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Boosting Supply Chain Agility and Sustainability with Industry 5.0: The Power of Additive Manufacturing and Digital Reverse Engineering

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Prof. Dessouky
Editor-in-Chief
Computers & Industrial Engineering

February 18th, 2024

Dear Prof. Dessouky Editor-in-Chief, and Guest Editors Prof. Tornese, Prof. Sassanelli, Prof. Bressanelli and Prof. Chiappetta Jabbour.

Congratulations on your interesting Special Issue on *Redesigning industrial systems supporting a systemic shift towards a Sustainable Circular Economy for achieving Net-Zero*. We are grateful to have been informed and hope that our research manuscript entitled "*Boosting Supply Chain Agility and Sustainability with Industry 5.0: The Power of Additive Manufacturing and Digital Reverse Engineering*", will be suitable for your journal.

My colleagues and I conducted research and coauthored the manuscript. We have all approved the paper for submission to *Computers & Industrial Engineering*, and I have been chosen as the corresponding author. Each of the authors confirms that this manuscript has not been previously published and is not currently under consideration by any other journal.

The paper, the result of collaborative research between universities and companies, proposes a product development methodology called AdM (Additive Digital Molding) that integrates three digital technologies. AdM combines design through 3D printing and injection molding to centralize all manufacturing in one room. This approach is ideal for highly customized products and in cases where sourcing is difficult, secrecy is required, or production flexibility is needed. It also has a low investment cost and is suitable for Industry 4.0 and 5.0, SMEs and entrepreneurial initiatives. Finally, AdM opens new business models with direct and "home" production, contributing to the sustainable development goals of Agenda 2030.

Believing that the topic is consistent with the goals of SI, we hope that readers of the journal will find interest in our article because of the interdisciplinary methodological approach and managerial solution we propose.

Thank you for your interest and consideration.

Yours sincerely,

Davide Settembre Blundo

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Title Page (with Author names, affiliations, Acknowledgement)

Boosting Supply Chain Agility and Sustainability with Industry 5.0: The Power of Additive Manufacturing and Digital Reverse Engineering

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Graphical Abstract (for review)

Highlights

- Additive Digital Molding (AdM) centralizes design, 3D printing, and manufacturing, enabling sustainable, on-demand production.
- Supply chain agility is increased to meet specific customer needs with rapid prototyping and flexible AdM processes.
- Low-cost, digital AdM enables companies to thrive in the connected manufacturing of Industry 4.0 and 5.0.
- SMEs and entrepreneurs gain supply chain control and efficient product development with AdM.
- Shortening the supply chain, reducing waste, home manufacturing, and contributing to UN goals with AdM's responsible production approach.

Boosting Supply Chain Agility and Sustainability with Industry 5.0: The Power of Additive Manufacturing and Digital Reverse Engineering

Abstract: This paper presents and tests a product development methodology that, through three enabling technologies based on digitalization, centralizes all sourcing and manufacturing activities in a single workspace. To that end, it is proposed to integrate three methodologies which are Digital Reverse Engineering for the design, Additive Manufacturing (or 3D Printing) of molds, and finally Plastic Injection Molding for final production. This combination gives rise to a technological mix acronym called Additive Digital Molding which is applied to the case of making a highly customized product in isolation conditions. As a result, it is a powerful tool with a low investment cost that can be widely used within the industry 4.0 and 5.0 frameworks especially when sourcing problems occur, customization is needed, or secrecy is required. Furthermore, it is an ideal tool for SMEs and individuals to implement entrepreneurial ventures that require both greater control over the supply chain and agile development of production operations. Finally, it must be highlighted the potentiality of Additive Digital Molding as enabling technology for bringing in new business and entrepreneurial models through direct manufacturing and home manufacturing as well as its contribution to meet the Sustainable Development Goals of the 2030 Agenda.

Keywords: Supply chain integration; Industry 4.0; Industry 5.0; additive manufacturing, digital reverse engineering; sustainability.

1.INTRODUCTION

The increasing frequency of supply chain disruptions within sourcing and manufacturing sectors underscores the intricate interconnectedness of global economies (Suresh et al., 2020). Supply chains play a pivotal role in ensuring the seamless flow of essential supplies to societies, making their continuity paramount (Han et al., 2020). However, recent disruptions have posed significant threats to global growth, challenging the resilience of supply chains (Theyel et al., 2018). Factors such as shortages of raw materials, congested ports, and geopolitical tensions exacerbate these challenges, creating an urgent need for transformative measures (Ando & Hayakawa, 2022). To mitigate risks and enhance resilience, businesses are compelled to reevaluate their operational strategies. This includes adopting shorter logistics chains (Miguel et al., 2024) and embracing sustainable distribution models to adapt to evolving market dynamics (Hynes et al., 2021). Emphasis is placed on leveraging new technologies, particularly those aligned with the Industry 4.0 framework (Sassanelli et al., 2023) and its evolved iteration, Industry 5.0 (Vacchi et al., 2024), to optimize supply chain management practices. These technological advancements offer opportunities to streamline processes, enhance efficiency, and address emerging challenges, thereby enabling businesses to navigate disruptions more effectively and sustainably (Saccani et al., 2023).

1.1 Enabling technologies for supply-side management

Enabling technologies have been instrumental in shaping the course of industrial history, marking significant transitions from the age of mechanization to the age of automation (Kuo et al., 2021). The evolution of Industry 4.0, commonly referred to as the Fourth Industrial Revolution, is a defining moment characterized by its emphasis on digitization, flexibility, and connectivity (Belmonte et al., 2023). This transformative shift has not only modernized traditional manufacturing practices but has also propelled industries into a new realm of increased efficiency and productivity (Jamil et al., 2023). Industry 5.0 builds on the foundation laid by its predecessor, Industry 4.0, to drive innovation toward a more sustainable, resilient, and human-centered approach to industrialization (Golovianko et al., 2023). Unlike previous industrial revolutions, Industry 5.0 prioritizes the integration of technologies that not only optimize operational processes, but also prioritize environmental sustainability and social well-being (Ivanov, 2023). At the heart of Industry 5.0 are key enabling technologies such as the Internet of Things (IoT), Big Data Analytics (BDA), Additive Manufacturing (AM), Blockchain, Digital Twins, and Metaverse Supply Chain. These technologies serve as the building blocks for transforming supply chain management practices to achieve sustainability and resilience in the face of evolving challenges and disruptions (Agrawal et al., 2023). The integration of these advanced technologies heralds a paradigm shift in the industrial landscape, signifying a departure from traditional models of industrialization (Konstantinidis et al., 2022).

