Journal of Cleaner Production 461 (2024) 142271

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Industry 5.0: A new strategy framework for sustainability management and beyond

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ARTICLE INFO

Handling Editor: Jin-Kuk Kim

Keywords:
Manufacturing strategy
Business model
Design and operations of manufacturing systems
Sustainable manufacturing
Resilient manufacturing
Human-centric manufacturing

ABSTRACT

Industry 5.0 (I5.0) can be described as the integration of sustainability, resilience, and human-centricity into industrial value creation. A novel framework for shaping a manufacturing strategy for the future Industry 5.0 paradigm is proposed. The I5.0 strategy framework consists of two main elements: (1) a process model and (2) a system model. The process model is based on the Design and Operations (DesOps) methodology while the system model discusses a fluid physical system as well as a fluid cyber system as relevant components of an I5.0 manufacturing system-of-systems. The research intends to contribute to the academic and industrial discussion towards forming a more practical guideline for managing the emerging I5.0 approaches and related technologies and to enable manufacturing companies to improve and maintain their competitiveness in a future I5.0 environment. Additionally, the authors aim to expand the knowledge foremost in the research field of strategy design and implementation by providing a decision-support framework for facilitating sustainable, resilient, and human-centric value creation.

1. Introduction

Industry 5.0 (I5.0) can be described as the integration of sustainability, resilience, and human-centricity into industrial value creation (Directorate-General for Research and Innovation, 2021). The idea of I5.0 currently gains more and more international attention across policymakers and the academic community while remaining rather disregarded throughout the industry. This might be because many companies and especially small and medium-sized enterprises (SMEs) still struggle to create value based on Industry 4.0 principles and technologies, e.g., as described in (Pfeifer, 2021). However, with the ongoing need to mitigate and adapt to a more uncertain and dynamic globalization due to changing climate and shifts in the geopolitical landscape, sustainability, resilience, and human-centricity of the I5.0 paradigm might likely become more relevant for industrial companies in the next decade.

Against this backdrop, the paper aims to discuss a framework for shaping a manufacturing strategy for the future I5.0 paradigm. An I5.0 manufacturing strategy is coined by defined process steps and phases and is aimed at continuously improving sustainability, resilience, and human-centricity within value creation to realize competitive advantage through the application of a fluid manufacturing system with the Industrial Digital Twin as the key enabling technology.

The proposed I5.0 strategy framework consists of two main elements: (1) a process model and (2) a system model. The process model determines the relevant phases and system elements for designing and operating the I5.0 manufacturing strategy from a process perspective. In addition, the system model focuses on elaborating the key artifacts of the manufacturing system, from a system perspective, by describing relevant domains and sub-systems for designing and operating an I5.0 manufacturing strategy.

The research intends to contribute to the academic and industrial discussion towards forming a more practical guideline for managing the emerging I5.0 approaches and related technologies and to enable manufacturing companies to improve and maintain their competitiveness in a future I5.0 environment, since manufacturing strategies are

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https://doi.org/10.1016/j.jclepro.2024.142271
Received 27 September 2023; Received in revised form 28 March 2024; Accepted 15 April 2024
Available online 16 April 2024

responsible for shaping the company's business model. From an academic perspective, the research intends to expand the knowledge foremost in the field of strategy design and implementation by providing a novel decision-support framework for facilitating sustainable, resilient, and human-centric value creation.

The paper is subsequently composed of the following sections: Section 2 describes the state-of-the-art for I5.0 and manufacturing strategy as well as the derived research gap for the I5.0 strategy framework. Section 3 outlines the research approach including the research question and research methodology. Section 4 introduces the I5.0 strategy framework including its process and system model. Section 5 verifies the proposed I5.0 strategy framework in the context of its contribution to the I5.0 main pillars, discusses the research results including their limitations, and highlights a plan for future validation and evaluation of the conceptual framework. Eventually, section 6 provides a summary of the research.

2. State-of-the-art

2.1. Industry 4.0

Industry 4.0 (I4.0) was introduced as the fourth industrial revolution, a strategic initiative of the German government (Kagermann et al., 2012). Currently, more than 40 analogous programs exist in modern economies, e.g., US 'Advanced Manufacturing Partnership', Chinese 'Made in China', British 'Smart Factory', Japanese 'Super Smart Society', and others (Kumar and Kumar, 2020; Vidosav et al., 2022). In terms of capabilities of current technologies, it is revolutionizing possibilities and the way that industrial companies are operating, e.g., through the application of advanced manufacturing technologies. In terms of manufacturing paradigms, it evolves from well-known advancements in computer integrated manufacturing (CIM) and flexible manufacturing systems (FMS) (Scheer, 1994). The mass digitization observed in recent years is yet another current driver (Lindgren et al., 2019; Melville and Robert, 2020; European Commission, 2020). I4.0 is a network approach that complements CIM through ICT (Kolberg and Zühlke, 2015). Current developments in technology allow much more economically effective implementations of the CIM and FMS ideas.

With the adoption of the Agenda 2030 and the emergence of the Sustainable Development Goals in 2015 (United Nations), the academic and industrial community in Industry 4.0 started to shift their focus on sustainability and cleaner production. Specifically, new opportunities for sustainable manufacturing by utilizing I4.0 concepts and technologies were investigated, e.g., as discussed by (Stock and Seliger, 2016; Stock et al., 2018; Beltrami et al., 2021; Ghobakhloo, 2020). More specifically, some of the relevant research areas within sustainability and cleaner production in the context of Industry 4.0 can be clustered into:

- Research related to circularity and a circular economy including remanufacturing, e.g., as discussed by (Dantas et al., 2021; Rajput and Singh, 2020; Lopes de Sousa Jabbour et al., 2018; Kerin and Pham, 2019).
- Research addressing sustainable supply chain management, for example, as addressed by (Birkel and Müller, 2021; Sharma et al., 2021), including humanitarian supply chain management (Kumar and Singh, 2022) and decarbonization of supply chains (Sindhwani et al., 2023).
- Research linked to business ethics as demonstrated by (Shayganmehr et al., 2021; Luthra et al., 2021).
- Research focusing on sustainable business model innovations, e.g., as discussed by (Khan et al., 2021; Geissdoerfer et al., 2018; Yang et al., 2017).
- Research emphasizing on sustainable process design and operations, e.g., as presented by (van Erp et al., 2023; Liu and De Giovanni, 2019).
- Research coining suitability assessment and performance indicators, e.g., as described by (de Sousa Jabbour et al., 2018; García-Muiñ et al., 2021)

