFs have expanded to address diverse manufacturing processes, products, and educational objectives. They enable learners to explore and understand production and logistics processes in a simulated work setting, facilitating the development of specific competencies. However, the diversity in LF setups and goals makes it challenging to clearly identify their research and educational applications, as well as the learning outcomes they support. Learning objectives or learning outcomes are broad, subject-specific learning outcomes that define what students should be able to understand and apply after a learning experience, encompassing knowledge, skills, and competencies without being strictly tied to discrete, measurable behavioral objectives (Allan, 1996). This situation is particularly critical in sectors where technological innovation has penetrated more pervasively with a much faster evolution than in other sectors, as in the case of the manufacturing sector and particularly in activities related to production and logistics. Production activities, due to the added value brought to the process, were the first to be affected by these considerations, as reflected in the number of studies

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in the literature that have as their main objective the understanding of which activities can be fully automated and which ones require technological support but must still be performed by human operators (Sgarbossa et al., 2020). There are numerous studies on Learning Factories, and most of the learning factories that have been studied indeed concern production-related activities and operations. Regarding logistics activities, however, these studies are more recent and mainly concern operational rather than managerial/administrative duties, despite the strong push towards automation in recent years that has significantly changed the skills required of those working in this sector. In fact, there are very few studies on learning factories that have involved logistics activities (Vailati et al., 2023). In particular, this study tries to answer to a specific Research Question: "How can Learning Factories (LFs) be leveraged to bridge the skills gap in logistics management, ensuring alignment with industry demands in the context of automation and digital transformation?". To answer to this RQ, a learning framework for engineering skills related to the learning factory will be proposed (Section 2). Specifically, for the construction of the framework, an analysis of the skills required to warehouse managers will be conducted based on scientific literature (Section 3.1), and based on the ESCO database (Section 3.2). These will be compared to the skills that may be gained through the use of an automated warehouse station present in learning factories and described in Section 4. The proposed learning framework will finally be tested with a practical laboratory application (Section 5). The paper will finally include a discussion section of the results obtained and the conclusions of the research work (Section 6).

2. METHODOLOGY

The methodology outlines the generalized steps followed in the research workflow. The research workflow presented in Figure 1 equates to a proposed framework to follow for creating laboratory use cases aimed at developing, through Learning Factories, technical, methodological, personal, and interpersonal competencies (Hecklau et al., 2016) related to various job profiles that could be filled by management engineers. In this paper specifically, the research subject is the creation of a laboratory use case for developing competencies for a job profile related to the warehouse manager position. The framework initially involves an analysis of scientific literature related to the competencies pertaining to the warehouse manager role. The same research was repeated on the ESCO database. This research led to the definition of a list of competencies that takes into account the outputs of both research efforts. Subsequently, the characteristics, possible operations, and KPIs that can be collected from the learning factory station corresponding to an automated warehouse were analyzed in detail. In the final phase, based on the objectives of developing certain competencies and the limitations given by the Learning Factory characteristics, an initial laboratory use case was defined. The use case was then tested and analyzed to understand which competencies can effectively be learned through it.

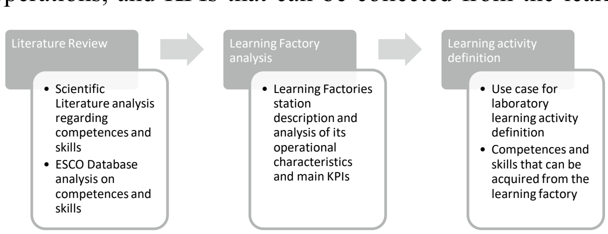

Figure 1. Framework for laboratory use case definition.

3. LITERATURE REVIEW

This section of the paper contains an analysis of the scientific literature (Section 3.1) and an analysis of the ESCO database (Section 3.2) aimed at defining the main technical, methodological, personal and interpersonal competencies that a warehouse manager must have. In the last section a synthesis of the competences emerged from the analysis of the two databases is presented.

