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Behind the definition of Industry 5.0: a systematic review of technologies, principles, components, and values

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ABSTRACT
This study addresses the emerging concept of Industry 5.0, which aims to tackle societal concerns associated with the ongoing digital industrial transformation. However, there is still a lack of consensus on the definition and scope of Industry 5.0, as well as limited understanding of its technological components, design principles, and intended values. To bridge these knowledge gaps, the study conducts a content-centric review of relevant literature and synthesizes evidence to develop an architectural design for Industry 5.0. The findings reveal that Industry 5.0 represents the future of industrial transformation, offering potential solutions to socio-economic and environmental issues that were inadequately addressed or exacerbated by Industry 4.0. The study provides managers, industrialists, and policymakers with a comprehensive overview of Industry 5.0, including its technological constituents, design principles, and smart components, emphasizing the importance of stakeholder involvement and integration for effective governance of digital industrial transformation within this framework.

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1. Introduction

While the literature provides controversial reports on the Industry 4.0 progression across various industries and regions [1,2], there are some debates on the prevalence of the fifth industrial revolution [3]. This conflicting pattern primarily manifests in the European Commission proposing the Industry 5.0 agenda in early 2021 while acknowledging that Industry 4.0 is far from its maturity [4]. The majority of current debates across high-level scientific, industrial, and policy-making institutions center around how the Industry 5.0 concept should be understood against Industry 4.0 [5]. Addressing these debates requires a comprehensive understanding of the Industry 4.0 concept, technologies, and principles. Thanks to the countless academic contributions to this discipline, the knowledge of Industry 4.0 and its capabilities has significantly advanced [6]. Industry 4.0 was first conceptualized as implementing the underlying technologies within the factory's four walls [7,8].

Nevertheless, this phenomenon is nowadays regarded as a paradigm shift in value creation and delivery involving the digitalization of all value partners [9]. In reality, the ripple effect of Industry 4.0 has reached far beyond the manufacturing industry [10], giving birth to unconventional concepts such as Agriculture 4.0 [11]. Previous studies have developed and presented numerous frameworks, architectural designs, and models to explain better the functionalities of Industry 4.0 and the underlying technologies. Contrary to Industry 4.0, the Industry 5.0 phenomenon is significantly understudied [4,12]. The technological constituents, components, and functionality of Industry 5.0 are ill-defined, and scholars lack a consensus in differentiating this phenomenon from its predecessor [13]. While preceding industrial revolutions took decades to unfold, Industry 5.0 seems to coexist with Industry 4.0 as a parallel phenomenon, causing much confusion and skepticism regarding the trajectory of the ongoing industrial revolution [14]. Industry 5.0 advocates offer two diverse perspectives while explaining the driving force behind this phenomenon. The first perspective assumes that the unprecedented growth of disruptive technologies such as 6 G, Artificial Intelligence (AI), and cognitive computing is revolutionizing the future of the workplace, seamlessly integrating humans with machines and the technological world around them [15,16]. The second perspective holds a holistic techno-cultural view of Industry 5.0 drivers and argues that this phenomenon directly addresses two significant drawbacks of Industry 4.0: technology and profit

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centricity [17,18]. The latter perspective has been recently propagated by the European Commission's agenda for Industry 5.0, arguing that this phenomenon must prioritize an eco-friendlier, human-centric, and resilient industry [4]. The controversies associated with Industry 5.0 are expected, given that this phenomenon is embryonic, and academia has yet to explore it in detail [19,20]. Accordingly, this study aims to address the following objectives:

- To explore the enabling technologies of Industry 5.0.
- To explain the techno-functional principles and components of Industry 5.0.
- To identify the Industry 5.0 strategic values.

The present study addresses this knowledge gap by developing an architectural design for Industry 5.0, which involves exploring and describing this phenomenon's technological constituents, techno-functional principles, components, and the scope of impact (intended values) that collectively contribute to the new human-centric, sustainable, and resilient manufacturing economy. To this purpose, the study conducts a content-centric review of Industry 5.0 academic literature and draws on evidence mapping to identify how Industry 5.0 and its constituents can fulfill the said objectives.

2. Literature review

This study follows the guides provided by Watson and Webster [21], for a content-centric literature review to identify the components, functions, and scope of Industry 5.0. Figure 1 describes the steps undertaken for this purpose. The systematic review process started with step A1, which included identifying the relevant documents within Scopus and Web of Science databases using the keywords shown in Figure 1 (step A1). The study included "society 5.0" within the search string since the concepts of Industry 5.0 and Society 5.0 appear to share many grounds [22]. The initial search within the two databases collectively identified 568 unique documents.