KEY STAKEHOLDERS	ENABLING TECHNOLOGIES	INTERCONNECTEDNESS	BENEFITS	CHALLENGE
Manufacturers: Utilize technologies to optimize production, personalize offerings, and manage resources efficiently. **Logistics Providers:** Enhance visibility, track shipments in real-time, and optimize delivery routes. **Consumers:** Gain transparency into product origins and environmental impact, personalize purchases.	**Internet of Things (IoT):** Connects physical assets, sensors gather data on production, logistics, and product usage. **Big Data Analytics (BDA):** Analyzes real-time and historical data to identify trends, predict demand, and optimize processes. **Additive Manufacturing (AM):** Creates customized components on-demand, reducing waste and shortening supply chains. **Blockchain:** Provides secure and transparent record-keeping, tracks product provenance and ownership. **Digital Twins:** Creates virtual models of physical systems, enabling simulation and optimization of supply chain operations. **Metaverse Supply Chain:** Creates immersive virtual environments for visualizing and collaborating on supply chain processes.	IoT data feeds into BDA for analysis. BDA insights inform AM production and logistics optimization. Blockchain verifies product data and ownership. Digital Twins guide real-time process optimization. Metaverse facilitates collaboration and decision-making.	**Increased visibility and transparency:** Real-time data insights improve decision-making and collaboration. **Enhanced efficiency and agility:** Optimized processes and on-demand production reduce costs and improve responsiveness. **Improved sustainability:** Reduced waste, optimized resource utilization, and transparency in product origins. **Greater resilience:** Digital twins and simulations enable proactive risk management and disruption mitigation. **Human-centric approach:** Immersive technologies and data insights empower workers and improve communication.	**Integration and interoperability:** Seamless integration of diverse technologies and data platforms is crucial. **Cybersecurity and data privacy:** Robust security measures are essential to protect sensitive information. **Skill development and workforce transformation:** Upskilling and reskilling workers are needed to adapt to new technologies. **Investment and cost considerations:** Implementing new technologies requires significant upfront investment.

Table 1: Conceptual framework representing the key technologies and their contributions to supply chain management in Industry 5.0.

Industry 5.0 emphasizes the imperative of striking a delicate balance between economic progress and social and environmental responsibility in shaping the future trajectory of manufacturing and supply chain management (Dwivedi et al., 2023). Industry 5.0 technologies represent a paradigm shift in supply chain management, offering a transformative approach that prioritizes resilience, sustainability, and human-centricity. By overcoming challenges and fostering collaboration, organizations can harness the power of these technologies to create a more efficient and responsible global supply chain ecosystem.The framework outlined in Table 1 illustrates the intricate network of interconnected technologies that enable stakeholders to achieve resilience, sustainability, and human-centricity in the supply chain. Overall, this framework highlights the transformative power of Industry 5.0 technologies in reshaping supply chain management. By addressing challenges and fostering collaboration, stakeholders can fully leverage these technologies to cultivate a more efficient, sustainable, and human-centered future for global supply chains.

1.2 Enabling technologies for supply chain management in turbulent times

The supply chain management landscape is rich with potential technology solutions, but their successful integration depends on a comprehensive and cohesive strategy (Ivanov & Dolgui, 2022). While initiatives within the Industry 4.0 and 5.0 frameworks show promise, further exploration and merging of technologies could unlock even greater potential (Xu et al., 2021). Among these, 3D printing (Mourtzis et al., 2022) and Reverse Engineering (RE) (Bao et al., 2022) stand out for their effectiveness in addressing supply chain disruptions (Bednarski et al., 2023). They offer various benefits, including customized production, reduced dependence on external suppliers, and environmental sustainability through additive manufacturing. However, injection molding, while not classified under Industry 4.0 or 5.0, remains a relevant technology primarily associated with Industry 3.0 (Moayyedian, 2018; P. Zhao et al., 2020). Despite its efficiency in mass production, it faces challenges such as long lead times, high costs, and limited flexibility due to the need to create molds (Kashyap & Datta, 2015). Technology lends itself to standard, fixed designs and mass production processes, which may not align well with today's volatile economic and political landscape, leading to disruptions in the supply chain system (Sharifi et al., 2021). Strategic integration and alignment with business objectives are critical to determining the effectiveness of each technology in mitigating supply chain challenges. In particular, 3D printing is emerging as a powerful solution that enables the rapid production of customized components without the need for traditional manufacturing equipment or expensive tooling (Boretti, 2024). This technology not only reduces dependence on external suppliers (Dolgui et al., 2020), but also drives innovation and market expansion (Piticescu et al., 2019) while minimizing environmental impact through optimized resource utilization (Shuaib et al., 2021). Digital Reverse Engineering (DRE) is a complementary technology to 3D printing that enhances its capabilities in various industries (Pudovkina et al., 2022; Suebsuwong, 2023). Originating from traditional Reverse Engineering (RE), which traces back to World War II military applications, DRE has evolved significantly with the incorporation of digital technologies such as CAD and 3D scanning, expanding its efficiency and applications (Arenkov et al., 2019; Zhang & Yu, 2016). Unlike traditional forward engineering processes, RE involves creating a digital CAD file from a physical product through steps such as 3D scanning and point cloud generation (Helle & Lemu, 2021). This digital file can then be used for manufacturing through a 3D printer, effectively coupling both technologies. Currently, this integration is integral to various industries, driving innovation and product development with advanced tools and techniques (López & Vila, 2021).

Despite the growing interest in these enabling technologies, research on their practical application to manage supply chain disruptions is still in its early stages (M. M. Meyer et al., 2021). This study aims to fill this gap by presenting an empirical example of creating a shortened supply chain using three technologies (AM, DRE, and IM) in a concept known as Additive Digital Molding (AdM). AdM represents an extreme case of supply chain shortening that can be applied even in non-industrial settings such as a garage or living room. In particular, the author implemented this approach in a dorm room during the Covid-19 pandemic, demonstrating its versatility and potential impact.

