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Converging on human-centred industry, resilient processes, and sustainable outcomes in asset management frameworks

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Abstract

The objective of increasing productivity while optimizing operational and organizational processes has focused Industry 4.0 (I4.0) on technological development without considering the impact of technology on people and the impact of mass production on the environment. These impacts have led to growing concerns about climate change and complex global risks. A new vision of the industry, called Industry 5.0 (I5.0), has emerged within the scientific community. This human-centred industry appears to be a bold turn from individual technologies to a systematic approach that enables industry to achieve societal and environmental goals beyond economic growth. Under this approach, the question is no longer whether asset management should change, but what that transformation should look like. This paper identifies areas for improvement of the asset management process and presents a framework that incorporates the core values of I5.0 within the overall asset management framework, in which the core principles remain, and the new technologies are the enabling functions. Though the primary focus of this paper on manufacturing and industrial systems, many of its concept and ideas are also relevant to asset management in the public sector infrastructure systems.

Keywords Asset management · Industry 4.0 · Industry 5.0 · Human factors · Sustainability · Resilience

1 Introduction

Asset management has undergone a significant evolution over the years, driven by the advancements in technology and industry. The fourth industrial revolution, referred to as Industry 4.0, have brought about new technologies and ways of working. These advancements have revolutionized the way assets are managed, enabling organizations to automate processes, optimize operations and make more informed and real-time decisions. This has led to more effective and efficient asset management practices and has enabled organizations to reduce operational costs and improve their overall performance. Industry 5.0, on the other hand, takes the integration of digital and physical systems to a whole new level, with the focus on enhancing the human experience through the use of technology. As the world becomes more decentralized a new future for work and the worker takes shape. The technology-driven transformation, changing risk and regulation, and the integration of ESG (environmental, social, and governance) criteria are impacting asset management processes. As a result, closer links between the concepts of human centricity, sustainability, and resilience must be established in the asset management framework. This balancing act will result in a more agile and responsive asset management system, capable of adapting to changing business needs and operating in an increasingly complex and dynamic environment.

This article lays the groundwork for potential solutions to govern the technological evolution toward the desired I5.0 scenario. In order to purposefully guide the process of worker centralization, sustainability, and resilience within I5.0, three main objectives of the paper were defined, namely: (i) to consider the impact of technologies on human factors and their effects on performance indicators; (ii) to consider the impact of the industry on environmental,

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social, and economic factors and the effects (disruptions) on system performance; and; (iii) incorporate the concept of resilience in order to guide the technological evolution toward the development of tools that enable industries to withstand small or large disturbances and ensure business performance.

The paper is structured as follows: Sect. 2 presents the evolution of asset management. Section 3 introduces Industry 4.0 and highlights crucial, yet overlooked areas in its conception and design. It then introduces the new vision of the industry called Industry 5.0, discussing the direction of technology, challenges, and key issues. Section 4 presents a global model integrated into the asset management framework allowing us to better understand the impact of technological evolution on Industry 5.0 and emphasizes an effective decision-making approach for the design and implementation of future technology tools. Section 5 explores potential changes in the asset management process brought about by Industry 5.0. The paper concludes in Sect. 6.

2 The asset management evolution

Technological evolution has shaped the history of industry and asset management (Fig. 1). The emergence of mechanical production infrastructure for water and steam engines in 1784 resulted in the first industrial revolution. A century later, electric power and assembly lines revolutionized industry, giving rise to the second industrial revolution. The next revolution (3rd Industrial Revolution, 1969) was the result of the widespread use of electronics, partial automation, and the emergence of information technology. Since then, the need for good practice guidelines (standards and other technical norms) was confirmed (and will continue to be fed by technology), particularly in the area of maintenance, with the appearance of guidelines such as total productive maintenance (TPM) and reliability centered maintenance (RCM) in the 1970s (Azid et al. 2019).

In the late 1980s, the International Organization for Standardization (Sterbenz et al. 2010) published the ISO 900X series to address various aspects of quality management. Subsequently, the U.S. Occupational Safety and Health Administration (Yarveisy et al. 2020) established minimum performance requirements for the control of machines and equipment that could harm employees through standard 29 CFR 1910.147.

The British Standards Institute (BSI) published BS 3843:1992, a guide to terotechnology (economic asset management) in 1992, followed by BS 3811:1993, a glossary of terms used in terotechnology in 1993. Subsequently, several conceptual models of asset management emerged. The Australian National Asset Management Manual was the first in 1994, followed by the New Zealand Asset Management Manual in 1995 and the International Infrastructure

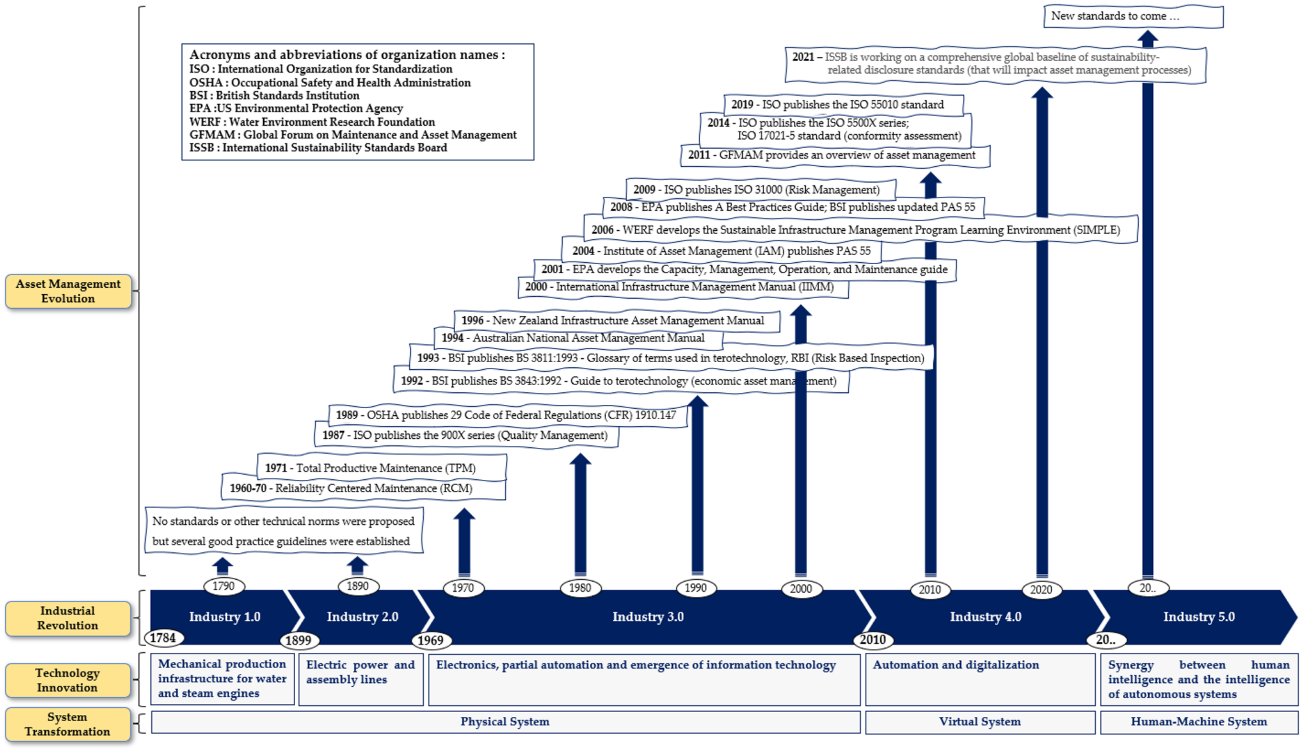


Fig. 1 Industrial revolutions with the evolution of the principal standards and technical norms of the asset management process

Management Manual (IIMM) in 2000, giving rise to the concept of the physical asset life cycle IIMM (2015).