2.2. Industry 5.0

I4.0, as previous industrial revolutions, is technology driven. Implementing I4.0 typically results in a cost-intensive innovation program for companies with the difficult estimation of the actual economic effectiveness. Researchers noticed synergies and contradictions of I4.0 technologies, operational performances, and environmental issues (Fiorello et al., 2023). Another perspective on the 'new industrial revolution', complementary to the I4.0 paradigm, is I5.0 as a policy idea launched by the European Commission, on the completion of a decade from the emergence of Industry 4.0 (Xu et al., 2021). Through virtual workshops with representatives of research and technology organizations across Europe, it was possible to develop a first conceptual understanding of I5.0: I5.0 recognizes the strength that industry has to achieve social objectives that go beyond job creation and growth, make production respect the limits of our planet and place the well-being of the involved humans at the centre of the production process (European Commission et al., 2020; Fernandes et al., 2023). Corporate Social Responsibility (CSR), which is the dynamic social responsibility that businesses, small, medium, and large, have at an economic, educational, environmental, and human level, has been a topic of discussion in the world of business and finance since the 1980s. Despite the topic's ever-growing relevance, there is still a lack of practical and normative work, resulting in limited implementation (Zhang et al., 2021). I5.0 is revolutionary in the sense of direct inclusion into the I4.0 paradigm of the non-technological and indirectly, or unrelated, supply chain and business model issues of sustainability, human-centricity, and resilience. This is important as relatively early phases of the I4.0 technologies' lifecycle apart from potential economic, environmental, and social benefits, e.g., through waste reduction or working conditions improvement (Ejsmont et al., 2020), imply serious questions and concerns regarding the related social threats, economic effectiveness, or environmental issues, e.g., through generating electro-waste, higher energy consumption, new safety issues of human-robot interaction, technophobia, and unemployment and privacy threats among others (Ejsmont et al., 2020). Although it is believed that the concept of I5.0 complements the approach presented by I4.0 (Laskowska and Laskowski, 2022), some authors claim that I4.0 and I5.0 are coexisting, and their delimitations need to be better clarified and discussed (Ghobakhloo et al., 2022). However, a study carried out by (Daniel et al., 2019) concludes that companies do not yet recognize the I5.0 paradigm due to their lack of maturity and capacity already achieved within the I4.0 paradigm. Thus, there is mostly a prevailing academically driven discussion about shaping I5.0.

It is argued that I5.0 was initially introduced as the human-oriented continuation of I4.0. From a business point of view, organizations are in the process of implementing the principles of I4.0 (Longo et al., 2020). For I5.0 to come to fruition, the focus must shift from utilizing "individual technologies" to a systematic approach, so that one rethinks how to: (a) combine the strengths of humans and machines; (b) create Industrial Digital Twins of entire systems; and, (c) widely use changeable systems, with special emphasis on generating actionable items, such as data for humans (Rožanec et al., 2022). I5.0 requires an approach focused on the interaction between people and digital technologies, at different levels of organizations in various types of processes that transmit, form, implement, host, and support the manufacturing strategy (Morton et al., 2022). Further, policymakers, at least on a European level, are strongly supporting the I5.0 paradigm with its emphasis on sustainable, resilient, and human-centric value creation. For example, the current European 95 billion Euro research program has considerable I5.0 research programs defined (European Commission, 2022). The consideration of the I5.0 paradigm by policymakers pressures industrial companies to investigate the potential impact of such an I5.0 paradigm to maintain and improve their competitiveness in a future regulatory landscape created by these policymakers. As the European manufacturing ecosystem with its rules and regulations often serves as a role model for global value creation, an I5.0 paradigm supported by European manufacturing companies might generate impacts on global value networks.

2.3. Manufacturing strategy in Industry 5.0

2.3.1. Shaping a manufacturing strategy in industry 4.0

A manufacturing strategy aims at configuring all manufacturing-related decisions to realize a competitive advantage in the marketplace (Dohale et al., 2022). For this purpose, the strategy specifies which manufacturing resources, performance, and capabilities need to be established and maintained (Dombrowski et al., 2016; Hilmola et al., 2015). Traditionally, different categories of decisions are considered within the manufacturing strategy definition such as capacity decisions, process decisions, facility decisions, make or buy decisions, and infrastructure decisions (Dohale et al., 2022; Dombrowski et al., 2016). Manufacturing strategies are currently shaped around the concept of I4.0 (Dohale et al., 2022), which impacts all the listed decisive areas and require a reference model for development and implementation. A relevant reference model is, for example, described by (Dombrowski et al., 2016) following a six-step development process: 1. External and internal analysis, 2. Analysis of the competitive position, 3. Coordination with other functional strategies and the corporate strategy, 4. Determination of the strategic manufacturing objectives, 5. Definition of the manufacturing strategy, 6. Implementation and review. Another example of developing a manufacturing strategy is presented by (Taisch et al., 2015), covering a systems-based model for sustainable manufacturing strategy formation. This approach is shaped by a so-called reference model with recursive system layers which is based on system theory principles and a Viable System Model and intends to support the decision-making towards implementing company-specific sustainable manufacturing improvement programs (Taisch et al., 2015). Van Erp and Rytter (van Erp and Rytter, 2023) propose another reference model for shaping a manufacturing strategy by introducing a DesOps process model for improving the digital and sustainable maturity of a manufacturing system.

2.3.2. Value creation in Industry 5.0

I5.0 gives wide attention and consideration to the main pillars: sustainability, resilience, and human-centricity (Directorate-General for Research and Innovation; Ruppert et al., 2022.). Considering **sustainability**, M. Ghobakhloo et al. (Ghobakhloo et al., 2022) determine which part of the strategic road map of I5.0 is expressed within 16 specific sustainability functions. In short, the I5.0 model's environmental sustainability goals are primarily supported by value network integration, sustainable thinking, smart automation, renewable integration, and smart products that are circular, operational, and resource-efficient. Regarding **resilience**, this can be perceived through the viability of the I5.0 supply chain and business model, as it is seen as a comprehensive adaptation perspective that expands the notion of "back to normal" of the supply chain and business model of a purely closed system with recovery capabilities. In this way, a supply chain can be considered viable if it can maintain the balance of the manufacturing ecosystem in different levels of exposure to uncertainty and changes (Ivanov, 2023). Examples of patterns for resilient business models are presented by (Neumann et al., 2021). **Human-centricity** is often discussed in connection with enabling the human operator. The Operator 4.0 and Operator 5.0 concepts developed by (Romero et al., 2020; Romero et al., 2016; Romero and Stahre, 2021) essentially reflect the human-centric aspect and discuss relevant characteristics and technologies of the human operator in this context. To bring human workers back to the operational level, I5.0 will combine humans and machines to further utilise human intellectual capacity and creativity to increase process efficiency by merging workflows and smart systems. While the main purpose of I4.0 is digitalisation and automation, I5.0 will result in a synergy between humans and autonomous machines (Nahavandi, 2019). In this context, some robot companies are highlighting collaborative robots, or so-called cobots, as one of the key technologies for fostering human-centricity in I5.0 (Universal Robots) by realizing a true work collaboration between machines and humans. However, practically implemented collaboration use cases between humans and robots with a feasible business case can hardly be observed in industrial applications yet. Another potential enabler of human-centricity discussed in academia is education (Gürdür Broo et al., 2022), engineering education must be transdisciplinary, more practical, have data fluency, emphasize management, and provide human-machine interaction experiences.