Supply chain, operations, and performance management (Sassanelli & Terzi, 2023) have traditionally operated under the assumption of continuous availability of resources to meet demand, with occasional fluctuations and interruptions. However, the landscape is now being challenged by prolonged outages and extreme disruptions, resulting in persistent shortages of components, energy, capital, and labor, as well as escalating prices (Gölgeci et al., 2023). These resource shortages and hyperinflationary risks present unforeseen challenges with potential global ramifications Ivanov & Dolgui, 2022b). While these shortages often have localized origins, they can trigger widespread disruptions in global supply chain networks, as documented in various studies (Dolgui et al., 2018;

Ivanov et al., 2014; Li et al., 2021; Llaguno et al., 2022; Park et al., 2022). Delayed shortages stem from severe pandemic-related causes and chronic long-term issues such as semiconductor shortages, skilled labor shortages, and geopolitical risks such as protectionism and political unrest (B. H. Meyer et al., 2023). Recent events, such as the Covid-19 pandemic and the war in Ukraine, have exacerbated these challenges and exposed major gaps in supply chain resilience and resource management (Cui et al., 2023). In addition, other notable issues have emerged, including consumers' increasing preference for product customization (Xiao & Khan, 2024), their inclination toward self-empowerment and entrepreneurship (Inglet, 2022), and the wide range of activities aligned with the goals of the 2030 Agenda (Barakat et al., 2023). These challenges pose significant hurdles in terms of industrial management and responsible production (Kumar et al., 2023), overwhelming the capabilities of Industry 4.0 and 5.0 technologies (Narkhede et al., 2024). To address these challenges, there's a growing trend toward reshoring, nearshoring, and offshoring supply chains, especially for resource-intensive operations (Fernández-Miguel et al., 2022). This strategic shift aims to improve product development, quality control, customization, speed to market, delivery performance, and cost leadership (Theyel et al., 2018).

1.3 Gaps and Scopes

In the previous sections, we reviewed the recent literature on enabling technologies for supply chain management in Industry 5.0. It was found that while interest in these technologies is growing, research on their practical applications for managing supply chain disruptions is still in its infancy. Therefore, two main gaps in the literature were identified:

- **Practical applications for managing disruptions:** More research is needed to understand how enabling technologies can be used to effectively and sustainably manage supply chain disruptions.
- **Integration and implementation:** There is a lack of comprehensive understanding of the specific challenges and opportunities associated with integrating and implementing these technologies in business contexts.

To address the identified gaps, this study has three objectives. First, it aims to develop and test a technology-based tool to enhance companies' control over their supply chain flow (Qudrat-Ullah, 2023). Second, it aims to design a product development process model that meets the mass customization needs of the market while empowering SMEs and entrepreneurs to develop their production processes and business models (Lamperti et al., 2023). Finally, it seeks to provide solutions that go beyond the goals of Industry 4.0 and align with the principles of Industry 5.0: sustainability, resilience, and human centricity (Grosse et al., 2023).

Since possible solutions must be accompanied by their enabling technologies, the research questions will be formulated in conjunction with them. This is done under the assumption that a new enabling technology facilitates a new performance improvement process leading to a new superior business model. (Fernández del Hoyo, 2009).

- Based on these previous considerations, this work aims to answer the following research questions:
- **RQ1.** *How can the problem of supply chain disruption be solved in a crisis and what enabling technologies would be needed to do so?*
- **RQ2.** *How can the growing demand for production customization be met efficiently, or is mass customization possible here, and what enabling technologies would be needed for this?*
- **RQ3.** *How to address the maximum number of UN Agenda 2030 goals with a supply management strategy based on enabling technologies that go beyond jobs and growth to sustainable, resilient, and human-centric approach?*

The paper is organized as follows. Section 1 reviews the relevant recent literature with a focus on supply management and manufacturing integration. The research context and methodology are described in detail in Section 2. Section 3 presents the results and findings of the development and application of the enabling technology. Section 4 discusses the implications of the findings, both theoretical and managerial. Finally, Section 5 concludes the paper by highlighting its limitations and suggesting directions for future research.

2.RESEARCH CONTEXT AND METHODOLOGICAL DESIGN

2.1 Research context

This study presents an innovative production process and a novel management business model that encompasses a comprehensive 360-degree integrated workflow, from design to final product manufacturing, all within a single space, with the aim of achieving sustainability and mass customization goals (Roskladka et al., 2023).

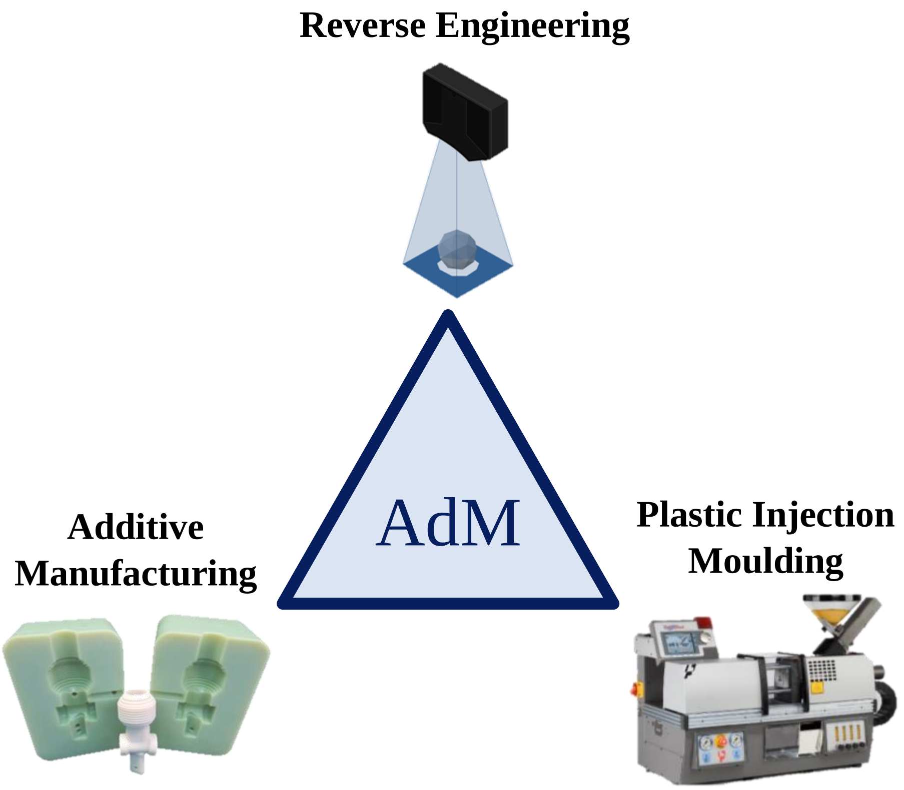

Figure 1: Additive Digital Molding (AdM) methodology diagram (Icons source: Scanner[1], Molds[2], Molding[3]).