In the 2000s, the U.S. Environmental Protection Agency (Maddikunta et al. 2021) developed a guide on capacity, management, operations, and maintenance. In 2005, the Institute of Asset Management (Keenan et al. 2021) published the PAS 55 "Specification for Optimized Management of Physical Assets". A year later, the Water Environment Research Foundation (WERF) developed the Sustainable Infrastructure Management Program (SIMPLE) learning environment to provide a comprehensive understanding of asset management at the strategic and operational levels, and to promote information exchange among asset management practitioners. The "best practices guide" (Maddikunta et al. 2021) for asset management was released in 2008 and the ISO 31000 standard on risk management was not published until 2009, focusing on the importance of economic resilience, environmental impact, and safety outcomes.

At the dawn of the fourth industrial revolution, the Global Forum on Maintenance and Asset Management (GFMAM) provided an overview of asset management that included resilience analysis as an essential component GFMAM (2014). At this time, the focus on modular replacement, risk, and reliability gave rise to the concept of smart manufacturing for the future; the fourth industrial revolution was underway. In 2014, ISO published the ISO 5500X series highlighting the potential benefits of implementing good asset management. The ISO 17021-5 standard (conformity assessment) then defined the human skills required for this process. Finally, in 2019, ISO published the ISO 55010 standard to guide the alignment of financial and non-financial functions and thus improve internal control of the asset management system.

Today, the potential for greater innovation power through synergy between human intelligence and the intelligence of autonomous systems seems to be pushing the industry toward a new revolution called Industry 5.0. This evolution presents itself as an opportunity to create a new techno-social system that fills the current lack of recognition and respect for the principles of social and environmental well-being. To make these new connections, decision-makers must, within the framework of asset management, establish closer links between the core values of I5.0: human centricity, resilience, and sustainability.

The Asset Management Framework has been developed to unify generic competency requirements that apply to all organizations and sectors. It is based on optimizing the delivery and performance of physical assets. Concepts such as asset information, strategy and planning, and life cycle delivery and asset management decision-making have become ingrained in the I4.0 culture. Today, the emergence of the I5.0 concept prompts a discussion of the key asset management topics that need to be addressed in order to provide ideas for possible improvement of the asset management process. The focus is no longer on whether asset management needs to change, but what that transformation should look like.

2.1 Asset management: a comprehensive insight

To illustrate the breadth of activities within the scope of asset management, the interrelationships between activities and need to integrate them and the critical role for asset management to align with and deliver the goals of an organization's strategic plan, asset management activities can be described, at a high-level overview, through a suite of subject groups. Each group encompass several subjects with complex inter-relationships between most of them. The importance of each individual subject depends on its specific sector and organizational purpose and context.

Central to an effective asset management system is the alignment of the organization's asset management activities—and the resulting outputs from these assets—with its overarching objectives. Such alignment ensures that those involved in day-to-day asset management can trace their activities back to the broader organizational goals. These activities include integrating the asset management policy, strategy, objectives, and planning.

One primary objective for any organization is maximizing the value derived throughout an asset's lifecycle. The type of asset procured affects its performance, associated risks, maintenance requirements during its operational phase, and eventual decommissioning cost and procedures. Operational and maintenance strategies further determine an asset's performance, useful life, and end-of-life complexities and cost. With industrial advancements, the decision-making process regarding these factors is increasingly shifting towards data-driven paradigms.

Effective implementation of asset management plans hinges on meticulous control of activities and the associated risks throughout an asset's lifecycle. Key subjects in this sphere encompass asset acquisition, operations, maintenance strategies, and the eventual disposal or renewal of assets. Prioritizing a holistic approach to these activities empowers organizations to extract maximum value from assets at every stage of their life and minimizing downstream costs.

One of the key enablers across the breadth of asset management activities rely on asset data and information. Todays the importance of proper data management for informed decisions is growing fast but there is a discernible lag in standardizing process. Typically, organizations do not have perfect, or even adequate, asset information process. Topics to develop or improve could range from data collection methods, technological tools for data analysis, and how this data informs asset management strategies.

A successful and robust asset management strategy requires the right organizational structure and skilled individuals. This often nudges organizations towards reevaluating traditional ways of thinking and working. Introducing these new dimensions of asset management thinking often poses challenges in the reviews of organizational structures, the roles and responsibilities and the contractual relationships. Effective leadership is therefore crucial for building an organization, with the appropriate culture, which supports the delivery mature asset management capability.

Lastly, the fundamentals of asset management also lie in rigorous risk management strategies and consistent performance evaluations. The goal is to identify, understand, and manage potential asset-related risks as well as external risk and conduct regular audits or review to ensure optimal asset performance. Essential areas of focus include developing effective feedback mechanisms, ensuring that organizational objectives align with outcomes, and continually enhancing asset management activities. The necessity for standardized tools and methodologies for periodic asset assessments is a growing need in the new industry landscape.

Several conceptual models were proposed by the members of the Global Forum. However, there isn't a universally perfect model to describe asset management. As organizations' needs change, asset management continues to evolve, and certain elements of these conceptual models are likely to change over time. On this basis, this paper introduces new subjects and elements to integrate in these groups (also called pillars), aiming to align with the anticipated needs of the emerging industrial landscape.

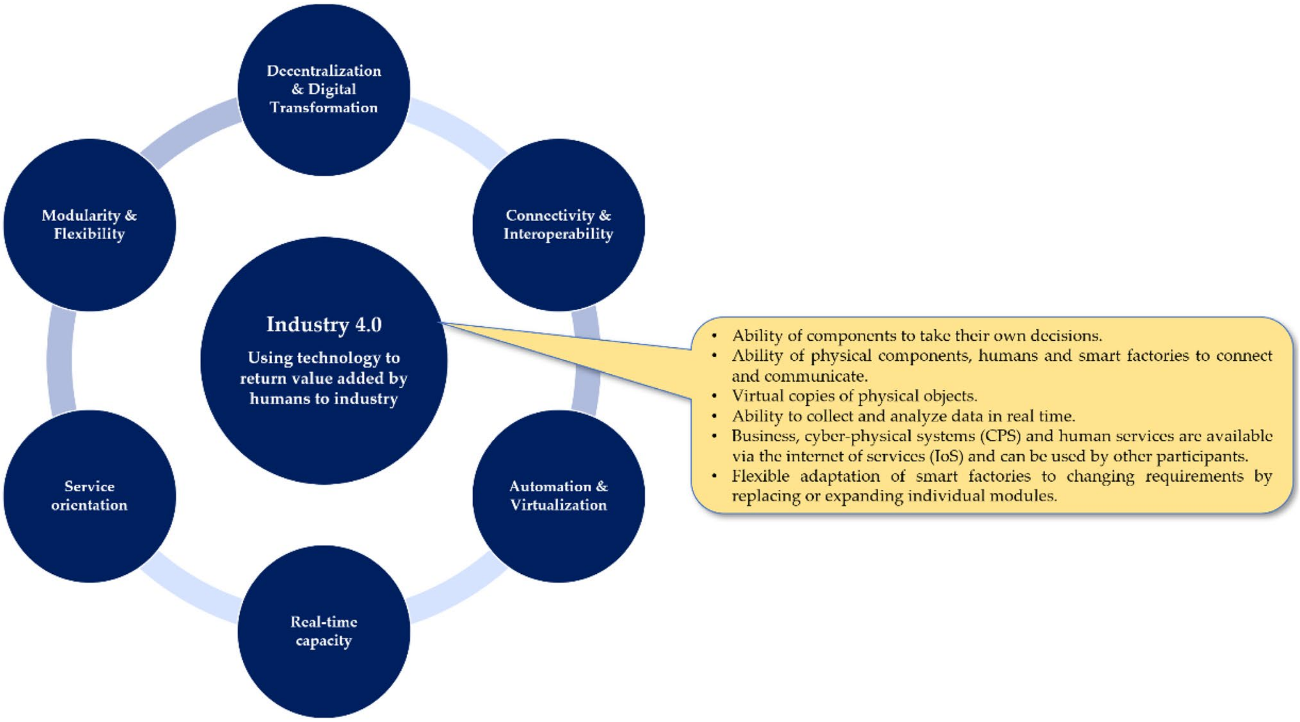
Regarding our work, the most complete and adaptable model is the IAM's model. This model organizes asset management into six comprehensive subject groups: strategy & planning, asset management decision-making, life cycle delivery, asset information, organization & people and risk & review. Together, they cover a total of 39 distinct asset management subjects (IAM 2015). In the next section, we highlight the objectives of the future industry and propose a complementary approach to the model to achieve these objectives.