3.1 Scientific literature review

Regarding the scientific literature review, an analysis was conducted on the main bibliographic databases (i.e., Scopus, Science Direct, WOS) using the following query "warehouse manage*" AND "competenc*" AND "skill*" and limited the research to the English articles. No exclusion criteria have been defined regarding the time period and both journal articles and conference proceedings have been taken into account. The search yielded 43 documents, which were reduced to 17 after reading the titles and abstracts. Following the full reading of the articles, only 6 articles were considered relevant to the research objectives. At this point, the authors of this paper individually and separately classified the competencies reported in the paper inductively into technical, methodological, personal, and interpersonal competencies according to Hecklau's classification. Competencies whose classification did not immediately reach convergence among the authors were discussed until consensus was reached. The result of the classification is shown in Table 1.

Table 1. Scientific Literature Review Results.

Competence Type	Key Competences	References
Technical Competences	Proficiency in Industry 4.0 technologies (IoT, RFID, autonomous robots, blockchain)	(Belmonte et al., 2023; Tikwayo & Mathaba, 2023)
	Data analytics skills	(Kramarz & Kmiecik, 2022; Tikwayo & Mathaba, 2023)
	Integration of automation tools for warehouse tasks	(Hasan & Niyogi, 2024; Tikwayo & Mathaba, 2023)
	Forecasting and predictive modeling expertise	(Kramarz & Kmiecik, 2022; Min, 2007)
Methodological Competences	Process optimization using	(Bahr et al., 2022; Tikwayo & Mathaba, 2023)

	Lean, Agile, and related methods	
	Application of gamification to boost engagement and productivity	(Bahr et al., 2022)
	Hierarchical problem-solving for collaborative tasks	(Hasan & Niyogi, 2024)
	Sustainability-focused operational strategies	(Kramarz & Kmiecik, 2022)
Personal Competences	Adaptability to technological and industry changes	(Tikwayo & Mathaba, 2023)
	Continuous learning mindset to acquire new skills	(Belmonte et al., 2023)
	Ethical awareness, especially in technology and HR policies	(Bahr et al., 2022; Min, 2007)
	Resilience in high-pressure environments	(Min, 2007)
Interpersonal Competences	Leadership skills for managing and motivating diverse teams	(Bahr et al., 2022; Min, 2007)
	Collaboration with internal and external stakeholders	(Hasan & Niyogi, 2024; Kramarz & Kmiecik, 2022)
	Effective communication with stakeholders to ensure alignment	(Kramarz & Kmiecik, 2022; Min, 2007)
	Employee retention strategies such as recognition programs and cross-training	(Min, 2007)

3.2 ESCO database analysis

The European Skills, Competences, Qualifications and Occupations (ESCO) database, a framework developed by the European Union to facilitate the integration of labor markets throughout Europe (https://esco.ec.europa.eu/it), plays a primary fundamental role in identifying the most valuable skills in the manufacturing sector. ESCO constitutes a comprehensive and multilingual classification of knowledge, skills, and abilities related to work in three categories (skills, qualifications, and occupations), promoting the use of a helpful standard glossary for effective communication and understanding among labor market actors, such as workers, employers, and education providers (Lagorio et al., 2024). In this research, the competencies and skills associated to the "warehouse manager" job profile have been analyzed. Then, the authors carried out a similar process to the one carried out for the scientific literature analysis in order to inductively classify also the skills coming from the ESCO database in the same four categories previously considered (i.e., technical, methodological, personal, interpersonal). The results are presented in Table 2.

Table 2. ESCO Database analysis.

Technical	Methodological	Personal	Interpersonal
Comprehend financial business terminology	Apply safety Management	Create a work atmosphere of continuous improvement	Build business relationships
Identify stoftware for warehouse management	Improve Business processes	Create solutions to problems	Coach employees
Ensure efficient utilisation of warehouse space	Manage dispatch software systems	Exert a goal-oriented leadership role towards	Give Instruction to staff
Ensure stock storage safety	Manage inventory	Reliability	Manage staff
Maintain financial records	Manage third-party logistics providers	Analyse and write written reports	Provide staff training in warehouse management
Maintain physical condition of the warehouse	Manage warehouse operations		Train employees
Maintain stock control systems	Manage warehouse organisation		use different communication channels
Maintain warehouse database	Meet productivity targets		Work in a logistics team
Monitor security procedures in warehouse operations	Oversee warehouse value-added activities		
Monitor storage space	Plan future capacity requirements		
Oversee freight-related financial documentation	Plan the dispatching of products		
Perform cost accounting activities	Plan the stocking of products		
Use a warehouse management system	Schedule shifts		
Knowledge of warehousing regulations	Project management		

4. LEARNING FACTORY ANALYSIS

This section contains a detailed description of the SIF400 LF located at the University of Bergamo (Section 4.1) and a focus on the description of the automated warehouse station (Section 4.2).