Step A2 involved defining the three exclusion criteria. In step A3, the 568 documents identified in step A1 were subjected to the exclusion criteria, leading to a shortlist of 52 papers. Next, the backward review of eligible documents was conducted (step B1), which involved the backward assessment of the 52 eligible documents identified in the previous step to identify other related documents requiring further consideration. Step B1 led to identifying 64 documents. In step B2, the 64 newly identified documents were subjected to the exclusion criteria, leading to 13 additional eligible documents. As a result, the extended pool of eligible documents included 65 documents (52 + 13). Step C1 involved the forward review and identifying additional related documents citing the 65 eligible documents using Google Scholar and Web of Science, which identified 33 additional documents. Through step C2, the 33 newly identified documents were subjected to the exclusion criteria, and, as a result, 7 additional eligible documents were shortlisted. By the end of step C2, the final pool of eligible documents consisted of 72 (52 + 13 + 7) documents.

In step D, the two content assessors performed the evidence synthesis and independently scrutinized the content of each eligible document qualitatively. The content assessment team strictly followed the necessary steps to ensure the validity and reliability of the content analysis. These steps, for example, involved designing and following a comprehensive review protocol and the underlying coding scheme, text denoising procedure, data management, and collaborative disagreement tracking. As Industry 5.0 is in its embryonic stage, including gray literature like the European Commission Industry 5.0 directives [23] helps better dissect the ongoing trends in technological advancements that sometimes the academia lag behind. The advantages of benefiting from the gray literature, such as reducing publication bias or enriching the overall findings, have been widely acknowledged [24]. Therefore, the content-centric review of Industry 5.0 literature was complemented by the selective review of Industry 5.0 gray literature, primarily identified across the forward and backward review steps.

3. Methodology and content synthesis

Industry 5.0 appears to be unfolding, making it hard to define within the scholarly literature. Industry 5.0 builds on the idea of Industry 4.0 to represent a socially pulled and technologically pushed digital transformation phenomenon. Therefore, the study drew on the Industry 4.0 literature (e.g [1; 25]., to contextually define Industry 5.0 based on its underlying technologies, design principles, and components to address the vagueness surrounding this concept. The Industry 4.0 literature proposes that the digital manufacturing ecosystem under Industry 4.0 consists of several components, such as smart factories, smart suppliers, and intelligent customers [1,26]. Industry 4.0 transformation also entails manufacturers integrating a large spectrum of mature standard technologies and emerging disruptive technological innovations [27].

Similarly, the study proposes that integrating various standard and emerging technologies across the entire value network is at the heart of the Industry 5.0 transformation agenda. Alternatively, scholars argue that manufacturing digitalization under Industry 4.0 also involves developing necessary design principles that allow components such as smart factories to leverage technological constituents effectively [26,28]. Consistently, the content analysis also identifies the

Step A1: The initial identification
Objective: Identifying relevant documents within Scopus and Web of Science databases
Search string: (TITLE-ABS-KEY ("Industry 5.0") OR TITLE-ABS-KEY ("fifth Industrial revolution") OR TITLE-ABS-KEY ("5IR") OR TITLE-ABS-KEY ("5th Industrial revolution") OR TITLE-ABS-KEY ("society five") OR TITLE-ABS-KEY ("Society 5.0"))
Documents identified in stage A1: (n=568)

Step A2: Defining exclusion criteria
EXC1) The document does not have its main body of text written in English.
EXC2) The document uses keywords such as *Industry 5.0* merely as a cited expression.
EXC3) The document does not discuss the definition, scope, components, or functionality of Industry 5.0 whatsoever.

Step A3: Screening
Documents removed due to EXC1 (n=18), EXC2 (n=202), and EXC3 (n=296)
Total number of documents excluded in step A3 (n=516)
Total number of eligible documents identified in step A3 (n=52)
The initial pool of eligible documents (n=52)

Step B1: Backward review
Going backward by reviewing the documents cited by the 52 documents identified in step A3 to determine prior *related* documents that require consideration.
Documents identified in step B1 (n=64)

Step B2: Screening
Article removed due to EXC1 (n=2), EXC2 (n=14), and EXC3 (n=35)
Total number of documents excluded in step B2 (n=51)
Total number of eligible documents identified in step B2 (n=13)
The extended pool of eligible documents (n=52+13=65)