3 I5.0: repurposing I4.0 technologies

In the midst of the Industry 4.0 boom, the emergence of the Industry 5.0 concept is dividing industry leaders, with some believing it is still too early for a new industrial revolution (Nahavandi 2019), and others pointing out that moving in this direction may be too costly in the short term (Madsen and Berg 2021). Clearly, the concept of I5.0 seeks to bridge all the asymmetries of I4.0, pursuing the development of complex and hyperconnected digital networks in a secure, human-centred, sustainable, and resilient way.

3.1 I4.0: a technology-driven industry

The fourth industrial revolution, commonly referred to as Industry 4.0 (I4.0), emerged in 2011 as part of Germany's high-tech strategy that merges the virtual and real worlds, focusing on applications of robotics, digitization, and automation (Kagermann et al. 2011). The term I4.0 corresponds to a global transformation using digital integration and intelligent engineering in which machines redefine themselves in the way they communicate and perform individual functions. This transformation is primarily based on the use of Cyber-Physical Production Systems (CPPS), which is characterized by the widespread application of Cyber-Physical Systems (CPS) in manufacturing and production (Vogel-Heuser and Hess 2016). Cyber security has thus been one of the major issues in the development of I4.0, with priority actions developed in the area of safety and security (Kagermann et al. 2013). The widespread deployment of sensors combined with a range of new technology (IoT, Big Data, Cloud Computing, and Artificial Intelligence) has made it possible to create a world in which "things" are endowed with some degree of intelligence, and moreover, are more connected to each other. The concept of I4.0 has evolved very quickly in different fields (health, economy, agriculture, etc.) and is used in different ways by think tanks, business leaders, international organizations and policy-makers, each bringing their own neologisms and specific definition. Thus, the literature becomes awash with definitions of the term "Industry 4.0," with over 100 directories as of 2016 according to Moeuf et al. (2018), which vary considerably in their direction and scope. However the set of definitions generally agree on clear and generally accepted key design principles that serve as guidelines for I4.0 implementation (Fig. 2), namely decentralization, interoperability, virtualization, real-time capability, service orientation, and modularity or flexibility of smart factories (Hermann et al. 2015). More explicitly, these principles can be described through the application of new information and communication technologies (ICT) on which I4.0 is based such as the Internet of Things (IoT), Cloud Computing, analysis, management and value creation from Big Data, the Smart Factory (SM), etc. To achieve these design principles, I4.0 needs to focus on three characteristics, namely horizontal integration (the use of technologies to exchange and manage information between different agents), vertical integration (the integration of various IT systems at different hierarchical levels, creating a flexible and reconfigurable system), and end-to-end digital integration (Shafiq et al. 2015). Thus, potential benefits such as reduced expenses, costs, and lead times; increased operational process efficiency; and improved organizational flexibility can be realized, and the goals of improved productivity and quality can be achieved.



- Ability of components to take their own decisions.
- Ability of physical components, humans and smart factories to connect and communicate.
- Virtual copies of physical objects.
- Ability to collect and analyze data in real time.
- Business, cyber-physical systems (CPS) and human services are available via the internet of services (IoS) and can be used by other participants.
- Flexible adaptation of smart factories to changing requirements by replacing or expanding individual modules.

Fig. 2 Key design principles to guide the implementation of I4.0

Clearly, I4.0 is rapidly transforming almost all professional fields with new planning methods, optimized decision-making, the creation of new services and better energy management (Shrouf et al. 2014). However, many industry and academic experts have begun to criticize and question this techno-centric approach leading to a highly automated industry (in which the human being is increasingly pushed aside by delegating most of the tasks and decisions to intelligent and autonomous systems). System intelligence (software) should be at the service of humans to support decision-making and not considered the decision-maker. This technology-driven development (not to mention the cognitive limitation of the latter), with the sole goal of increasing profit has inadvertently ignored its social and environmental impact, even if the literature contains recommendations to consider sustainability and the human being (Xu et al. 2021).

As highlighted in Fig. 3, the number of publications (according to the Scopus database) on Industry 4.0 research dealing with human or environmental factors, but more generally with a human-centred or sustainable industry according to environmental and societal dimensions (and not from an economic point of view) and focusing on the resilience of physical or cyber systems has increased, but represents only a fraction of the number of publications published on I4.0 topics during the same period.

From a human-centred perspective, current publications have focused on presenting future scenarios, challenges, and opportunities for human work in relation to I4.0 technology systems (Kadir et al. 2019). Indeed, experts assert the relevance of the human role in the manufacturing landscape (Fantini et al. 2020). The concept of “Operator 4.0” seeks to provide solutions to reintegrate the human into the control loop of industrial systems to maximize (economic) performance (Longo et al. 2017). Much of the research today is focused on the concept of human–machine co-working in hopes of returning humans to an effective, rather than artificial, place in industry (Pacaux-Lemoine et al. 2017). However, the impacts of the current state of industry on the specific characteristics of workers, namely cognitive, physical, motor, interactive, perceptive, sensory or psychosocial capacity, are still not taken into account in the design

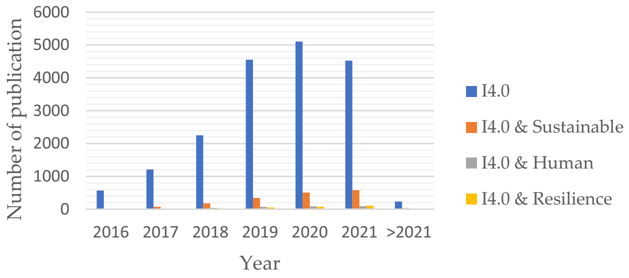


Fig. 3 Number of publications on I4.0 by year addressing different concepts: sustainability, human centricity, and resilience

of systems. These "human factors" affect the performance of humans and accordingly ultimately the performance of systems (Neumann et al. 2021). On the user perspective, service delivery centered on efficiency, often sidelining personalization. Feedback mechanisms were predominantly reactive, with user engagement often secondary to process optimization. Although inclusivity initiatives existed, they were often siloed and not fully integrated. As for regulations, compliance was paramount but often lacked a user-centered approach. It is therefore important to establish a clear definition of the term "human-centred" in order to provide the necessary technology to extend worker capabilities by considering the emerging issues of health, safety, ethics, among others surrounding technologies that interact with humans and emphasizing holistic user experiences, proactive feedback, comprehensive inclusivity, and sustainability intertwined with core business objectives (humans at the centre of automation and decision-making).

On the aspect of sustainability, I4.0 has focused mainly on the economic dimension (e.g., solving the maintenance optimization problem, while forgetting the essential—the role of the human). The area of environmental and social sustainability has received very little attention in the I4.0 literature, although it is more significant than the attention given to human factors (Fig. 3). Through real-time data collection and the use of new technologies, I4.0 has enabled efficient resource allocation and greenhouse gas mitigation (Müller et al. 2018). In addition, automation has facilitated the application of circular economy principles, especially within supply chains (Lopes de Sousa Jabbour et al. 2018). However, undeniable changes in climate, caused by a massive increase in pollution and waste from mass production, have forced governments to guide industry behaviour and decisions to achieve the goal of climate neutrality. Accordingly, the European Commission has developed the "Green Deal" followed by the action plan for the development of the bioeconomy for the benefit of society and the environment. Today, research is focused on the development of technologies to cope with the depletion of energy sources and to fight against climate change (Kamble et al. 2018).