4.1 Learning Factory description

The LF system set up at the SLIM (Smart Living In Manufacturing) laboratory within the Department of Management, Information, and Production Engineering at the University of Bergamo (UNIBG) in Italy features an assembly, sorting, and packaging line. This setup incorporates SMC's SIF 400 - Smart Innovative Factory, which replicates a smart and interconnected manufacturing environment, covering the entire process from initiating a production order to dispatching the final product. The line comprises seven modular stations as illustrated in Figure 2.

The factory enables the production of customizable products, represented by containers of various shapes (square or cylindrical) filled with differently colored balls (blue, red, or yellow) in varying quantities, depending on the specific stock-keeping unit (SKU) requirements.

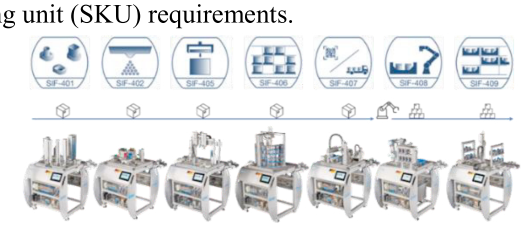

Figure 2. The SIF-400 Learning Factory at the UNIBG SLIM Lab.

Upon request, the system can produce either individual containers or packaged sets. The production process progresses from station SIF-401 to SIF-407 for single products, while stations SIF-408 and SIF-409 manage the packaging of multiple items. Additionally, the system supports make-to-order and make-to-stock production, with individual products stored at SIF-406 and packaged units at SIF-409. The line can be operated manually using Human-Machine Interfaces (HMI) available at each station or through an integrated approach managed by the Manufacturing Execution System (MES), known as SIFMES. For this study, only the initial stations (SIF-401 to SIF-406) were utilized.

4.2 Automated Warehouse description

The SIF station regarding the container warehouse is called "SIF-406". This station acts as an autonomous warehouse, and the operation of storing the product (i.e., semi-finished or finished product) is carried out at this station. Storage occurs in a vertical semi-circular warehouse distributed amongst five levels and ten columns, allowing up to fifty containers to be stored with their respective pallets. The station allows the insertion, extraction, or internal movement of the containers on the pallets in this warehouse, as the process requires. Operations begin to occur when the station receives the order either from the MES (integrated mode) or from the HMI of the station itself (manual mode) which the user manually activates. Different storage policies could be implemented through three different warehouse management modes:

- *The variable mode:* each location in the warehouse can contain any article. This way, articles arriving at the warehouse will have to find the first free location.
- *The fixed mode:* each location in the warehouse is associated with a specific article. This way, upon arrival, articles must identify a vacant location that corresponds to their assigned reference. To change the assigned reference to one or more locations, it is possible to use one "assign" button on the MES.
- *The "organized mode":* the articles are categorized into three groups: A, B, or C. Each group has an assigned warehouse section consisting of one or more columns.

Regardless of the mode used, the SIF-406 warehouse employs a cost management system that enables the evaluation of the storage options and determines the cost associated with not being able to fulfil certain storage requests. In particular, in the default condition, each enabled position in the warehouse costs 1 € and there is a 6 € additional cost for each container that has not been able to access the warehouse because they did not meet the conditions (i.e., no empty space for that product).

When the integrated mode is used, is also possible to access some performance indicators linked to productivity (i.e., OEE), warehouse status (i.e., free, occupied, and disabled positions), and energy measurements (i.e., energy consumption in kw/h, compressed air consumption).