Step C1: Forward review
Going forward using Web of Science and Google Scholar to identify unchecked *related* documents citing the eligible documents identified across steps A3 and B2.
Documents identified in step C1 (n=33)

Step C2: Screening
Article removed due to EXC1 (n=1), EXC2 (n=9), and EXC3 (n=16)
Total number of documents excluded in step C2 (n=26)
Total number of eligible documents identified in step C2 (n=7)
The final pool of eligible documents (n=52+13+7=72)

Step D: Content Analysis
Content analysis of eligible documents and identification of Industry 5.0 components, functions, and scope

Figure 1. The process of conducting the content-centric review of Industry 5.0 literature.

design principles that are critical to Industry 5.0 and its values.

Overall, the synthesis of Industry 5.0 literature in the present study involves analyzing the enabling technologies, techno-functional principles, components, and the scope of impact (value) of this phenomenon. Having these synthesis objectives defined, the study implemented a comprehensive evidence-mapping protocol to identify and characterize the available evidence within eligible documents. The research team strictly followed six widely accepted content grouping steps [29] to satisfy the synthesis objectives while ensuring the reliability and validity of the insights extracted. The evidence and insight grouping first involved identifying the key themes that emerged from the Industry 5.0 literature. In the second step, a code was assigned to each instance of a theme under technologies, principles, components, and values of Industry 5.0. In step 3, the assessors grouped the codes into broader themes to better summarize the data and identify the critical findings. In step 4, the assessors extracted the sub-themes in each category (e.g. technologies) to better understand the data. In step 5, the assessors individually reviewed the codes and groups to ensure they accurately represented the data. Further, under this step, the assessors collaboratively reviewed the groupings and tracked disagreements to ensure they captured all key findings. Finally, step six involved summarizing the key themes, groups, and sub-themes and fulfilling the synthesis objectives by identifying various constituents of Industry 5.0.

3.1. Enabling technologies of Industry 5.0

Enabling technologies of Industry 5.0 consist of digital, information, and operations technologies that collectively derive the ongoing and upcoming digital transformation under Industry 5.0. Enabling technologies can be subcategorized into *facilitating technology* and *emerging technology* clusters.

Facilitating technologies such as big data analytics, cloud computing, or enterprise systems are the most fundamental building blocks of Industry 5.0. Most of these technologies were introduced under the third industrial revolution and widely commercialized under the Industry 4.0 paradigm, becoming an indispensable part of most industrial ecosystems [30]. The facilitating technologies characterize differently in complexity, interconnectedness, and how they impact business processes and products. The extant literature has thoroughly investigated the definition, properties, and business implications of facilitating technologies (e.g [1].

The emerging technologies of Industry 5.0 are the most innovative and disruptive technological innovations that build on the facilitating technologies to create more productive yet eco-friendly and human-centric methods of value creation [6]. Industry 5.0 draws on these technologies to offer an environmental and human-centric approach to digitalization and promote societal and ecological values [3]. The evidence synthesis identified nine emerging technologies that support the concept and core objectives of Industry 5.0. The following section describes each of the emerging technologies of Industry 5.0 concisely.

Cognitive Cyber-Physical Systems (C-CCP) is an upgrade over the cyber-physical-social system. Besides acknowledging the role of humans in Cyber-Physical Systems (CPS), communication-wise in particular, it benefits from a certain degree of machine consciousness [31]. Instead of sense-plan-act, C-CCP operates on the sense-analyze-compute-act cycle. Under this cycle, C-CCP can be characterized by the four properties of self-knowledge, self-monitoring, self-awareness, and self-informing, which allow it to respond under all circumstances proactively [32]. C-CPS also recognizes the role of human cognition in the CPS, offering a smoother and safer man-machine interaction across operations [33]. C-CCP is expected to be more effective in pattern detection across ongoing operations, self-recognition, failure correction, and informed decision-making [34]. Sensors, actuators, robotic units, control systems, wireless communications technologies (5 G and 6 G), and the human-machine interface are among the major components of C-CCP [35].