In recent years, the term resilience referring to the ability of systems to cope with disturbance has been introduced into the I4.0 literature. Industry has had a particular interest in managing supply chain disruptions (Ivanov et al. 2019). Research has led to new theoretical and practical solutions for emerging proactive and reactive strategies as well as contingency plans that allow structural and parametric adaptation in response to fluctuations induced by small- or large-scale disruptions (Ivanov and Dolgui 2021). Smart technologies, on the other hand, enable adaptive rerouting and resource allocation measures in the face of disruptions. However, digital technologies have accelerated the interactions between different networks, transforming the industry into complex and interdependent systems, making them more vulnerable to both cyber and physical disruptions (Panetto et al. 2019). It is therefore imperative to integrate the notion of resilience from design to planning to respond to different types of disruptions and represent, for users and operators, a technically and economically feasible, as well as ecologically sustainable, alternative.

To achieve this triple objective of an efficient, responsible, and resilient innovation ecosystem design, Özdemir and Hekim have identified four assumptions and shortcomings, which they call asymmetries (Table 1), as yet uncontrolled in I4.0 that need to be taken into account in the development of the future industry to achieve a dynamic and anticipatory governance of the societal context and impacts associated with the applications of

Table 1 Addressing the lack of symmetry in the Industry 4.0 ecosystem

Asymmetrical innovation in Industry 4.0	Symmetrical innovation for Industry 5.0	Axis
Extreme integration without a safe exit strategy from networks	Define safe exit strategies from integrated networks, or prudent measures to contain local failures within a highly connected network	Resilience
Filter bubbles versus open systems	Reduce the real threat of filter bubbles to openness, efficiency, and creativity by reconciling (i) lack of reflexivity and awareness on how our own values influence the type of conclusions we draw in science and society, and (ii) lack of appreciation of the societal and human power-related contexts in which science and technology are situated	Human centricity (Human in industry: workers)
Acceleration versus deceleration of innovations	Consider both acceleration and deceleration as the twin governance narratives to foster the long-term sustainability of innovation ecosystems	Environmental sustainability
Technology versus societal outcomes	Broaden our understanding of Industry 4.0 outcomes and its multiple possible futures in society to dismiss technological determinism	Human centricity (Human in society)

new technologies (Özdemir and Hekim 2018). The study (Keenan et al. 2021) highlights the conceptual, empirical, and practical relationship between the concepts of resilience and sustainability in economic policy and investment strategies to provide a heuristic that assesses the expected and unexpected costs and benefits of the latter. The structural reorganization of economies, production systems, and supply chains induced by resilient processes can lead to sustainable social and environmental transformations. And conversely, sustainability policies can support future resilient processes. Clearly, sustainability and resilience are deeply interconnected concepts. This interconnectedness needs to be constantly emphasized in the process of standardizing resilient processes and sustainable outcomes.

Table 1 highlight the fact that Industry 4.0 focuses on highly integrating systems and processes, but not emphasize how to safely disconnect or exit from these tightly bound networks. It therefore becomes necessary to define safe exit strategies from integrated networks, or prudent measures to contain local failures within a highly connected network.

The term "Filter bubbles" (Table 1) refer to situations where algorithms selectively show users content similar to their preferences, limiting exposure to diverse viewpoints. This contrasts with "open systems" which encourage free exchange and broad access to information. The progression towards Industry 5.0 emphasizes the importance of breaking down filter bubbles. This involves being aware of and challenging our own biases and understanding the social contexts that influence scientific and technological outcomes.

Acceleration versus deceleration of innovations (Table 1) contrasts the pace at which innovations are introduced and adopted. Industry 4.0 may prioritize the rapid introduction of innovations, while industry may consider both speeding up and slowing down innovations as necessary. In Industry 5.0, there's a push for understanding the benefits of both quick innovation and slowing down to ensure sustainable and well-thought-out innovative practices.

Finally, Table 1 highlights the fact that Industry 4.0 may have a primary focus on technological advancements, often neglecting the broader social impacts of these innovations. As we move towards, there's an emphasis on understanding not just the technological aspects but also the societal consequences of these innovations. This shift rejects the idea that technology alone dictates the future, emphasizing the role of societal choices and values.

I4.0 can therefore be described as an Industrial Revolution with positive economic benefits, but potentially dangerous or even negative social, societal, and environmental consequences. Clearly, a new vision of industry leading to a fair balance between these dimensions is necessary for the development of sustainable and resilient systems. This forward-looking exercise has led to the conception of a future industry called "Industry 5.0".

3.2 I5.0: a human-centred industry

The term Industry 5.0, initially called "Industrial Upcycling", was introduced in 2015 by Rada (2015) as the first industrial evolution to rely on I4.0 technology. Rada (2018) focused on circular economy processes and the concept of zero waste by introducing the 6R methodology (Recognize, Reconsider, Realize, Reduce, Reuse, and Recycle) through the principle of "Logistics Efficiency Design" (LED) (transparency, benefit sharing and efficiency in the supply chain). Other authors have then taken an interest in the concept by questioning the place and role of the human being in this industry of the future. Different visions of I5.0 have also emerged in the literature; some consider the concept to be a chronological continuation of I4.0 (Demir et al. 2019), others consider I4.0 and 5.0 as a single industrial revolution using the term techno-social revolution (Xu et al. 2021), and still others see it as an alternative to the current I4.0 paradigm (Özdemir and Hekim 2018). In 2021, the European Commission described the substance of this concept as a complementary approach to I4.0 leading to a coexistence between emerging trends and the needs of society. The desire to make European industry socially and environmentally responsible has led to a consensus on the need to drive innovation from individual technologies to a systemic approach. The reflection of a set of high-level experts resulted in the three pillars of I5.0 (Fig. 4), namely sustainability, human centricity, and resilience (European_Commission 2021).

The concept of sustainability will necessarily lead to the integration of environmental factors into business models, the deployment of tools to achieve the ambition of carbon neutrality by significantly reducing greenhouse gas emissions as well as the development of new tools, resources, and knowledge to ensure the efficiency of the circular economy. In his exploration of this interplay, Yossi Sheffi highlights the tensions businesses often face when navigating the pressures from various stakeholders to adopt sustainable practices, set against the backdrop of economic realities. Using real-world case studies, he illustrates the challenges and nuances of implementing green initiatives. He emphasizes the balance companies must strike between genuine sustainability efforts and profitability. A salient theme is the divergence between customer demands for sustainable products and their readiness to bear the associated costs (Sheffi 2018). In this sense, evolving technologies such as AI and additive manufacturing will play an important role in ensuring present and future needs within planetary limits.

The human-centred approach must contribute, on the one hand, to the well-being of the worker by focusing on designing a safe and inclusive environment responsible for mental and physical health as well as developing a digital educational ecosystem for better training, retraining, and upgrading. From a user's perspective, this approach must ensure