Maddikunta et al. argue that key enabling technologies for I5.0 are digital and automation technologies such as edge computing, digital twins, or cobots and potential applications for intelligent healthcare, supply chain management, cloud manufacturing, manufacturing/production, smart education, and disaster management (Maddikunta et al., 2022). Leng et al. present a tri-dimension system architecture of I5.0 including a technology, application, and reality dimension (Leng et al., 2022). However, these concepts seem to miss some clear delimitations to I4.0, since often enabling technologies, applications and implementation overlap with the I4.0 paradigm and its modern interpretation for example promoted by (Kagermann and Wahlster, 2022).

Consequently, the authors define value creation in I5.0 as value creation that is equally centred around sustainability, resilience, and human-centricity as the three leading pillars while utilizing advanced digital and automation systems across the value chain. The concrete implementation of these advanced digital and automation systems depends on the specific application area such as manufacturing, healthcare, energy, shipping, or education.

2.3.3. Towards a definition of manufacturing strategy in Industry 5.0

In the context of I5.0, a manufacturing strategy can be developed by utilizing a process model that includes the relevant process phases to design and operate a sustainable, resilient, and human-centric strategy while utilizing advanced digital and automation systems relevant to manufacturing.

Matrix manufacturing systems with spatially arranged process modules similar to a matrix are described as advanced digital and automated manufacturing systems which are offering high flexibility and productivity of value creation (Schmidtke et al., 2021; KUKA). In this context, fluid manufacturing systems are discussed as the most mature form of a matrix manufacturing system and incorporate mobile process modules for dynamically creating temporary layouts and arrangements of the manufacturing equipment (Fries et al., 2021; Hellmich et al., 2022). The key enabling technology for fluid manufacturing is the Industrial Digital Twin (IDT) , since it allows for dynamically connecting the data streams of the manufacturing assets (Van Erp et al., 2022; van Erp et al., 2023b). The IDT technology with its standardized sub-models and relevant industrial use cases is developed and maintained by the Industrial Digital Twin Association (Industrial Digital Twin Associationa; Industrial Digital Twin Associationb).

Consequently, the authors define a manufacturing strategy in Industry 5.0 *as a manufacturing strategy with defined process steps and phases, aimed at continuously improving sustainability, resilience, and human-centricity within value creation to realize competitive advantage through the application of a fluid manufacturing system with the IDT as the key enabling technology.*

2.4. Research gap and contribution

Current academic and industrial literature does not address the aspect of how I5.0 can be utilized and implemented from a

Table 1
Summary of research gap and study justification.

I4.0 manufacturing strategy …	• … aims at continuously improving the business competitiveness while considering sustainability aspects. • … can be characterised by a reference model including a defined (1) process model, i.e., concrete steps and activities for designing and implementing the strategy, and (2) system model, i.e., relevant manufacturing artifacts from a strategy perspective. • … utilises I4.0 artifacts including advanced manufacturing systems such as matrix manufacturing.
I5.0 manufacturing strategy …	• … aims at continuously improving business competitiveness while equally considering resilience, sustainability, and human-centric aspects. • … can be characterised by a reference model including a defined (1) process model, i.e., concrete steps and activities for designing and implementing the strategy, and (2) system model, i.e., relevant manufacturing artifacts from a strategy perspective. • … utilises I5.0 artifacts including fluid manufacturing systems enabled by the IDT technology.
I5.0 manufacturing strategy will potentially support companies in the future to …	• … enhance the adoption of cutting-edge I5.0 artifacts such as fluid manufacturing, the IDT, and the Operator 5.0 which in turn allows the realization of new business model innovations. • … improve the resilience of the manufacturing system towards internal and external shocks. • … anticipate and reduce risks from current and upcoming sustainability regulations, e.g., by improving digital transparency across value chains. • … improve human-centricity and thus better working conditions and well-being of employees by enabling competency building, empowering human craftsmanship, and facilitating human-machine collaboration. • … improve resource productivity and reduce the environmental footprint by optimising digital and physical assets.

manufacturing strategy perspective. Akundi et al. (Akundi et al., 2022) analysed a set of databases for an array of terms within the I5.0 spectrum, noticing a high frequency of mentions of enabling technologies, whilst terms relating to manufacturing strategies were mentioned less often. This data is further supported by the work of Espina-Romero et al. (Espina-Romero et al., 2023), where studying the Scopus database showed a much higher occurrence level of technology-related terms, such as "big data" and the "internet of things, in comparison to terms relating to manufacturing processes and systems, concluding that the electronics sector is, as of 2022, the most influential in I5.0 research. Furthermore, a trend in research is presented, suggesting both the manufacturing and public services sectors of I5.0 have only started to generate some momentum as of 2022. Even though electronics are a cornerstone of I5.0, the design and implementation of smart manufacturing technologies must be complemented by modernized manufacturing strategies that allow companies to unlock the full value of such resources. This literature gap might lead to barriers for manufacturing companies to efficaciously consider the I5.0 paradigm from a strategic perspective. In other words, shaping an adequate I5.0 manufacturing strategy is a relevant task for realizing a company's long-term competitiveness, but hardly any guidelines or recommendations for tackling this particular task are available in academic literature.

This paper aims to bridge this gap. The authors intend to present a conceptual framework for designing and operating a manufacturing strategy in the context of I5.0, i.e., addressing the resilience, sustainability, and human-centric pillars equally while maintaining and improving the competitiveness of the industrial company. The presented framework intends to be a first contribution to the academic and industrial discussion towards forming a more practical guideline for managing the emerging I5.0 approaches and related technologies, and thus to eventually enable manufacturing companies to improve and maintain their competitiveness in a future I5.0 environment. Additionally, from an academic perspective, the authors want to expand the knowledge foremost in the research field of strategy design and implementation by providing a decision-support framework for facilitating sustainable, resilient, and human-centric value creation. For this purpose, the framework comprises a process model, covering the relevant process phases for designing and implementing the I5.0 strategy, and a description of the relevant sub-systems and domains which are strategically relevant for creating an I5.0 manufacturing system.

Table 1 provides a summary of the intended research gap and justification of the study by highlighting the knowledge gained related to transitioning from an I4.0 to an I5.0 manufacturing strategy as well as the potential future perception of an I5.0 manufacturing strategy from an industrial perspective.

3. Research approach

The main research question is: *How can industrial companies design and operate an I5.0 manufacturing strategy for maintaining and improving their long-term competitiveness?*

Two sub-research questions are derived to support the answering of this main research question:

1) What is a suitable process model with relevant process phases that an industrial company can utilise to design and operate an I5.0 manufacturing strategy?
2) Which are important system components of I5.0 manufacturing systems that a company can consider to design and operate an I5.0 manufacturing strategy?