The foundation of this approach lies in the strategic use and combination of techniques such as digital reverse engineering and 3D printing, which are fundamental pillars of Industry 4.0 and provide a competitive advantage to integrating companies (Deloitte, 2020). In addition, this research advocates the merging of three technologies: two from the realms of Industry 4.0 and 5.0 (digital reverse engineering and additive manufacturing), and one traditional technique (injection molding). The result

[1] https://www.shutterstock.com/es/image-vector/laser-scanner-3d-icon-trimble-1898415574
[2] https://www.protolabs.com/
[3] http://www.arburg.com/english/products/po_a0001.htm

is a unique blend of technologies called Additive Digital Molding (AdM), which represents the convergence of additive manufacturing, digitalization and injection molding. To the best of our knowledge, no such technological combination has been developed before. While hybrid projects can be found in the existing literature, none have successfully integrated different technological frameworks as proposed here (Kumari et al., 2023).

Figure 1 illustrates this trio of technologies that, through digitization, culminate in an autonomous production process that consolidates all manufacturing activities into a single space. This integrated approach is especially important in times of supply chain disruptions such as pandemics, conflicts, or remote locations.

$$AdM = Additive\ Manufacturing + Digitalization\ (DRE) + Plastic\ Injection\ Molding$$

To validate the AdM concept, a case study was conducted focusing on a PlayStation 4 "trigger".

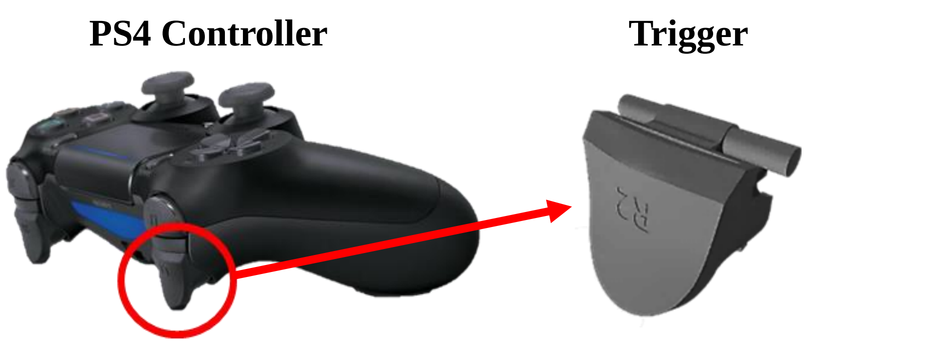

Figure 2: Elements used as a case study (Icons source: PlayStation 4[4], Trigger[5]).

This component was selected for analysis due to its suitability for customization and its short design and manufacturing cycles, making it an ideal candidate for applying the research findings to new processes and business models. Despite its seemingly simple appearance, this chosen product meets all the necessary criteria for this project, from its initial design phase to its final application. Therefore, the trigger serves as the focal point of the project case, as shown in Figure 2, which illustrates its integration into a PlayStation 4 video game controller.

[4] https://www.vsgamers.es/product/gamepad-original-sony-ps4-dualshock-negro-v2

[5] CIM designed by the authors

2.2 Methodological design

This study adopts pragmatism as an epistemological approach (Ullah, 2020) to evaluate the feasibility and effectiveness of Additive Digital Molding (AdM) technology. It is based on the practical application of theoretical knowledge to demonstrate its practical utility in real production. The comparative analysis between the traditional production flow and the proposed production flow with AdM makes it possible to highlight the potential advantages and disadvantages of this innovative technology.

In this section, we outline the methodology of our research, focusing on the integration of different technologies within a coherent framework. A systematic organization is critical to ensure the feasibility of a project that combines different technologies, ensuring compatibility and synergy. Two distinct flows define the structure of the research: the logical sequence of product manufacturing and the research flow, which traces the study of each technology used. For the sake of clarity and completeness, we have chosen to present the research flow, which is considered more academic and explanatory.

Figure 3 illustrates the research workflow, contrasting the logical production process with the research process pursued in this study. The production workflow outlines three key stages: 3D design through reverse engineering, mold printing, and plastic injection part manufacturing. Conversely, the research process delves into the options explored for each technology, facilitating informed decision-making.