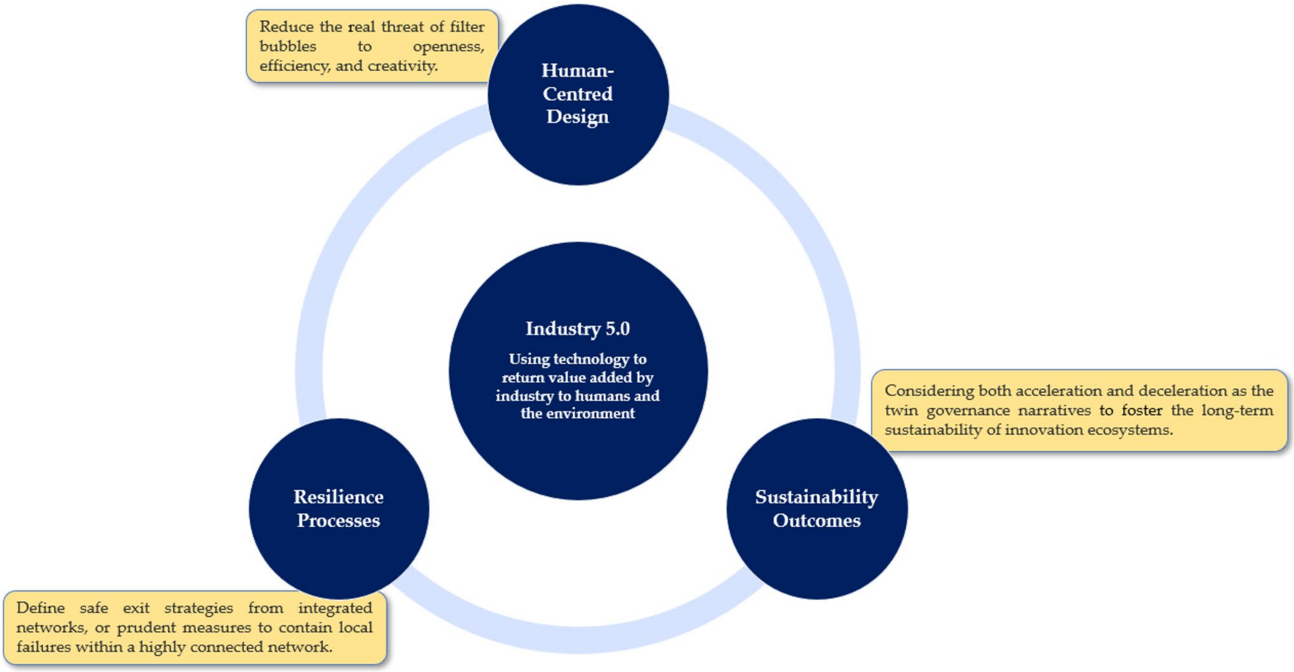


Fig. 4 The links between symmetric innovation for Industry 5.0 and the three concepts of human centricity, resilience, and sustainability

that products and services are designed with user safety, data privacy and accessibility in mind. It's crucial to create mechanisms for user feedback, ensuring that their concerns and needs are consistently addressed. Both workers and users should benefit from transparent practices, ethical standards, and a commitment to continuous improvement in the face of evolving societal needs. On the other hand, this approach must integrate the notion of social well-being, focusing mainly on the deployment of services for the protection of personal data, the respect of individual's autonomy, cultural sensitivity and the social connectivity as well as the establishment of regulation for artificial intelligence. The discussion social well-being should holistically encapsulate the elements that influence the mental, emotional and communal health of individuals and communities. And as the objectives of I5.0 go beyond employment, the social protection and health systems will have to be reformed. Thus, this process must integrate the impact of technologies on workers and the impact of industry on society, through decision-making on the evolution and use of new technologies. Rather than obtaining a model where the human is at the service of technology, this approach strives to put technology at the service of the human.

Finally, resilience refers to the need to ensure the proper functioning of organisms in the face of disruptions in the context of the complexity and high-density interconnection of the modern world. The industry of the future must be able to adjust quickly to face constant change. Emerging and systemic risks such as geopolitical changes, climate change, meteorological phenomena or natural crises, such as the Covid-19 pandemic, highlight the fragility of current globalized production systems. By embedding disaster resilience into the core of industrial processes, businesses not only safeguard their assets and stakeholders but also position themselves to seize new opportunities that arise in the wake of challenges. Yossi Sheffi, in his seminal works, underscores the distinction between "resilience"—the capability of enterprises to recover from disruptions—and "robustness"—the inherent ability to resist such disruptions from the outset. Through numerous real-world examples, he illustrates the financial and reputational repercussions of unanticipated disruptions and emphasizes the balance between operational efficiency and vulnerability. Sheffi accentuates the vital role of leadership, culture, and continuous learning in bolstering resilience. Moreover, he outlines the strategic significance of collaboration with stakeholders and diversification of supply chains. His insights suggest that while resilience is intricate, it offers a competitive advantage, transforming potential setbacks into opportunities (Sheffi 2015a, b). In this sense, the expected properties or necessary conditions, such as robustness, reliability, redundancy, vulnerability, survivability, resourcefulness, recoverability, rapidity, adaptability or absorbability, for a complex and highly interconnected system require the inclusion of resilience. To align decision-making with the resilience objective of I5.0, common models in resilience analysis must emerge.

I5.0 is thus defined as a smart industry that is mindful of fundamental human values and capable of adjusting its design, management, and control to preserve the planet while prioritizing worker well-being over economic growth (Xu et al. 2021). Özdemir and Hekim (2018) define I5.0 as "an evolutionary, incremental (but critically necessary) advancement that builds on the concept and practices of I4.0" (Özdemir and Hekim 2018). The European Commission defines I5.0 as an industry with the power "to achieve societal goals beyond jobs and growth to become a resilient provider of prosperity, by making production respect the boundaries of our planet and placing the well-being of the industrial worker at the centre of the production process" (European_Commission 2021). The full definition of I5.0 seems to be a balancing act, requiring arbitration between regulatory, financial, technical, human, economic, technological, social, and environmental constraints.

The combined potential of six categories integral to a Technology Framework to be developed for I5.0 has been identified (European_Commission 2020), namely:

1. Individualized human–machine interaction for greater innovation power,
2. Bio-inspired technologies and smart materials for a transition to a more nature-friendly world: an advanced bioeconomy,
3. Digital twins and simulation to model complex systems in their entirety and the interconnections between these different systems,
4. Data transmission, storage and analysis technologies to enable data interoperability in a secure manner,
5. Artificial intelligence to improve complex decision-making processes, and
6. Technologies for energy efficiency, renewable energies, storage and autonomy, mainly to reduce greenhouse gas emissions: an active fight against global warming.

Thus, I5.0 technology will open doors to applications such as smart education, intelligent healthcare, supply chain management, disaster management or cloud manufacturing (Maddikunta et al. 2021) and will thus bring maximum flexibility to production and manufacturing procedures with greater power of innovation thanks in particular to synergy between human intelligence and the intelligence of autonomous systems. These attractive benefits seem to be driving organizations to accept, adopt, and standardize more advanced technologies. Specifically, in the manufacturing and production sector, thinking about the new tools needed to achieve the long-term goals of I5.0 has already begun (Table 2) (Nahavandi 2019).

From the beginning of the fourth industrial revolution, a collective awareness about the need to integrate the notion of sustainability in the development of industry emerged. As shown in the literature review by Kamble et al. (2018) as well as the bibliographical review by Tavares-Lehmann and Varum (2021) on I4.0, many studies focus on adopting the concept in I4.0 to reconcile economic growth and environmental protection. The research highlights the major role of artificial intelligence and the relevance of Big Data for the deployment of sustainable supply chains. Substantial investments from government agencies have enabled and continue to enable the implementation of new technologies and the deployment of appropriate infrastructure. The Green Deal project (Commission_European 2019) followed by the Fit for 55 initiatives (Conseil_de_l'Union_européenne 2021)

Table 2 New technologies for I5.0 production and logistics systems

Development of I5.0 tools	I4.0 technologies requested	Added value for the future industry	Objectives of I5.0	Axis
Interoperability of networked sensor data	Big Data processing	Faster customization processes	Improved decision-making with distributed intelligence on the network	Resilience
Multiscale dynamic modelling and simulation	Cyber-Physical System (CPS), digital twins (DT)	Increased quality and cost reduction	Waste reduction in process flow and system design	Sustainability
Trackers	Internet of Things (IoT) and machine learning (ML)	Improved real-time production monitoring	Optimal and efficient management of resources and reduction of material waste	Sustainability
Virtual training	Virtual and augmented reality combined with Big Data and artificial intelligence (AI)	Creation of a qualified workforce	Reduction of health and safety risks for workers	Human
Intelligent autonomous systems	Artificial intelligence	Ability to make decisions under unforeseen circumstances	Securing knowledge transfer	Resilience
Sensor technologies and machine cognition	Machine learning (deep and reinforcement)	Faster customization processes	Primitive vision, sensory abilities, and emotional intelligence enhancement (cobots)	Human

will force industry leaders to consider environmental factors as a design requirement and thus focus part of research and innovation on bionics or to a larger extent synthetic biology (Sachsenmeier 2016).