The research methodology applied for pursuing and answering the research questions is essentially based on expert research. For this purpose, the authors derived best practice approaches from the state-of-the-art for the process model as well as for the system model of an I5.0 manufacturing strategy. These approaches were used to create an initial draft of the I5.0 manufacturing strategy framework which was then further refined within an iterative process of joint discussions among all experts, i.e., the authors, to improve the framework until a consensus was eventually reached.

For the process model, by analogy, the agile development procedures known from the IT and software domain is a best practice approach when it comes to the integration of design and operation practices. These procedures have a well-proven effectiveness when relatively frequently new software editions are released, and therefore, development and operations teams have to interact daily. Grounding on expert knowledge and deduction, it is argued that within the I5.0 paradigm, there is a strong need for frequent iterations and revisions of a manufacturing strategy due to uncertain design and operation environments. Therefore, design and operations teams in a manufacturing enterprise must cooperate daily, thus, creating an analogy to design and operations teams in the IT and software industries. Considering these similarities, the DesOps/DevOps methodology, e.g., as described by (van Erp and Rytter, 2023; van Erp et al., 2021; Dash, 2018) is assumed to be the benchmark and good practice which can be transferred and adjusted to the requirements of a future I5.0 manufacturing domain.

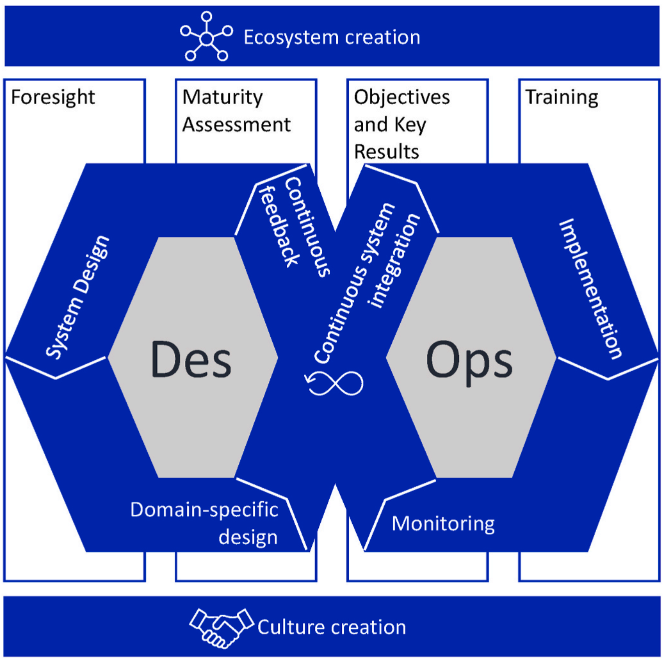

Fig. 1. DesOps process model (following the ideas presented by (van Erp and Rytter, 2023; van Erp et al., 2021; Dash, 2018)).

For the system model, the authors focused on deriving concepts for highly advanced digital and automation systems in the context of manufacturing. Thus, fluid manufacturing as described by (Fries et al., 2021; Hellmich et al., 2022) and the IDT, flowing the technology from (Industrial Digital Twin Associationa; Industrial Digital Twin Associationb), are considered state-of-the-art artifacts for composing a manufacturing system in I5.0.

4. Framework

4.1. Process model

The process model for developing a strategy follows the idea of the Design (Des) Operations (Ops) approach (Fig. 1) presented by (van Erp and Rytter, 2023; van Erp et al., 2021) which itself is inspired by the philosophy of DevOps and DesOps in the field of software development as highlighted by (Dash, 2018). The DesOps process is based on a process with six circular DesOps process steps, arranged according to an infinity symbol, and supplemented by four supporting processes. This arrangement intends to highlight the continuous and never-ending nature of strategy development. The **DesOps** process model is framed by two additional components: culture creation and ecosystem creation.

Consequently, for the I5.0 manufacturing strategy process model, the DesOps model from (van Erp and Rytter, 2023) based on (van Erp et al., 2021) has been expanded and rearranged by introducing the new components "culture creation" and "ecosystem creation", by following the argumentation of (Dash, 2018), as well as the new component "foresight" to be consistent with the spirit of designing and operating an I5.0 manufacturing strategy with resilience, sustainability, and human-centric as leading principles.

DesOps in I5.0 allows for an agile development philosophy enabling a quick and flexible adaptation of the strategy while its circular design enables the integration of the lifecycle of a strategy. These characteristics specifically facilitate the development of a resilient manufacturing strategy, since manufacturing companies can quickly adapt their strategy to unforeseen events, and internal or external shocks in a geopolitical environment with growing uncertainty.

According to (Cillo et al., 2022), companies need to prioritize sustainability in the organizational **culture**, to effectively ensure that sustainability goals are central to the business strategy. Many studies carried out confirm that an organizational culture that is oriented towards sustainability becomes a prerequisite for the complete adoption of sustainability principles at the corporate level (Islam et al., 2019). Not only that, but an organization's cultural commitment to sustainability is also a relevant prerequisite for improving economic performance and long-term growth (Linnenluecke and Griffiths, 2010).

The emergence of a dynamic and digital economy, together with the technological changes relevant to I5.0 that also constitute its **ecosystem,** requires new studies and best practices regarding human resource management models, as well as the adaptation of business strategies (Cillo et al., 2022). In agreement with (Theofilou et al., 2020), companies that include a human-centred approach can develop resilience and agility in social and economic contexts considered turbulent and unstable. A human-centred approach can enable companies to identify motivation and people management attitudes to drive organizational performance. This human-centred and sustainable innovation typical of I5.0 is an urgent and sensitive topic. Numerous studies emphasize that the modern challenges of customization, personalisation and technological updating can only be overcome by human involvement (Kumar et al., 2021).

4.1.1. Main process components

4.1.1.1. DesOps. The DesOps phases are key building blocks for structuring the manufacturing strategy design process. The initial idea and scientific foundation for the DesOps approach are explained in (van Erp and Rytter, 2023; van Erp et al., 2021; Dash, 2018). The manufacturing strategy itself is determined by concrete design solutions for realizing the transition from an initial maturity level of a manufacturing system to a future, intended maturity level. The six main process phases are characterised by a circular model of process phases that cover the whole lifecycle of a strategy. The six main process phases are initiated by the *system design* process for conceptualizing the overall strategy as explained by (van Erp and Rytter, 2023; van Erp et al., 2021). The *domain-specific design* aims to detail the relevant strategy domains, i.e., value creation, value delivery, and value network, and their sub-systems of the conceptualized manufacturing strategy. *Continuous system integration* ensures functionality and interoperability across these different strategy domains. *Implementation* transfers the developed domains into an operational state. For example, the different elements of the manufacturing system, e.g., a matrix manufacturing system with its equipment, organization, humans, product, and processes as well as connected supply chain and business models are implemented. The operational system is *monitored* according to defined key performance indicators. Learnings from the system operation and monitoring and further improvement ideas are *continuously fed back* into the system design phase. This enables a data-driven continuous improvement of the manufacturing strategy.