5. USE CASE DEFINITION AND APPLICATION

Considering the characteristics of the automated warehouse station and the warehouse manager competencies that emerged from both the scientific literature analysis and the ESCO platform analysis, a laboratory use case was defined to enable their development. Specifically, through a DOE analysis, a production mix of 50 products was defined to be sent to the warehouse for saturation, based on product availability (i.e., circular boxes - empty or filled with 5, 10, 15 grams of blue, red, and yellow balls – and square boxes – empty or filled with 15, 30, 45 grams of blue, red and yellow balls). The use case was designed to evaluate warehouse management strategies considering different organizational models, high-volume stress conditions, and sustainability. Four strategies—variable, two ABC-based, and fixed—were tested to reflect diverse organizational approaches. A high workload (50 products, processed in 10-product batches) was implemented to assess efficiency under peak conditions. The study focused on stocking times, energy consumption, and errors across multiple stations. Sustainability was analyzed through energy consumption optimization, demonstrating that a weight-based storage strategy reduced energy use by 13%. These aspects ensure a comprehensive understanding of efficiency, adaptability, and sustainability in warehouse automation. Four warehouse management strategies were considered:

- a variable one with the rule: the fastest location to reach is used first.
- two "organized" strategies based on two different ABC categorizations, one based on colours and one based on weights.
- a fixed strategy where boxes with greater weight are located in the lower rows while empty boxes are in the highest row.

To simplify the execution of the experimental trial, reshuffling or picking operations were not considered, focusing only on storage strategies. For each of the described strategies, the warehouse was saturated with a mix of 50 products defined through DOE. Orders were launched through the learning factory's MES, always repeating the same sequence and launching the order of 50 products in batches of 10 products. With the aim of simplifying the execution of the experiment for the use case, among all KPIs related to automated warehouses discussed in the literature and those measurable through the learning factory, it was decided to consider only stocking times, energy consumption, and number of errors. It was also decided to monitor these data not only in relation to the automated warehouse station but across the first four stations of the line (also including SIF-401, SIF-402, SIF-405) to evaluate the impacts of the automated warehouse and its management strategies on the entire semi-automated line. The use case was carried out by a team composed of two master's students, one PhD student, and two professors. The experimental results regarding the performance of the tested strategies are reported in Table 3.

Table 3. Automated warehouse station case results analysis.

	Time (hh:mm:ss)	Average (hh:mm:ss)	Std Dev (hh:mm:ss)	Cons (kWh)	Average Cons (kWh)	Std Dev	TC Corr
Variable	00:24:04	00:04:49	00:00:05	134	26.8	14.3	0.70
Organized (quantity)	00:23:02	00:04:36	00:00:14	90	18	23.5	0.25
Organized (color)	00:23:46	00:04:45	00:00:08	163	32.6	40.5	-0.28
Fixed (weight)	00:23:38	00:04:44	00:00:12	70	14	16.9	-0.53

The table shows the total production times (processing of 50 products), the average processing times of a batch (10 products) and its standard deviation, the energy consumption for each test (50 products), the average consumption from processing a batch (10 products) and its standard deviation. Furthermore, the correlation between times and total consumption has been calculated. It can be noted that while for times the results are very similar across the strategies, regarding energy consumption the same cannot be said at the individual station level, where standard deviations higher than the mean can be observed. This is also why the correlation between times and consumption (predictably existing and positive) is valid only for the variable strategy application scenario, the only one in which the standard deviation of the station's energy consumption, although high, was lower than the mean. This irregularity and inconsistency are due to how the energy consumption data is recorded by the PLC sensor. The recording of energy consumption data in the LF database does not occur at regular intervals (even though in the MES it is possible to observe consumption for a user-selected time period), but when an event occurs (e.g., product movement, activation of a safety control sensor, activation of the reset button in case of detected error). This characteristic of the line leads to the inability to make robust considerations about the energy consumption of individual stations for short periods of time (typically less than half an hour). Given the limited time frame associated with monitoring a single station, the number of events that determine energy consumption database recording is highly variable. Consequently, the results collected may not be accurate or comparable between one batch and the next. It is more interesting to observe Table 4, which shows similar results in terms of times, consumption, errors, and possible correlations between them regarding the entire line (in this case four stations in total).