Contrary to sustainability, the I4.0 literature is sparse on the impacts of individual technologies on humans and does not consider their repercussions on system performance. However, significant advances in artificial intelligence and robotics research show that humans are on the eve of a close interaction with robots and more generally with technology in both the workplace and personal life. Thus, I5.0 involves several challenges regarding the integration of robots or cobots (collaborative robot) if the goal is to maintain the central place of humans in organizations and in society (Demir et al. 2019):

- The evolution of ethics, behaviour, and organizational and social structures;
- The changing role of humans through education, training, and acceptance of robots in the workplace;
- Trust (for employees) and confidentiality (for employers) for successful collaboration, human–robot co-working; and
- Regulation and jurisdiction regarding the ethical issues of robots in the work environment and in the daily life of humans.

These main issues make it possible to consider it a design requirement and not as a cost.

More generally, I5.0 involves more research organizations from different sectors than I4.0, each with their own contributions, technologies, and challenges. Despite a lot of room for interpretation and a somewhat different vision, Industry 4.0 and Industry 5.0 remain management concepts at heart. The goal of mass production has focused on the development of I4.0 on technology. CPS combined with IoT, cloud computing, Big Data and artificial intelligence have made it possible to create “smart factories” or “smart manufacturing”. I5.0 calls for environmental care while supporting intelligent autonomous system development contingent on worker and social well-being. Future research seems to focus on new applications of 4.0 technologies to support the bioeconomy and human–robot co-working (Madsen and Berg 2021). However, fundamental concerns of the future industry must be put forward (Özdemir and Hekim 2018):

- How to reduce the vulnerability of highly integrated systems to systemic risks?
- How to build new, fair, and equitable social and political power structures?

Answers must be found in the coming years. This is beyond the scope of this research. We present here a reading of the paradigm supported by I5.0 (human-centred, resilient, sustainable) on both the conceptual level and in terms of its implementation.

1. This article focuses on the consideration of the impacts of new technologies in the industry on human beings in their work environment. The objective is to provide a solid foundation for a field that forces managers to reconcile economic growth and worker well-being in order to design human-centred technological systems.
2. This article also aims to consider the industry impact (positive and negative) on the environmental and social aspects. The objectives here is to inspire the managers to acknowledge the repercussions of disruption on long-term business viability and to identify alternative solution that led to sustainable business on all areas while minimizing their impact.
3. This article also emphasizes the importance of enhancing the efficacy of mitigation strategies and encouraging turning complex systems into adaptive systems that can adapt to unpredictable hazards and events. The objective is to move towards a solution that ensure industrial stability in an ever-changing environment.

Our work is an integral part of a global methodology, presented in Sect. 4, which integrates these three objectives within the framework of asset management.

4 Global methodology: strategic decision-making for technology development and implementation of I5.0 within an asset management framework

The development of technology is the driving force behind industrial revolutions and its direction has always been motivated by return on investment in the industrial sector. However, the development and implementation of new technology are motivated in I5.0 concept by human and environmental well-being beyond economic growth. The challenge is therefore how to govern the technological evolution and purposefully guide the process of centralizing workers, sustainability, and resilience within I5.0 to move toward the desired scenario.

Industry can be viewed as an interdependent system of systems, where the interaction between its various dimensions (operational, organizational, financial, etc.) makes it difficult to accurately predict its behavior or evolution. The behavior of the system cannot be determined solely by the characteristics and behaviors of its individual parts, leading to emergent behavior. In such an environment, resilience helps to analyze the impact of rare and extreme events (that are generally unpredictable) on complex systems.

Incorporating resilience into asset management would enhance the efficacy of mitigation strategies, turning complex systems into adaptive systems that can adapt to unpredictable hazards and events.

The concept of human centricity invites a fundamental consideration of human aspects in the design and development of technologies interacting with humans, in particular collaborative systems, in order to optimize the performance of the new tools, and to reduce the risks related to the use of such tools or to their impacts (social and societal). Reducing such risks favours their dual in terms of resilience; the concept of human centricity is key for a system to be resilient. Moreover, rethinking sustainability, rethinking the role of humans within productive organizations and rethinking the interactions of humans with their environment over the long-term from an internal perspective implies resilience, and from an external perspective implies sustainability. Thus, if it is a matter of resilience versus human centricity or sustainability versus human centricity, for an interdependent system to be resilient and sustainable, respectively, it must maintain the conditions of its equilibrium and control its impact. Failure to do so would be synonymous with risk that the system will have to face and could consequently affect its resilience and sustainability. Human centricity is a necessary condition in this new approach. Moreover, as explained in Sect. 2, the concepts of resilience and sustainability are deeply interconnected. However, resilient processes do not necessarily lead to sustainable transformations and conversely sustainability policies may be in opposition to future resilient processes.

Through this analysis, we argue that a non-human-centric organization could not be a resilient organization, just as a resilient system could not lead to a sustainable system. Similarly, a non-sustainable organization could not lead to a human-centric and resilient organization. This interconnection needs to be constantly brought forward when standardizing the human-centred concept, the resilience processes and the sustainability outcomes, in order to invite a new way of thinking that induces a new way of doing and not just a single way of doing (methodology change).

To better understand the influence of technological evolution on Industry 5.0, and the impact of industry transformation on the asset management process, this paper proposes a comprehensive framework (Fig. 5) that aligns technology evolution with the I5.0 process of worker centralization, sustainability, and resilience within the overall asset management framework. The systematic consideration of the three