4.1.1.2. Culture creation. Creating a manufacturing culture is supplementing the DesOps process model. Culture is determined by the values that the manufacturing strategy is essentially based on, which are influenced by its stakeholders and their patterns of interaction. These values are operationalised through concrete principles and practices for the way how people interact and work together throughout the manufacturing system (Dash, 2018). In I5.0, sustainability, resilience, and human-centricity are placed at the centre of value creation. Hence, the culture should reflect these priorities through specific principles and practices. For example, van Erp et al. (van Erp et al., 2023c) propose integrated values based on secure, smart, shared, synergetic, and satisfying innovation pathways with dedicated principles as central ideas for sustainable value creation. Resiliency and human-centricity can be supported, to the same degree, through principles and practices that

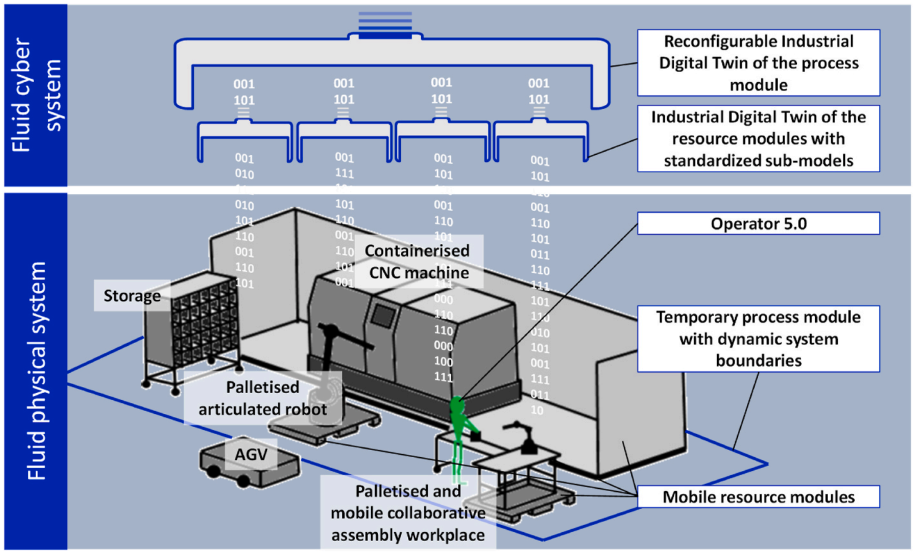

Fig. 2. System components for a fluid manufacturing system in I5.0.

support a safe and healthy work environment across the manufacturing system while also putting the well-being and empowerment of stakeholders such as employees in the centre of attention (Neumann et al., 2021). A leadership aligned with the overall manufacturing strategy and its culture further facilitates a resilient and human-centric organization.

4.1.1.3. Ecosystem creation. The manufacturing ecosystem is created by interacting or independent groups of entities, i.e., stakeholders, practices, procedures, principles, methods, tools, and technologies which form an integrated whole for coining the manufacturing strategy (Dash, 2018). In general, these entities must facilitate the design and operation of the other framework components. In other words, the entities must supplement the values and principles outlining the manufacturing culture, the implementation of the foresight process and maturity assessment, the pursuit of the OKRs, the training of relevant stakeholders, as well as the implementation of the DesOps phases. Usually, the entities are oriented on state-of-the-art in industrial practices such as reflected in industrial standards and guidelines, e.g., ISO standards, or hardware and software solutions, e.g., cobots or Generative AI tools.

4.1.2. Supporting process components

4.1.2.1. Foresight. Foresight incorporates the process of developing multiple possible future scenarios which serve as the foundation for creating a robust manufacturing strategy by developing an understanding of how the environment of the manufacturing systems with its internal and external factors is going to evolve within the next years (Gausemeier et al., 1998). It can help to project different future development pathways for the value creation, value delivery, and value network of the organization as well as potential regulatory and geopolitical frame conditions (Gausemeier et al., 1998). For example, it could be useful to make projections of what digital technologies the suppliers might use in the next 10 years. Based on this understanding, robust manufacturing strategies can be created that can help to cope with the identified set of potential future scenarios. For this reason, foresight activities essentially support the resilience of the organization, as also highlighted in (Neumann et al., 2021).

4.1.2.2. Maturity assessment. Maturity assessment aims to continuously track the I5.0 maturity level of the manufacturing system. For this purpose, the assessment includes the key pillars: sustainability, resilience, and human-centricity. Since digitalisation and automation are relevant enablers for these three I5.0 key pillars, they must also be considered as part of the maturity assessment. Usually, the maturity assessment within each of the different pillars is structured according to different levels ranging from a lower maturity to a higher maturity state. Typical maturity levels, for example, for assessing the state of automation of a manufacturing system range from level 0 ″No Autonomy" to level 5 ″System Autonomy" (Plattform Industrie 4.0, 2019). Creating an understanding of the I5.0 maturity helps an organization to set the right OKRs for further improving the initial maturity state of the manufacturing system. Additionally, the continuous aspect of assessing the I5.0 maturity allows for tracking the success of the manufacturing strategy via tailored metrics.

4.1.2.3. Objectives and Key Results. Objectives and Key Results (OKRs) define the project management framework for developing a robust manufacturing strategy to maintain and improve the long-term competitiveness of the organization while improving the I5.0 maturity of the manufacturing system. The OKRs must reflect the different future scenarios from foresight as well as the current state of the maturity assessment. Foresight creates a strategic vision and sets the strategic business model focus areas for the OKRs to maintain and improve competitiveness. The maturity assessment together with the strategic vision and business model focus area create the foundation for kicking off the initial OKR cycle to support the transformation of the manufacturing systems towards I5.0 higher maturity levels. In general, the OKR cycles follow the OKR framework, e.g., as presented in (Doerr, 2018; Wodtke, 2016). The OKR management framework follows an agile project management approach and thus can be specifically suitable to flexibly adapt the manufacturing strategy in more uncertain industry environments, for example, to cope with unforeseen geopolitical conflicts. OKRs thus also function to improve the overall resilience of the organization.

4.1.2.4. Training. Training translates the manufacturing strategy into concrete knowledge, skill, and competency development for the involved stakeholders. A suitable training concept incorporated into the DesOps cycle is explained in (van Erp and Rytter, 2023; van Erp et al., 2021). Realizing higher manufacturing maturity levels or adopting new or changing business models often requires the application of new principles, practices, procedures, methods, tools, and/or technologies throughout the manufacturing system. For example, the application of new Generative AI tools for supporting the assembly process requires new knowledge, skill, and competency to operate the AI tools as well as to interpret their output. Consequently, the stakeholders such as manufacturing operators must be continuously trained to efficaciously implement the new I5.0 manufacturing strategy. The planning of the training course can include the following key activities: definition of the training curriculum, identification and selection of relevant stakeholders, e.g., educators and learners, creation of educational content, definition of roles and expectations on educators and learners, development of a concept for quality assurance and the communication between the stakeholders, implementation of the educational contents including a suitable project management for the training (Stock et al., 2017).