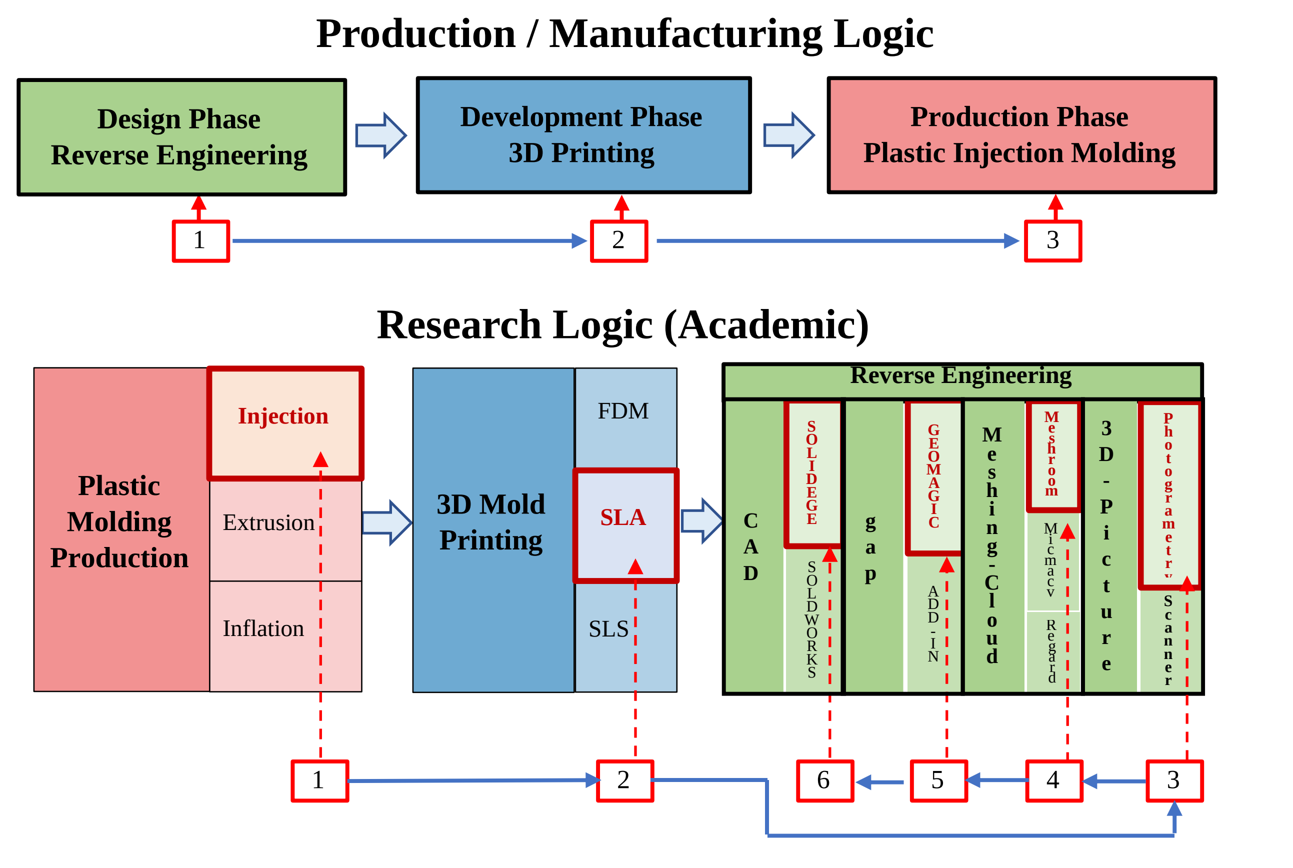

Figure 3: Flowchart of research and technology implementation (Source: author's own elaboration).

Three key techniques are used in Production Logic with Enabling Technology (AdM) as presented at the top of Figure 3:

- Reverse Engineering (Digital) [1]: Utilizes techniques like photogrammetry, laser scanning, or LiDAR-type proximity sensors to digitally extract element geometry, beneficial for complex parametrization or product adaptation.
- 3D Printing / Additive Manufacturing [2]: Employs 3D printing for product development, offering flexibility in shaping complex geometries, albeit with limitations in robustness and quality for large-scale production.
- Plastic Injection Molding [3]: Widely adopted for mass production due to its capability to generate large batches at low cost, although hindered by expensive mold production and limitations in complex geometry manufacturing.

In detail, the three research stages are as follows at the bottom of Figure 3:

1. **Plastic Molding Production [1]:** The first technological decision must be made among the three plastic molding production options: Injection, Extrusion and Inflation being injection molding the most suitable choice for the type of product. This election leads to the next 3D Mold Printing tech.
2. **3D Mold Printing [2]:** Selecting Stereolithography (SLA) among the 3D mold printing options enables the use of high-strength resins, aligning with the final production stage that requires a highly resistant mold.
3. **Reverse Engineering (Digital):** This stage entails four steps of highly software usage**:**
   - First **[3]**, obtaining the 3D form through photogrammetry which was simply performed with a smartphone camera.
   - Then **[4].**, transforming the previous result in a meshing cloud through a well-known free software: Meshroom **.**
   - Later **[5]**, addressing photogrammetry gaps using Geomagic from 3D Systems for result refinement.
   - Finally **[6]**, performing the mold design CAD software, using SolidEdge from Siemens.

Recognizing the strengths and limitations of each technique, we propose their integration to capitalize on strengths and mitigate weaknesses. Specifically, manufacturing plastic injection molds directly on a 3D printer, facilitated by Formlabs technology, promises significant time and cost savings, transforming production timelines from weeks to hours.

3.RESULTS

This section presents the results of the study in three parts. The first part details the steps taken to design the process and manufacture the customized product selected as the case study. The second part explores the additional impacts of applying AdM technology to new entrepreneurial ventures, such as direct manufacturing and home manufacturing. The third part evaluates the contribution of AdM technology to achieving the principles of Industry 5.0, namely sustainability, resilience, and human-centricity, by assessing its alignment with the Sustainable Development Goals (SDGs) of the 2030 Agenda.

3.1 AdM Laboratory Test

Regarding the first part, it has been shown that developing a project based on the AdM process and applying it to the object in question (the trigger) is a complex undertaking. It involves the validation of a process integrated with many others, essentially a "process of processes" that can be divided into six stages. These stages were validated before being subjected to laboratory testing, which was ultimately successful in all stages at the second attempt, after some necessary adjustments. The results and validation of the stages of the AdM new product development methodology are shown in Figure 4 below.