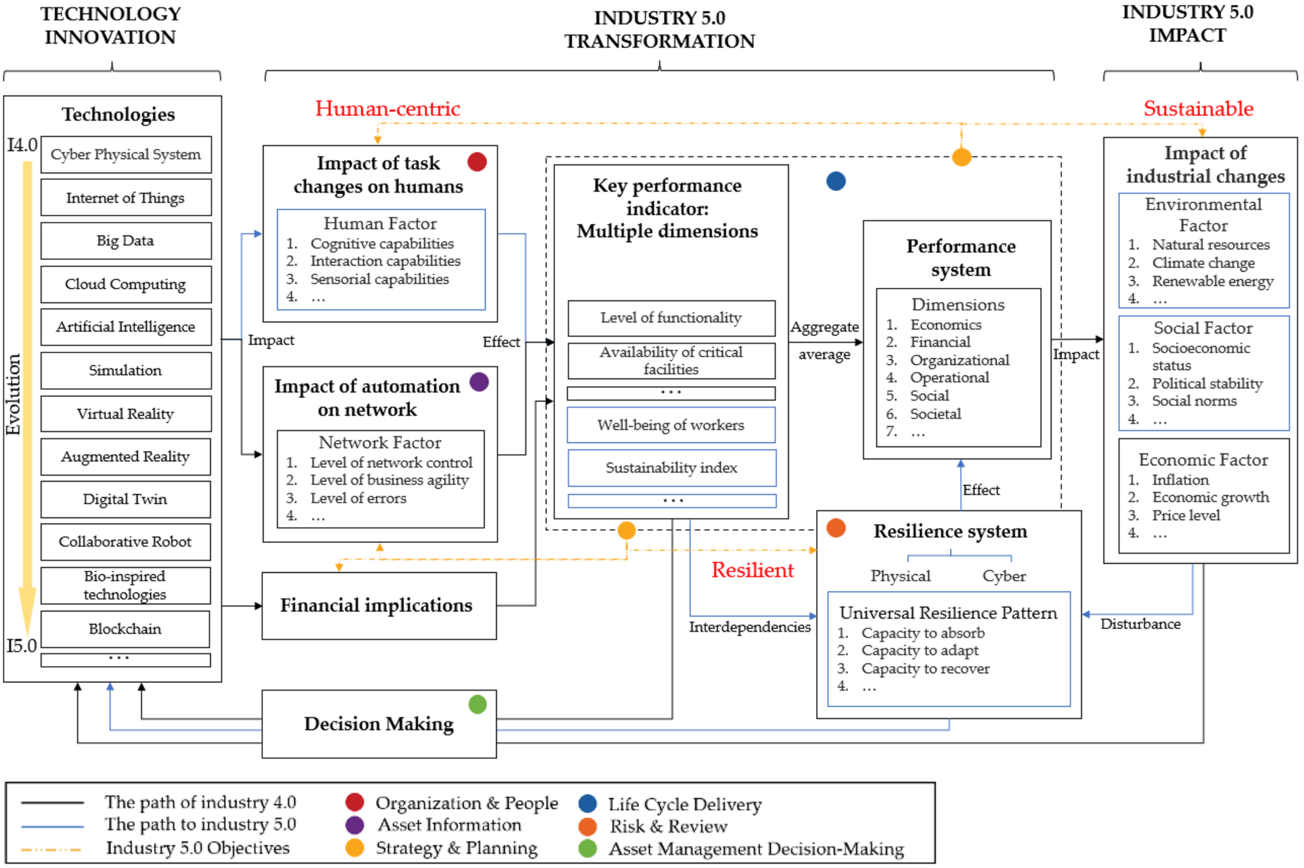


Fig. 5 Toward Industry 5.0: a design model for human-centred, sustainable and resilient systems. Author's own design

core values of I5.0 leads to strategic decision-making for the design and implementation of future technology tools.

Figure 5 models the influence of technological innovation on industrial evolution and its impact on different levels: environmental, social, and economic. As presented in the Sect. 2, the conceptual asset management model generally describes the role of asset management through pillars or subject groups. Figure 5 represent the organization & people, asset information, strategy & planning, life cycle delivery, risk & review, and asset management decision-making pillars by colored dots. Each one is associated with one or more black boxes. The black boxes represent the industrial design principles that require integration of certain elements (represented by blue boxes) and extension of others (represented by black boxes). Each of these black boxes should contains all asset management subjects (related to the associated pillar) that explain the asset management activities of an organization depending on its need and objectives. Figure 5 only illustrates the interactions between subjects that need to be in-depth and the elements that need to be added and pillars for the I5.0 industrial need. The complex inter-relationships between this subject are draw using different arrows. The I4.0 trajectory is depicted in black lines and the evolution to I5.0 in blue lines.

In the actual landscape, when decision-maker considers the integration or development of a technology within their organization, the principal questions to ensure alignment with organizational goals and feasibility are the benefits and value addition on the system performance (part of the group subject asset information system) and the cost implication and return on investment (part of the group subject strategy & planning). The implementation of the technology in the industry improves the control of the activities (part of the group subject life cycle delivery). With a setback, we can clearly see an economic impact. These dynamic changes force organizations to use technological tools differently, or to adopt new technologies (part of the group subject asset management decision-making). This looping process (model by the black arrows) is not adapted to the industry's new challenges.

To address this issue, the first step is to consider the impact of new technologies on the human task and their effect on the system performance. When human factors are integrated in the asset management process the decision-maker could drive the evolution of the technology by place the human as a worker at the center of the industry while continuing to ensure a value add on the network factor and respecting financial restrictions.

The second step is to understand the impact of industry transformation on the environmental, social and economic factors. Each industry sector, and indeed each organization, should assess the impact and identify the consequences on its operational environment. When these elements are considered in the "risk & review" and "strategy & planning" pillars, the decision-maker could drive the evolution of the technology to support the process of sustainability without limiting it to the economic level.

The third step is to ensure that the effect of the human task changes on the organization KPIs and their interdependencies are properly considered in the resilience models and conduct resilience assessments on environmental, social and economic disturbance (and not restricted to the economic side). This enables decision-maker to force the development or adaptation of new technology with a view to maximize the human well-being in the workspace and to minimize the impact on environmental and social factor on a long-term perspective.

The last step is to delve into and establish a clear view of the complex inter-relationships between these new subjects (establish in the step 1 to 3) and all other current subjects implemented into each subject group or pillar of the asset management. Different industry sectors may have varying perspectives of these connections, but it is crucial to integrate them in a way that ensures they play an essential role in the management of the system without treating any of these new subjects as freestanding.

The path to achieve the I5.0 objectives (human centricity, sustainability, and resilience) is represented by orange dotted lines. These connections highlight the new interaction between elements of pillars "strategy & planning", "organization & people" and "risk & review". Human factors assessment is now related to the performance results. Additionally, the KPIs interdependencies and environmental, social and economic disturbance are integrated in the resilience assessment of the organization and its effect on the overall system performance is considered.

The previous four main stages describe how the asset management process could drive the technology innovation. This explanation offers a clear overview of the key elements of asset management that will play a central role in the upcoming industry I5.0. To grasp why driving technological innovation through the asset management process might be a potential catalyst for achieving Industry 5.0 objectives, we outline the four steps as follows:

Step 1. *Govern the technological evolution in order to place the human (as a worker) at the centre of the industry.*

The development and deployment of new technologies allow the path toward automation and digitalization of increasingly complex and interconnected networks to continue. However, this process affects human tasks at almost every level and the apparent changes in cognitive, interactional, sensory, psychosocial, and more capacities affect human performance. To date, the effect of human factors on human performance has been ignored since the joint goal of well-being and performance is often perceived in the literature as being in conflict. By jointly considering the effectiveness and efficiency of technology input into the system (the relationship between human performance and the "human-centred" objective of the I5.0 strategic plan and the means implemented, respectively) in the performance indicators, decision-makers will be able to direct technological evolution to be human-centred in the industry while maximizing network performance and minimizing costs. In this way, the model addresses the lack of attention paid to humans in I4.0 research and development.

Step 2. *Guide technological evolution to support the process of environmental, social and societal, and economic sustainability.*

Economic sustainability has been the focus of I4.0. However, the goal of growth has generated mass production that contributes to climate change. The increase in the occurrence and severity of disruptive events has therefore made governments and industry aware of the importance of respecting environmental limits. Moreover, the clear decline in the ratio of the number of new jobs created to the number of jobs lost by the accumulated automation of the I4.0 and the lack of solution has a significant impact on the social and more generally societal level. Thus, the model seeks to consider the impact of these three factors or dimensions and their effects on the long-term performance of the system. By incorporating this concept (known as the Triple Bottom Line) into the model, decision-makers will be able to support, in an equitable manner, the development of technologies to achieve the goal of sustainability.

Step 3. *Lead the technological evolution to establish a physically and cyber resilient industry.*

The increasing complexity and interdependence of systems make them more vulnerable to systemic risks. It is therefore imperative to integrate a resilience indicator that assesses a system's ability to effectively reduce both the magnitude and duration of deviation from the target system's performance level. Depending on the objectives and the means implemented, criteria are used to evaluate the performance of the system on each dimension (economic, operational, societal, etc.). The "multidimensional KPIs" represent a sort of summary dashboard of all these criteria. The level of these indicators affects a system's restoration process after a disruptive event. Assessing resilience will help inform decision-making and guide technological evolution in response to fluctuations induced by small or large-scale disturbances. The model thus aligns with the goal of transforming the industry into a resilient provider of prosperity.

Step 4. *Integrate technology evolution processes into the overall asset management process.*

Changing customer expectations, increased competition from new digital entrants, tougher regulations, or the need for digital transformation across the enterprise all mean that the asset management process must continuously evolve. To create a new techno-social environment, decision-makers need to make stronger connections between I5.0 processes, outcomes, and values. The key elements of I5.0 redefine, in a sense, the balance between the notions of cost, risk, and performance leading to a greater and deeper focus on certain aspects of the asset management process. As previously discussed, asset management and industrial evolution processes are indissociable and Fig. 5 highlights the potential impact of I5.0 on the asset management pillars. As seen in the figure, the impact on humans and the resilience system are directly linked to I5.0, making it crucial to re-examine and adapt these principles for the upcoming human-centred and resilient industry. The proposed model therefore indirectly initiates the first steps of this reflection.