4.2. System model

The purpose of the process model is to describe the relevant process phases for designing and improving the manufacturing strategy according to future business and manufacturing needs and requirements. Additionally, the system model describes the relevant system components, i.e., sub-systems and domains, of the I5.0 manufacturing system. A future-oriented manufacturing system in the sense of an I5.0 allows the implementation of a fluid manufacturing system with a focus on the mobility of manufacturing equipment as elaborated in section 2.3.3. The implementation of such a fluid manufacturing system requires a fluid physical system as well as a fluid cyber system. Fig. 2 illustrates the relevant system components for a fluid manufacturing system in I5.0.

A **fluid physical system** should support the realization of temporarily changing process modules with integrated mobile resource modules in the sense of a fluid manufacturing system (Fries et al., 2021). This allows for dynamically arranging the manufacturing assets such as machine tools or assembly workplaces in new layouts according to changing manufacturing requirements and tasks, e.g., changing parts, materials, or production volume.

The **fluid cyber system** allows an integration of the manufacturing assets with the different IT layers such as cloud and edge infrastructure, Industrial Internet of Things (IIoT) platforms and software or data ecosystems for a future data economy (Van Erp et al., 2022). The core technology for realizing this integration across the different IT layers is the IDT. The IDT technology is determined as the standardized Industrial Digital Twin for manufacturing systems, enabling the interoperability via standardized IDT sub-models (Industrial Digital Twin Associationa; Industrial Digital Twin Associationc) for structuring data of manufacturing assets, and exchanging data between these assets and different IT service layers. Considering the resilience pillar in I5.0, the IT infrastructure must be capable of mitigating the negative impacts of possible interruptions such as network failures very quickly. To this end, a resilient manufacturing strategy based on IIoT networks represents a fundamental aspect in facilitating the production and recovery of the supply chain, when destabilized.

4.2.1. Fluid cyber system

4.2.1.1. Reconfigurable Industrial Digital Twin (IDT) of the process module. A fluid physical system with dynamically arranged manufacturing assets must be linked to a suitable cyberinfrastructure. Process modules in fluid production are only temporarily created for one or more specific production tasks for a defined period (Hellmich et al., 2022.). The IDT of the process module is therefore also only created temporarily essentially based on the respective IDTs of the resource modules as well as process-module-specific sub-models, e.g., by following the sub-model standard from the Industrial Digital Twin Association (IDTA) (Industrial Digital Twin Associationc). For example, the IDT of a temporary process module, which offers manufacturing skills through two resource modules, an articulated robot, and a CNC drilling machine, might be composed of the two IDTs of the robot and CNC drilling machine as well as process-module-specific IDT sub-models such as functional safety and carbon footprint (Industrial Digital Twin Associationc). After the resource modules are rearranged into new process modules due to new production tasks, also the IDT of the process modules is reconfigured according to the new arrangement of manufacturing assets.

4.2.1.2. Industrial Digital Twin (IDT) of the resource modules with standardized sub-models. The temporary process modules IDT is composed of IDTs of its resource modules with standardized sub-models. Standardized sub-models facilitate data interoperability between the value network actors as well as easy horizontal and vertical integration in manufacturing systems (Plattform, 2019; Industrial Digital Twin Associationd). The sub-model standard of the IDTA is defined based on consensus among a wide variety of industrial companies (Industrial Digital Twin Associationc). This also ensures the technological acceptance of the sub-model standards within the industry. The IDT of a resource module can be aggregated from the IDTs of its equipment components. For example, the IDT of the resource module, i.e., an articulated robot, can be composed of the IDTs of the electric drives, the IDT of the gripper, as well as of other robot-specific IDTs. In contrast to the temporary composition of the process modules IDT, the resource module IDT is usually coined by a more permanent IDT architecture.

4.2.2. Fluid physical system

4.2.2.1. Operator 5.0. The digital technologies present in I5.0 bring a new paradigm in manufacturing processes, resulting in the elimination of repetitive jobs. I5.0 seeks to apply human intelligence expressed in systems to meet the requirements of a human operator (Javaid and Haleem, 2020). A fluid manufacturing system requires new capabilities, i.e., competencies, skill, and knowledge, from the humans on the management and shopfloor level while it also allows a dynamic and continuous human-centric design of the process module with dedicated resource modules according to the needs of the operators (ARENA2036). An opportunity in this regard would be, for example, to dynamically arrange the mobile equipment, e.g., assembly workplaces or machine tools, in such a manner that the teamwork preferences or the biorhythm of the involved individuals get supported. These novel opportunities of fluid manufacturing might require humans to rapidly adapt to new production environments. The Operator 5.0 concept is currently being discussed as a scientific idea that can facilitate these capabilities (Gladysz et al., 2023). A future Operator 5.0 is shaped by different human-centric principles, methods, and tools related to the super-strength, augmented, virtual, healthy, analytical, social, collaborative, smart, resilient, and cognitive dimensions of human work (Gladysz et al., 2023).

4.2.2.2. Temporary process module with dynamic system boundaries. The key building block of a fluid manufacturing system are temporary process modules with dynamic system boundaries (Fries et al., 2021; Hellmich et al., 2022). Process modules consist of different mobile resource modules that offer a set of manufacturing skills to fulfil a specific manufacturing task (Hellmich et al., 2022). For example, a process module can be composed of different resource modules to fabricate and assemble a specific part of a product. Temporary in this sense means that the process module only exists for a limited period and dissolves, gets reconfigured, reduced, or expanded with a change of the production task or other external factors (Fries et al., 2021; Hellmich et al., 2022.). If, for example, a new operator with individual capabilities enters the manufacturing system, a new temporary process module might be created that reflects the individual capabilities of the operator in a suitable manner (ARENA2036,). The temporary time horizon for the existence of the process module might vary from hours to days, weeks, or even months. Dynamic system boundaries in this sense are linked to the possibility of adding and removing mobile resource module to the process module, i.e., to reconfigure the process module, according to the manufacturing requirements, for example, a new product might require

Table 2
Impact description of framework elements on I5.0 pillars.