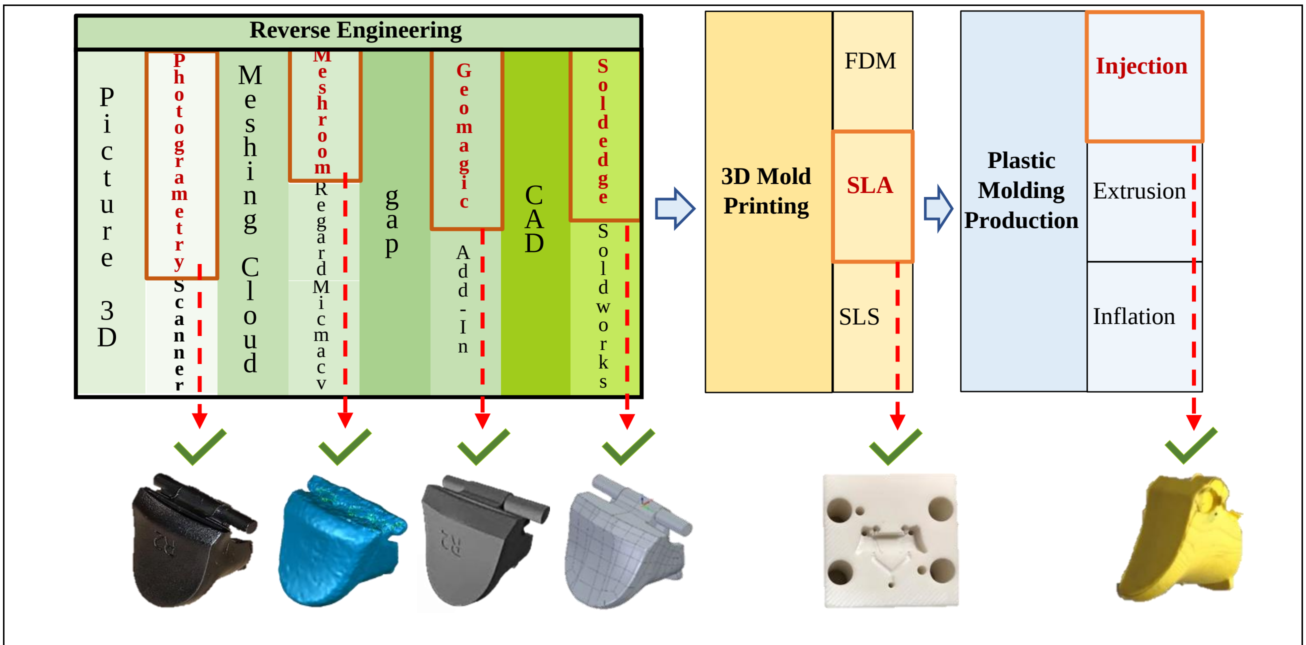

Figure 4: AdM methodology validation overview (Icons source: PlayStation 4[4], Trigger[5]).

The highlight of this process lies in its ability to integrate traditional technology with the advances of the 4th Industrial Revolution, with the aim of increasing efficiency while adhering to the principles of sustainability, resilience and human-centricity that characterize the 5th Industrial Revolution.

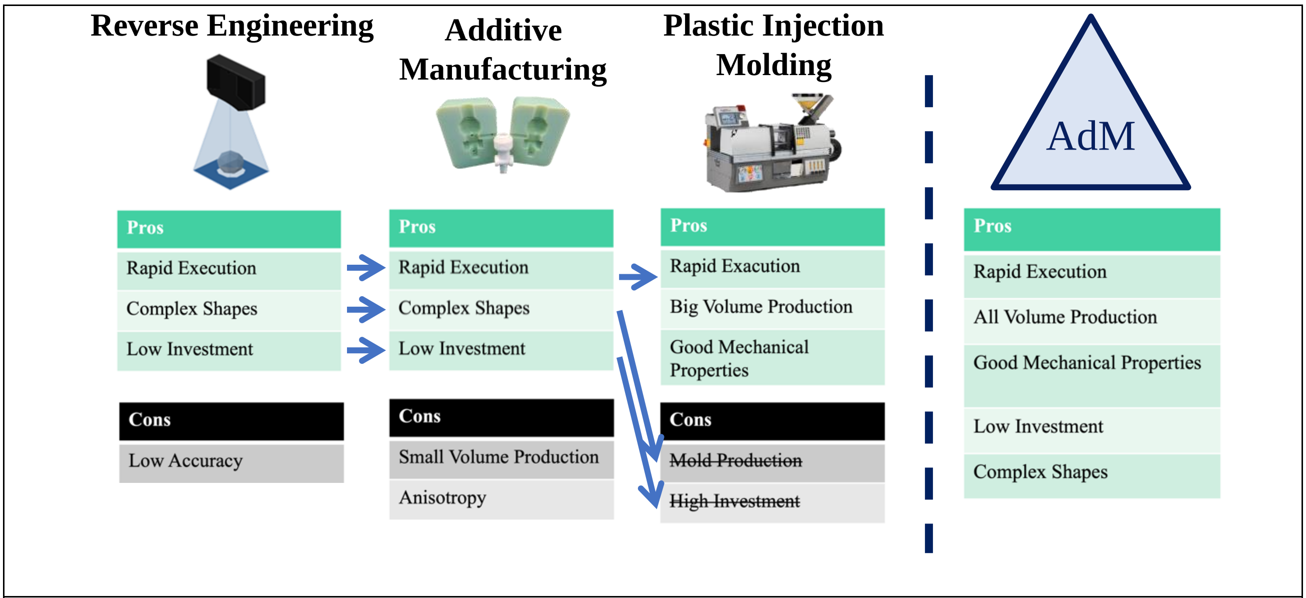

Figure 5: Combination of the three technologies resulting in the AdM (Icons source: Scanner[1], Molds[2], Molding[3]).

Thus, this study aims to increase the production efficiency of injection molding by combining it with the flexibility offered by AM/3D printing techniques. This integration enables the creation of products with complex geometries that are achieved through digital reverse engineering. Figure 5 illustrates the combination of these three technologies, referred to as AdM, and outlines the advantages and disadvantages of each enabling technology individually. Then, it highlights the combined benefits, including rapid execution, suitability for any volume production, favorable mechanical properties, low investment requirements, and the ability to produce complex geometries. It is worth noting that AdM, as an enabling technology, can effectively combine the first two steps of digital reverse engineering (via 3D scanning) and additive manufacturing (via 3D printing) to produce highly customized products that go beyond molds. Examples of such applications include new product prototypes, specialty items, and even standard products tailored for remote locations. Two notable applications of this approach are direct and home manufacturing. In summary, this initial result demonstrates how the use of the AdM technology mix can provide a robust solution to addressing Research Question RQ1: " *How can the problem of supply chain disruption be solved in a crisis and what enabling technologies would be needed to do so?*".