5 Discussion

5.1 Framework developed process

After understanding industry best practices and standards in the asset management, identifying the actual challenges of Industry I4.0—especially its negative impacts on social and environmental aspects—and highlighting the objectives of the new vision of the Industry I5.0, it became clear that there's a need to establish connections between the new industrial objectives and the asset management process. As most organizations rely on conceptual asset management models (that are constantly evolving to meet changing needs) to identify what is required to be in place for management system, we aimed to introduce a complementary approach to these models. Our approach aligns the necessary and complementary elements to be considered for Industry 5.0 management system.

5.2 Framework's user

The proposed model is intended for organizations and research institutes that have an interest directly in the management of physical assets. Asset management organizations that contribute to the continuous development of the asset management process are invited to delve deeper into or adapt certain elements of the framework with the aim of advancing conceptual asset management models in line with the objectives of I5.0. Governmental institutions can draw inspiration from the model or use it as a basis for developing tools for decision-making regarding investment policies in technology development. Our upcoming research will expand the concept to the public sector and present a comprehensive model and complementary to the conceptual asset management model, thus facilitating the transition towards an industry where technology is at the service of the human.

5.3 Application and utilization of the framework

This model was developed in recognition that asset management standard for asset management would identify what is required to be in place for the management of I5.0 systems but would not address how asset management could be implemented. This paper provides the initial step in expanding the asset management process to the human-centered, sustainability and resilience factor, considering the interdependence of these three concepts. To implement the framework, an organization should focus on three key aspects:

1. Determining the measurement of task changes' impact on human workers.
2. Recognizing the influence of industrial changes on the environmental and social dimensions.
3. Evaluating the system's resilience based on the specific nature and context of the organization.

These components constitute the "blue box" within the model.

To achieve this, initial steps involve defining human factors, quantifying the impact of emerging technologies and considering their effects on Key Performance Indicators (KPIs). Subsequently, specific environmental and social factors must be chosen, tailored to the organization's domain, to identifying potential short and long-term disturbances. Finally, the impact of resilience levels on the system needs quantification, considering interdimensional dependencies and potential disturbances, and incorporate these findings into the decision-making process. Each of these components should be incorporated into the organization's asset management process, illustrated in Fig. 5.

Additionally, the "black boxes" of the model are expected to already be functional within organizations following structured asset management processes, allowing to understand aspects such as the automation impact on networks and its financial implications, as well as the consequences of industrial changes on economic dimension.

Once all the elements are in place, an iterative process can be employed across diverse technological tools or implementations to identify strategies that optimize worker well-being, curtail environmental and societal impacts, and foster resilient, sustainable systems. This approach empowers organizations to harmonize their goals with Industry 5.0 principles.

5.4 I5.0 objectives integration in asset management

The way an organization operates and its culture, combined with the skills and knowledge of its employees, shape the processes that support effective asset management. The integration of new technologies into the management process can bring changes to the organizational structure and culture, which can impact the performance of workers at almost every level. To achieve optimal balance between technological evolution, organizational environment and performance, it is important to consider the human factors in the asset management process. This includes the impact of technology on human interactions and how human capabilities and limitations must be taken into account in the design of these technologies. The integration of human factors into the organizational structure and culture, and competency management will help reflect the evolution of performance and address both positive and negative impacts.

On the other hand, to properly assess resilience, it is necessary to understand it as the opposite of risk and establish a consensus on both the procedures and processes for resilience analysis. According to the terms used in the literature, it's difficult to determine if resilience should be an integral part of the risk management process or defined as an independent, yet complementary process to risk management. When resilience is defined as a measurable capability or set of capabilities of a complex system, the proposed resilience evaluation processes are usually independent of the risk management process. However, another view is that these capabilities create the resilience of a system, defining a system's resilience as "the risk of not achieving desired functionality, for a specific time, after an event." In other words, a system is considered resilient if the risk of not achieving desired functionality is low enough. In this case, the resilience and risk process are intrinsically integrated (Logan et al. 2022). This second approach allows for resilience to be implemented through disaster risk reduction plans, making the practice of resilience easier in some sense. To that end, some approaches aim to minimize expected performance loss by evaluating all possible scenarios of random, cascading, or spatial failures to optimize the restoration strategy/planning for system components and thus maximize resilience (minimize the risk of not achieving desired functionality) (Alkhaleel et al. 2022).

Recently, research has integrated the notion of extreme event risks (weather events, pandemics, etc.) into the risk management process (Komljenovic et al. 2016). This has marked an important evolution in the field, leading to new risk evaluation models that can quantify the impact of extreme disturbances. Some studies have shown the need to expand risk evaluation by including new factors (social, environmental, etc.) to better capture the interactions of a system and improve the management process (improve resilience) to maintain networks (Mentes and Turan 2019). In a complex environment where information changes and new types of events occur, many emerging global challenges are emerging. Today, the integration of the resilience concept complements risk analysis tools (Zio 2016). In this direction, the European Commission has provided a first uniform and comprehensive methodology for risk and resilience evaluation. The project results are integrated into the new ISO 31050 standard currently under development (Jovanovic and Roylett 2022). The European Commission supported the Smart-Resilience project, which resulted in an innovative concept for quantifying resilience called the "resilience cube" (Steinbeis EU-VRI GMBH 2019). The process is based on a composite resilience indicator made up of expert opinions (semi-quantitative), measured values (quantitative), and Big Data values (a new addition to resilience evaluation). All dimensions of resilience and different phases are integrated, but for simplicity, the interaction/interdependence between dimensions is not necessarily considered. The goal is to make resilience evaluation easily and quickly integrated into operating platforms. To address this gap, our research is focused on developing a resilience metric based on big data analysis. The increasing availability of data in industry opens doors to the development of objective global functions based on big data, capable of capturing the dynamics and interdependence of the state parameters of each dimension (Sonal and Ghosh 2022). In this view, we aim to derive a multidimensional objective function suited for complex systems that reflects changes (positive or negative disturbance) in one of the system's weighted parameters.

To improve the asset management process and make it more mature, it's crucial to drive the development of technology into tools that help the industry handle disruptions and maintain sustainability (such as standardizing the resilience assessment process). The impact of industry changes must also be integrated into the asset management process to balance economic activity while ensuring environmental responsibility and social progress.

6 Conclusion

This study presents a comprehensive literature analysis of the impact of I5.0 (human-centred, resilient, sustainable) on both the conceptual and practical levels. The current asymmetries of I4.0 must be evaluated to achieve the objective of an efficient, responsible, and resilient innovation ecosystem design. The paper raises a significant question about the evolutionary direction of asset management process and offers a fresh perspective on how industries can progress with a more holistic and inclusive approach. This involves driving technological advancements to place the human (as a worker) at the center of the industry, to support the process of environmental, social, and economic sustainability and to establish a resilient industry. The human-centred perspective is crucial in promoting effective technology design and incorporates responsibility in terms of environmental and societal impact. The concepts of resilience and sustainability, which have been previously studied on their own, require a convergent analytical formalism, numerical tools, and technologies.

In the literature, no universal or general methodology explicitly describing the convergence of human-centred industry, resilience processes, and sustainable outcomes in asset management has been proposed. The main areas for further exploration of human resources, organizational resilience, and sustainability within the context of asset management have been identified. This research aims to contribute to the development on the private sector (manufacturing and industrial systems) of a new model that supports the evolution of complex technological systems and aligns with the emerging techno-social environment. The public sector infrastructure systems asset management is beyond the scope of this paper. Our future studies will aim to extend the scope to the public sector. To demonstrate the feasibility and the efficacy of our proposed framework, a practical application is essential. As presented in the paper, this practical application should focus on three keys elements. In this way, we started to develop a universal approach for evaluating the resilience of the energy production system considering the interdependency of the different dimension. Our research will continue with a focus on developing the remaining elements required for a comprehensive practical application. We've started an in-depth work, but it's still in progress and will be a forthcoming component of our research.

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Declarations

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