Framework elements	I5.0 pillars		
	Human-centricity	Sustainability	Resilience
DesOps	• Integrating different stakeholders' perspectives into the design and operation phases of the manufacturing strategy • Fostering collaboration between teams in different domains	• Emphasizing the life-cycle perspective of designing and operating the manufacturing strategy/system • System-perspective enables an easier consideration and forming of industrial symbiosis networks	High process changeability to quickly react to changing objectives and frame conditions and therefore a high changeability of the manufacturing strategy
Foresight	Anticipation of regulatory and technology developments in the area of human-centricity	Anticipation of sustainability-related regulations, challenges, and developments and creation of respective mitigation and adaption strategies	Development of robust manufacturing strategies for a variety of future scenarios
Maturity assessment	Tracking the human-centricity maturity level of I5.0	Tracking the sustainability maturity level of I5.0	Tracking the resilience maturity level of I5.0
Objectives and Key Results	• Aligning the expectations of employees by defining the OKRs bottom and top-down • Transparent and traceable contribution of teams to success and thus improved motivation • Easy integration of human-centric objectives	Easy integration of sustainability-related objectives for realizing industrial symbiosis networks, for improving the water, energy, and material consumption, or reducing emissions	• Flexible adaptation of the manufacturing strategy in more uncertain industry environments to unforeseen events • Easy integration of resilience-related objectives
Training	Empowering employees by building I5.0 knowledge, skills, and competencies	Raising awareness about sustainability challenges and how to cope with them	Raising awareness about potential risks and how to cope with them
Culture creation	Utilization of principles and practices which are putting the well-being and empowerment of stakeholders such as employees in the centre of attention	Utilization of principles and practices that support sustainability pathways of designing and implementing the manufacturing strategy	Utilization of principles and practices that support a safe and healthy work environment
Ecosystem creation	Utilization of practices, procedures, methods, tools, and technologies for human-centric value creation	Utilization of practices, procedures, methods, tools, and technologies for sustainable value creation	Utilization of practices, procedures, methods, tools, and technologies for resilient value creation
Fluid cyber system	• Fluid arrangement of IDTs following the physical manufacturing system supports a data-driven continuous improvement of the working environment with a focus on the human. • IDT provides the standardized sub-models required for implementing the human-centric Operator 5.0 approach	• IDT facilitates the monitoring of sustainability-related indicators and data-driven decision-making based on these indicators. • IDT facilitates the standardized cross-company exchange of data streams and consequently the easier establishment of industrial symbioses networks and transparent supply chains	• Fluid arrangement of IDTs following the physical manufacturing system supports a high level of changeability for mitigating and adapting to unforeseen situations. • Simulation models integrated into the IDT allow the development of robust strategies by testing different manufacturing scenarios
Fluid physical system	• Operator 5.0 facilitates different human-centric principles, methods, and tools • Temporary process modules with dynamic system boundaries and mobile resource modules allow a dynamic human-centric arrangement of the manufacturing equipment according to the individual dispositions and preferences of the operators and teams	Fluid arrangement of the manufacturing equipment in combination with the fluid cyber system supports a data-driven continuous improvement of the emissions, the water, material, and energy consumption of the manufacturing system as well as the connection of the manufacturing system to cross-company industrial symbiosis networks	Temporary process modules and mobile resource modules allow a high level of changeability across the different hierarchy levels of manufacturing by focusing on mobility and a fluid re-arrangement of equipment according to manufacturing needs.

a new assembly step and thus also a new assembly-related resource module.

4.2.2.3. Mobile resource modules. Key building blocks of a process module are mobile resource modules which can be easily moved inside the factory (ARENA2036) by using for example automated guided vehicles (AGVs) or autonomous mobile robots (AMRs) or through mobility directly inherent to the resource module itself, e.g., via wheels or rolls. A resource module is determined by a set of fabrication and/or assembly equipment that can fulfil one or more functional-connected and generic, i.e., product-independent, manufacturing skills (Hellmich et al., 2022) .

Standard pallets as a foundation for fabrication and assembly equipment can additionally support the mobility of resource modules since they can be easily moved around with forklift AGVs. Heavier equipment such as machine tools can be placed in standard ISO containers which also contain the required energy and ICT infrastructure for the operation of the machine tool (van Erp and Rytter, 2022). ISO containers can be transported with forklifts or portal/gantry cranes inside the factory. Standardized pallets and containers with confined space also support the design of the layout for the temporary process modules. Also, mobile resource modules based on pallets and containers are leading to clearly demarcated physical modules that can set the foundation for the IDT software architecture. In other words, the IDT software architecture of the process module depends on the physical architecture of the mobile resource modules.

5. Verification, discussion, limitations, and plan for future validation and evaluation

5.1. Verification

Verification aims to demonstrate the principal suitability of the proposed I5.0 manufacturing strategy framework for its intended purpose. Human-centricity, sustainability, and resilience are the main pillars of I5.0. The proposed strategy framework must contribute to improving these three pillars compared to the status quo in research and industrial practice. For this verification purpose, Table 2 elaborates on the potential impacts of the I5.0 manufacturing strategy framework on each of the I5.0 pillars as derived by the authors. The impacts are described specifically for each element of the framework's process and system model. The authors believe that the qualitative verification in Table 2 demonstrates the principal suitability of the strategy framework and its elements to integrate and improve human-centricity, sustainability, and resilience in different capacities.

On top of facilitating these three pillars, an I5.0 manufacturing strategy framework must improve the competitiveness of the respective company. The authors believe that designing and operating an I5.0 manufacturing strategy might lead to the following competitive advantages:

- Higher adoption level in terms of cutting-edge I5.0 artifacts such as fluid manufacturing, the IDT, and the Operator 5.0 which in turn allows the realization of new business model innovations.
- Improved resilience of manufacturing system towards internal and external shocks.
- Higher anticipation level and reduced risks from current and upcoming sustainability regulations, e.g., by improving digital transparency across value chains.
- Better working conditions and well-being of employees through competency building, the empowerment of human craftsmanship and facilitation of human-machine collaboration.
- Improved resource productivity and reduced environmental footprint by optimising digital and physical assets.

In conclusion, the strategy framework seems to be suitable for creating and implementing a manufacturing strategy in I5.0. However, a valid data-driven statement about the efficacy of the strategy framework compared to other frameworks cannot be made at this point and should be subject to future validation- and evaluation-oriented research efforts as described in 5.3.

5.2. Discussion

The proposed conceptual framework intends to answer the two research questions:

1) What is a suitable process model with relevant process phases that an industrial company can utilise to design and operate an I5.0 manufacturing strategy?
2) Which are important system components of I5.0 manufacturing systems that a company can consider to design and operate an I5.0 manufacturing strategy?

The first research question has been answered by describing the process model based on the DesOps methodology which comprises the six DesOps process steps, supplemented by culture and ecosystem creation, as the main process phases, and which are supported by foresight, maturity assessment, Objective and Key Results (OKRs) and training as the supporting process phases.

The second research question has been answered by presenting a system model based on a fluid cyber and physical manufacturing system. This fluid manufacturing system consists of temporary process modules which are in turn composed of mobile resource modules. Additional components are the reconfigurable IDT of the process and resource modules with standardized sub-models. Further, the novel Operator 5.0 facilitates the value creation across the manufacturing system.

In their combination, the process and system models support the design and operation of the system components of a manufacturing strategy in I5.0 and thus should offer a blueprint for designing and operating the manufacturing system-of-systems in a future I5.0 environment.

An initial verification (5.1.) demonstrates a positive impact of the process and system model from the I5.0 manufacturing strategy framework on the three pillars of I5.0, namely human-centricity, sustainability, and resilience. It is expected that each element of the framework listed in Table 2 might lead to a positive impact within each of the three pillars. Further, manifold completive advantages might be realised by improving the three pillars of I5.0 as described in 5.1.