3.2 Operational impact of the AdM methodology as an enabling technology

3.2.1 Direct Manufacturing

Direct manufacturing is a digital production process in which final products are manufactured directly from digital CAD models and 3D printers, bypassing the need for molds or castings (Gibson et al., 2020). This approach has gained traction in sectors such as fashion eyewear (e.g., Protos Eyewear) and jewelry (e.g., Mymo), driven by the emergence of 3D printing platforms and design consulting firms (e.g., Sculpteo) as well as distribution channels (e.g., Shapeways) (Rayna & Striukova, 2016)Click or tap here to enter text.. The transition to direct manufacturing via AdM represents a significant shift that changes the entire production function of a firm, not just specific elements such as prototype or mold design. There are several advantages to this phase:

- **Medium-scale mass customization:** AdM facilitates medium-scale mass customization, particularly beneficial for small and medium-sized enterprises (SMEs).
- **Consumer empowerment:** Consumers are engaged as "prosumers," allowing them to participate in design processes and potentially become entrepreneurs themselves.
- **Externalization of activities:** The adoption of crowdsourcing or forming external networks of collaborators for production opens avenues for entrepreneurial business models.
- **Long-tail economies:** AdM enables the profitable serving of niche markets, known as "long-tail" economies, by selling small quantities of a wide range of.

These advantages position the new technology favorably and, if effectively implemented, could challenge traditional production methods based on economies of scale and learning curves.

3.2.2 Home Manufacturing

Home manufacturing, where consumers use reverse engineering and 3D printing equipment to create objects themselves, presents another potential application. While home manufacturing has existed for nearly a decade, its adoption has been limited. However, with AdM, designing through reverse engineering with simple tools like smartphones is now feasible, and more consumers are purchasing 3D printers, not just hobbyists or engineering students (Wohlers, 2013). Yet, its viability hinges on overcoming challenges such as cost, size, and quality issues associated with regular use of the technology, justifying the investment in a home 3D printer (Rayna & Striukova, 2016).

Home manufacturing encompasses various applications of AdM technology, including rapid prototyping, mold printing, medium-scale customization, co-production, outsourcing, and long-tail economies, potentially leading to significant impacts. These include the elimination of distribution channels and competition between prosumers and businesses (Rayna & Striukova, 2016). Platforms may emerge to organize and connect prosumers, resembling an "Uberization" model with varying degrees of autonomy, as seen in platforms like Hubs.

Overall, home manufacturing could foster new entrepreneurial activities conducted from home with the support of AdM technology. This highlights how AdM, whether fully utilized or in a scaled-down approach, can effectively address the growing demand for production customization and even enable mass customization, addressing Research Question RQ2: "*How can the growing demand for production customization be met efficiently, or is mass customization possible here, and what enabling technologies would be needed for this?*"

3.2.3 AdM alignment with the SGD of the 2030 Agenda

In examining the broader impact of AdM technology on the Sustainable Development Goals (SDGs), the 2030 Agenda serves as a central framework. This agenda directly aligns with the principles of sustainability, resilience, and human-centeredness inherent in Industry 4.0 and, more specifically, Industry 5.0, which AdM embodies. Within this framework, the AdM methodology facilitates the achievement of both business objectives, in line with Industry 4.0, and social and environmental objectives, as emphasized in Industry 5.0. Moreover, AdM contributes to several SDGs simultaneously. Specifically, it directly aligns with SDGs such as: SDG 3 (Health and well-being), SDG 10 (Reduction of inequalities), and SDG 12 (Responsible Consumption and Production). These SDGs, highlighted in Figure 6, illustrate the overarching impact of AdM in addressing diverse societal and environmental challenges.

Figure 6: AdM alignment to the SDG of the 2030 Agenda. Source: (UN & Cf, 2015).

To understand the alignment with the SDGs, it's important to recognize how this project integrates three technologies into a cohesive and self-sustaining manufacturing process. This approach demonstrates sustainability and optimization in design and manufacturing through three primary pathways:

INTEGRATED SUSTAINABLE PROJECT = Reverse Engineering + 3D Printing + Plastic Injection

OPTIMAL DESIGN DEVELOPMENT = Reverse Engineering + 3D Printing

OPTIMAL MANUFACTURING DEVELOPMENT = 3D Printing + Plastic Injection

Digital Reverse Engineering, which designs products from 3D scans or photographs, offers significant benefits such as:

- Autonomy of design: It doesn't require outsourcing, making it accessible to SMEs or individuals. The equipment, such as a smartphone with a camera and affordable or free software, makes it possible to achieve SDG 10 on reducing inequalities and SDG 9 on innovation by design.

3D/AM printing, which focuses on building custom objects "layer by layer," offers benefits such as:

- Efficiency in the use of raw materials: There is no waste in the manufacturing process, which aligns with SDG 12 on responsible production and consumption.
- Resource efficiency: Eliminates the need for additional production tools, reducing resource consumption and supporting SDGs 12, 9, and 11.
- Object flexibility: It enables the production of different objects in a single piece, contributing to SDGs

12, 9, and 11.

Plastic injection molding is a cost-effective manufacturing method that aligns with SDG 13 of climate action due to its production efficiency and low energy consumption.

Analyzing the combined effect of these technologies, we begin with:

Optimal Design Development: contributes to:

- SDG 3 (Health and well-being) by producing customized medical prostheses and tissues.
- SDG 9 (Industry, Innovation, and Infrastructure) by driving innovation through rapid prototyping and tooling.

Optimal Manufacturing Development: helps to

- SDG 12 (Responsible Production and Consumption) by reducing investment costs and improving injection molding efficiency.

Integrated Sustainable Project: the triple combination of technologies offered by the AdM contributes to

- SDG 10 (Reducing inequalities) by reducing production costs.
- SDG 13 (Climate action) through high production efficiency and a low carbon footprint.