Table 4. Learning factory's use case results analysis

	Time (hh:mm:ss)	Cons (kWh)	Err	Corr TC	TE	CE	Station/Line
Variable	01:55:03	398	17	0.70	0.29	-0.23	0.34
Organized (quantity)	01:53:09	387	21	0.25	-0.12	0.25	0.23
Organized (color)	02:07:30	577	17	-0.28	0.03	0.54	0.28
Fixed (weight)	02:05:38	332	20	-0.53	0.90	0.69	0.21

Correlations were then tested between times and consumption (TC), between times and errors (TE), and between consumption and errors (CE). Furthermore, the relative impact of energy consumption of the single station related to the automated warehouse compared to the consumption of the entire line was also evaluated. Also in this case, it can be observed that the correlation between times and consumption of the entire line is valid only in the case of the "variable" strategy as it was for the single station, while the correlation between times and errors is strong and positive only for the fixed strategy. These inconsistencies are linked to the recording of energy consumption data and the management of errors and their subsequent adjustment within the line, which varies from station to station: in most stations, the occurrence of an error (i.e., product non-conformity) does not impact times since the "repair" activity is managed simultaneously with the handling of a new product. The most interesting finding that emerged from the analysis of the results obtained is the impact of the automated warehouse station. If we choose a variable warehouse management strategy, optimized only for storage times, the impact on line consumption is 34% of the total; as the strategy rationalizes storage based on weight (and consequently the energy needed for lifting, ranging from empty products to products containing 50g of balls), consumption decreases. For the strategy where heavier products are stored on lower floors, we have a consumption of 21%, representing a 13% reduction in the station's consumption impacts compared to the total line consumption. In addition to the numerical results, the competencies developed through the conduct of the laboratory tests, operational decisions, and analysis of results were also evaluated. This process was conducted in accordance with the framework presented in Section 3. The subsequent section will describe these aspects in detail.

6. DISCUSSION AND CONCLUSIONS

In this final section of the paper, a subsection is presented discussing the skills that may be gained through the use of an automated warehouse station present in learning factories (Section 6.1) and the conclusions of the research work (Section 6.2).

6.1 Discussion

Following the execution of the use case, a brainstorming session was conducted among the experimental team participants, which led to the filling of Table 5, which outlines the competences that emerged from the analysis presented in Section 3. In light of the executed use case, the operational decisions, and the abilities required to complete the laboratory experiment, the following competences and skills were identified as pertinent for a warehouse manager who is required to interact with an automated warehouse. As can be observed from Table 5, the presented use case allows the development of a good number of warehouse manager competencies (the ones marked with the thick).

Table 5. Learning factory's use case results analysis

Competence Type	Key Competences	Use case
Technical Competences	Mastering of Industry 4.0 tools (IoT, RFID, WMS, DSS)	✓
	Managing stock systems, safety, and inventory controls	✓
	Financial and cost accounting in warehouse management	X
	Efficient utilization and monitoring of warehouse space and energy consumption	✓
Methodological Competences	Process improvement (Lean, Agile), safety management, and productivity	✓
	Overseeing logistics and dispatching plans	✓
	Planning future capacity and warehouse layout	✓
Personal Competences	Continuous learning and adaptability to change	X
	Leadership with goal-oriented strategies and reliability	X
	Writing reports and communicating technical insights	✓
Interpersonal Competences	Team leadership, coaching, and fostering staff development	X
	Building and maintaining professional relationships	X
	Effective use of communication channels to align operations	✓

The identified competences can be grouped into technical, methodological, personal, and interpersonal skills, ensuring a well-rounded learning experience. While technical and methodological skills were strongly developed through data analysis and warehouse strategy evaluation, personal and interpersonal competences emerged through decision-making, teamwork, and problem-solving in an automated environment. This balance highlights the comprehensive learning potential of the use case. However, some limitations emerged, mainly due to the learning factory which does not make it possible to collect some data in a unique and clean way.

6.2 Conclusions

The framework presented in Section 2 proves to be a good system for designing use cases for the development of competencies related to management engineering. The present research work has limitations since the framework was only applied to one job profile related to warehouse and logistics, using only one line station for just one simplified use case. This latter limitation can easily be overcome by adding additional activities such as reshuffling and picking (and consequently adding considerations related to location strategies that take into account FIFO, LIFO, etc. logic) and by measuring additional KPIs such as OEE and costs. Regarding the extension to other job profiles, it can be observed that the suggested framework has such a level of generalization that it can be easily applied to other job profiles and other learning factory stations or activities that can be performed on it. Future research lines concern the realization of use cases that support the learning of fundamental competencies for a management engineer regarding production and logistics in manufacturing within an Industry 5.0 context using learning factories and other learning support technologies (e.g., virtual reality, AI).

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