In terms of the applicability of the process model, the conceptual framework has been derived from state-of-the-art and best practices which have already demonstrated their suitability for application in industrial practices. For example, the DevOps process phases in combination with OKRs as a simple management tool and a training phase for developing relevant competencies have been described as specifically suitable for application in SMEs (van Erp et al., 2021). The authors therefore believe that the process model is characterised by a general applicability for supporting the strategy design and implementation within manufacturing companies.

In terms of the applicability of the system model, the conceptual framework seems to be more suitable for discrete manufacturing companies rather than process manufacturing companies. The application of mobile resource modules and temporary process modules is often more difficult to realize within the process industry, especially within the food, pharma, or health sector with high regulatory barriers for making changes to the layout or equipment arrangements of the manufacturing system. However, the fluid manufacturing system seems specifically suitable for companies producing large-scale/XXL products such as trains, aircraft, wind turbines, or vessels. In this case, it can be beneficial to temporarily move the manufacturing equipment around rather than moving the bulky and heavy products around. Additionally, contract manufacturers with a high fluctuation in terms of product mix and volume leading to a high uncertainty for manufacturing requirements and tasks might specifically benefit from the flexibility of a fluid physical and cyber manufacturing system.

Future I5.0 manufacturing strategy research should focus on investigating the implications of I5.0 manufacturing strategies on different characteristics of manufacturing systems such as process vs. discrete manufacturing, small-vs large-scale manufacturing, high volume of production vs. low volume, high mix of product variants vs. low mix, etc, as well as on different manufacturing sectors. Besides, further research on the fluid manufacturing system might be required to create first use cases and demonstrators for the interplay of the fluid manufacturing system with the IDT technology and the Operator 5.0 as well as concrete design solutions for mobile resource modules and temporary process modules.

5.3. Limitations

The I5.0 manufacturing strategy framework has been developed by deploying a qualitative expert research method and is based on best practices in I4.0 and new I5.0 concepts described within academia and industry. Consequently, the underlying assumptions for shaping the resulting I5.0 manufacturing strategy framework seem functional for reflecting the future manufacturing needs of companies in an I5.0 environment. The presented framework is expected to support companies to improve their competitiveness while also improving their sustainability, resilience, and human-centricity performance. However, there are some limitations linked to this qualitative expert research method. Subjective interpretation, as well as different perceptions, biases, and competency levels of the individual experts, i.e., authors, has influenced the framework development, which might have led to ignoring, neglecting, or misinterpreting some relevant facts related to principles, methodologies, methods, tools, technologies, and applications relevant for I5.0 manufacturing strategies.

Further limitations are related to the missing quantitative validation and evaluation of the conceptual framework which so far only allows a limited interpretation of the framework's efficacy. Especially its applicability within the manufacturing sector as well as its efficiency and effectiveness in improving competitiveness, sustainability, resilience, and human-centricity should be supported by quantitative results in the future. For this purpose, section 5.4 elaborates on the plan for future validation and evaluation in more detail.

Other limitations are described for the applicability of the conceptual framework's system model. The conceptual framework seems to be more suitable for discrete manufacturing companies rather than process manufacturing companies since the process industry, especially within the food, pharma, or health sector, is typically characterised by high regulatory barriers for making changes to the layout or equipment arrangements of the manufacturing system in the sense of an I5.0 manufacturing strategy.

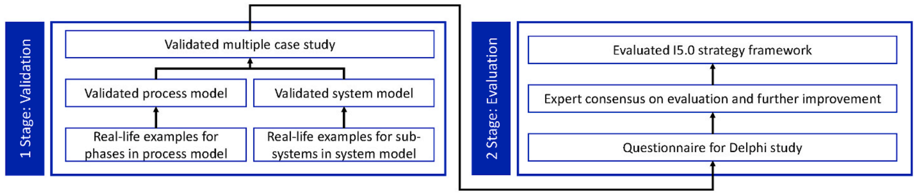

Fig. 3. Plan for future validation and evaluation.

5.4. *Plan for future validation and evaluation*

The future validation and evaluation of the proposed conceptual framework for designing and operating an I5.0 manufacturing strategy is planned as a two-stage process (Fig. 3). The first stage aims at validation of the framework based on a multiple case study while the second stage aims at evaluation of the framework based on expert opinion. The validation will be built on creating a multiple case study that comprehensively reflects the process and system model of the framework. For this purpose, real-life examples from existing industry business cases, industry association activities, and industry-led research projects in the field of manufacturing will be collected and analysed for the different process model phases and system model components of the framework. Subsequently, the validated multiple case study will serve as input for the evaluation stage. Specifically, the study will be utilized for the development of a questionnaire for a Delphi study. Conducting different rounds of questioning will create consensus among the panel of experts on the efficacy evaluation and further improvement potential of the I5.0 manufacturing strategy framework.

6. Summary

The authors aimed with this research to create a novel conceptual framework for designing and operating an I5.0 manufacturing strategy for maintaining and improving the long-term competitiveness of manufacturing companies. For this purpose, two sub-research questions were derived:

1) What is a suitable process model with relevant process phases that an industrial company can utilise to design and operate an I5.0 manufacturing strategy?
2) Which are important system components of I5.0 manufacturing systems that a company can consider to design and operate an I5.0 manufacturing strategy?

To answer the first sub-research question, a process model based on the Design and Operations (DesOps) methodology was introduced. It suggests six circular DesOps process steps, arranged according to an infinity symbol, and supplemented by four supporting processes. The specific nature of the DesOps process model should allow for an efficacious design and operation of the manufacturing strategy in an Industry 5.0 context.

To answer the second sub-research question, the relevant system components of manufacturing systems in Industry 5.0 were laid out. Considering the current developments concerning matrix and fluid production systems, a system model based on a fluid physical system as well as on a fluid cyber system was discussed and proposed as relevant system components. These two system components should offer a blueprint for designing the manufacturing system-of-systems in a future Industry 5.0 environment.

Eventually, the proposed process and system model were verified to demonstrate the principal suitability of the proposed I5.0 manufacturing strategy framework for its intended purpose. However, a valid statement about the efficacy, effectiveness, or efficiency of the strategy framework compared to other frameworks cannot be made at this point and should be subject to future validation- and evaluation-oriented research efforts.

For this reason, the authors will pursue the development of academic and industry-driven case studies in which the novel manufacturing strategy framework is partially or fully implemented to gather first quantitative data points about its principal efficaciousness.

CRediT authorship contribution statement

Tim van Erp: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Conceptualization. **Nubia Gabriela Pereira Carvalho:** Writing – review & editing, Writing – original draft, Investigation. **Mateus Cecilio Gerolamo:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Rui Gonçalves:** Writing – review & editing, Writing – original draft, Investigation. **Niels Gorm Malý Rytter:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Bartlomiej Gladysz:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

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

All data used to create this research is included in the manuscript and/or can be accessed via the list of references.

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