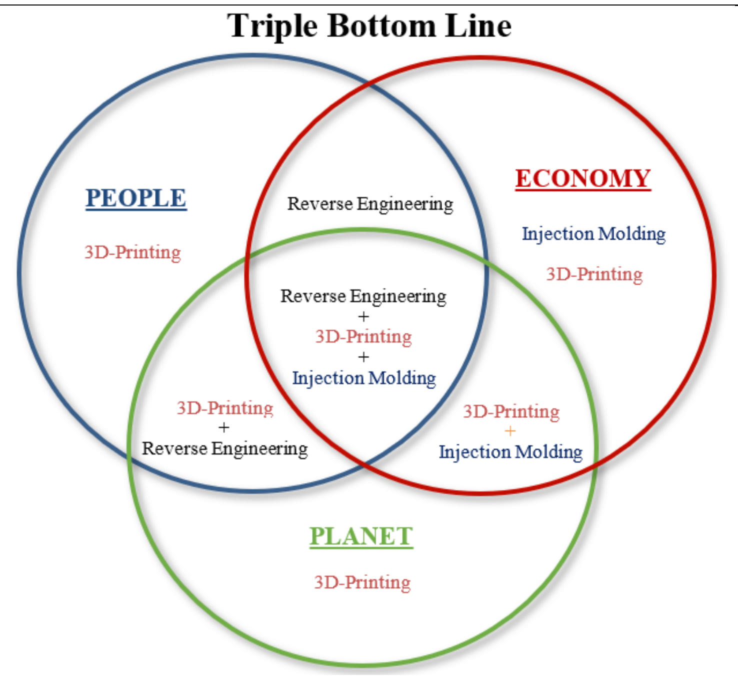

Figure 7: Mapping technology positioning and combinations within a triple bottom line framework.

As a final insight, the AdM approach can contribute to the achievement of six of the 18 Sustainable Development Goals (SDGs) outlined in the UN 2030 Agenda. These include SDGs 3, 9, 10, 11, 12, and 13. This addresses the third research question RQ3 of the study, which states: "*How to address the maximum number of UN Agenda 2030 goals with a supply management strategy based on enabling technologies that go beyond jobs and growth to sustainable, resilient, and human-centric approach?".*

In Figure 7, a summary of the preceding text is presented which illustrates all the AdM contributions to the SDGs on a spatial and graphical way. The figure illustrates the positioning of various technologies and their combinations within a Triple Bottom Line framework, highlighting that sustainability is grounded on three primary pillars: economic, social, and environmental and at the different interceptions among them (Epstein et al., 2018).

4.DISCUSSION

The AdM technology introduces significant theoretical and practical implications. Theoretically, it presents a model of "technology mix" characterized by extreme flexibility to adapt to various environmental and market conditions, potentially constituting a breakthrough innovation. Notably, it not only incorporates the latest technological advancements of Industry 4.0 but also integrates previous technologies synergistically, while exploring the potential of Industry 5.0. Moreover, it is scalable, accommodating combinations of two or three technologies depending on the desired end product (e.g., mold, prototype, final product). Therefore, the AdM's contribution as an enabling technology lies in facilitating optimal processes in manufacturing, resilience, and sustainability, with a focus on human-centricity. Notably, it also emerges as an affordable solution, as evidenced by its development during confinement in a single isolated location with minimal resources.

Practically, AdM has demonstrated successful performance in laboratory settings by executing all required process steps to produce the desired customized part within a remarkably short timeframe, with flexibility to accommodate adjustments. However, its efficacy in real business market scenarios remains unproven. Nonetheless, potential applications in business models such as direct manufacturing and home manufacturing which aim to achieve autonomous and integrated production by minimizing the supply chain, are very likely. Furthermore, successful macro-level applications, such as Protolabs (McClelland, 2022; Protobabs, 2023), operating a technology platform connecting on-demand digital factories with a global network of manufacturers, highlight promising avenues. Despite these successes, it is premature to fully anticipate and evaluate AdM's potential in new business models and scalable processes. Nevertheless, the examples provided suggest promising prospects for its future applications.

5.CONCLUSION

5.1 Main conclusions

An integrated and autonomous process like AdM is proving invaluable not only as an academic exercise, but also in situations requiring rapid prototyping, tooling, and flexible product design. These requirements are closely aligned with the demands of the modern Industry 4.0 landscape, which is characterized by a growing need for unique components, closed innovation, and patent development. In addition, the self-sufficient nature of AdM makes it particularly suitable for scenarios where traditional supply chains are disrupted, such as social emergencies or isolated environments such as space stations (Jiménez et al., 2020). This makes AdM an ideal solution for innovative sectors characterized by high competitiveness and continuous innovation, such as the automotive and electronics industries, as well as for sectors requiring specialized parts, such as aerospace, or requiring high product customization, such as health and medicine. Particularly noteworthy is its ability to provide fully autonomous manufacturing in a single location, often referred to as 360-degree manufacturing. In addition, the implementation of AdM has significant implications for the business landscape, entrepreneurship, society, and the environment. From an economic perspective, AdM can lower barriers to entry in the manufacturing industry by significantly reducing the costs associated with investing in, developing, and producing new products (Haleem & Javaid, 2019)(Shuaib et al., 2021). This, in turn, fosters entrepreneurship by facilitating the emergence of new business initiatives and opening up new markets through models such as direct manufacturing, home manufacturing, and the collaborative economy. In terms of societal and environmental impact, AdM leverages the technological advantages of Industry 4.0 while aligning with the principles of Industry 5.0, emphasizing sustainability, resilience, and human centricity. Its contribution is demonstrated by its alignment with the Sustainable Development Goals (SDGs) of the 2030 Agenda, including reducing inequalities, improving health and well-being, and using resources more efficiently (Berman, 2012).

5.2 Limitations and future research directions

Supply and production management is a dynamic field that continues to challenge both business and academia. Coping with disruptions and striving for effectiveness, efficiency, and optimization are ongoing imperatives that demand attention. A primary constraint arises from the way this field faces unanticipated shocks and chronic shortages of capital, skilled labor, materials, and energy. These constraints affect a wide range of initiatives, including the one under discussion. While AdM addresses capital and energy needs reasonably well, the scarcity of skilled labor to manage new enabling technologies persists and is expected to continue. In addition, human adaptation to innovation remains an ongoing challenge. A further limitation is the lack of validation of AdM in real-world business scenarios beyond the laboratory. While positive results can be expected based on similar initiatives, further market experimentation in different environmental contexts and sectors is essential.

Moving forward, companies, in collaboration with academia, need to explore new ways to anticipate and address these challenges. This includes:

- Using digital twin simulations to optimize supply networks (Burgos & Ivanov, 2021).
- Implementing the metaverse as an extension of digital twin simulations (Ivanov & Dolgui, 2023).
- Extending the application of machine learning to additive manufacturing (Qin et al., 2022).
- Leveraging AI to develop more human-centric processes through innovative human-machine interfaces (Adel, 2022).

Integrate quantum technologies into supply chain operations (Pelucchi et al., 2021).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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