Cognitive Artificial Intelligence (CAI), also known as artificial cognitive intelligence, is the byproduct of integrating AI and artificial consciousness [36]. The existing AI systems, including symbol processing-based and deep learning-based AI variants, have still not reached the pinnacle of their potential. This limitation particularly restricts the implication of AI for C-CCP, where the trustworthiness and reliability of autonomous physical systems are essential. Experts believe that attempting to create qualia out of the vastness of exploratory sensory information in parallel with natural language processing, data mining, and pattern recognition would allow CAI to understand the outside world better and think, re-learn, and act like a human. In turn, this could allow for self-healing AI to emerge that automatically would adopt component changes in the application [37]. CAI would be an indispensable technological constituent of Industry 5.0 as it helps stakeholders make better decisions, reduces information overload, decreases errors, improves health and safety, and generates more sustainable products and services [38].

Human interaction and recognition technologies (HIRT) play a significant role in enabling the human-centricity feature of Industry 5.0. The last-gen HIRT had many difficulties identifying the human's behavior spatial complexity, emotions, and action characteristics [39]. The emerging HIRT under Industry 5.0 agenda aims to optimally interconnect and integrate humans with machines so that the resulting human-machine interaction offers safer, streamlined, and more pleasant physical and cognitive tasks. Vision-guided robotics, short-wave infrared technology, sensor fusion, sensor data triangulation, embedded vision systems, adaptable human intention and trajectory prediction, and multi-lingual speech and gesture recognition are examples of vital emerging HIRT that can play a significant role in Industry 5.0 [40]. No sensing and cognition technology has the necessary emotional intelligence to seamlessly judge the ever-changing working condition and arrive at the best replication of what humans would genuinely do in a given situation. Indeed, HIRT may only deliver its functions while interacting with other technological constituents of Industry 5.0, such as CAI, C-CCP, cloud data, and edge computing [13].

Extended reality (XR) is an umbrella term for various immersive technologies, including traditional and emerging augmented, virtual, and mixed-reality technologies [41]. XR technologies, especially mixed reality, are an essential technological constituent of the fifth industrial revolution, as they offer numerous benefits to Industry 5.0 stakeholders [42]. Improved customer experience, advanced industrial and academic training, real-time immersive fault diagnostic of industrial operations, and improved safety and efficiency of industrial processes are a few examples of XR implications for Industry 5.0 [43]. The XR market is expected to grow within the next decade rapidly. However, the industrial application of modern immersive and XR technologies under the Industry 5.0 agenda might be hindered by particular technical challenges such as data processing limitations, motion tracking, and connectivity issues. Experts believe advancements in big data, edge computing, 6 G, and AI will alleviate these technical challenges as Industry 5.0 advances [44].

Industrial Smart Wearable (ISW) is essential to Industry 5.0 since the human worker will play an ever-more essential role in value creation under this paradigm [13]. The proliferation of more intelligent and advanced industrial wearables would allow workers to perform their tasks safer, faster, and more productively [3]. There is a diverse and growing range of emerging ISW available to businesses, which offer various functionalities in line with Industry 5.0 objectives. Bio-inspired protective gears and exoskeletons can improve industrial workers' capabilities, strength, productivity, and stability. Head-worn ISWs can enhance human operators' navigation and information-sharing capabilities, whereas clothing ISWs can use conductive or optical sensors to monitor and track the vitals of the workforce [45]. Experts even pursue embedded tracking ISW that monitors workers' mental and physical strain and stress. Within the Industry 5.0 context, ISW operates under C-CCP and relies on CAI and Industrial Internet of Things (IIoT) to communicate and interact with other facilitating and emerging technologies such as 3D printers, adaptive-collaborative bots, and autonomous vehicles [46].

Intelligent or Adaptive Robots are the next generation of industrial robotics that allow a higher level of human-centric automation in the Industry 5.0 business environment. Traditional robots are characterized as fast and productive, yet they need to be isolated by physical barriers for safety purposes. Collaborative robots, on the other hand, have been designed to work in collaboration with the human operator safely and without a physical barrier, but at the expense of lower speed and nominal load [47]. Intelligent (adaptive) robots can be regarded as an evolution of traditional and collaborative robots, highly productive robots capable of adapting to complicated environments and novel situations while accomplishing a more extensive set of complex tasks [48]. Precision component assembling, transportation of parts, advanced assembly, and soft-material surface processing are among the many application scenarios of adaptive robots under Industry 5.0 [49]. The prevalence of adaptive robots is expected to grow under Industry 5.0 as computer vision, machine cognition, edge computing, and AI technologies increasingly progress [50,51].

Intelligent Energy Management System (IEMS) offers important implications for energy efficiency and sustainability [1]. Although Industrial productivity as the primary techno-economic objective of Industry 5.0 favors energy efficiency, the digitalization of industrial operations, smart products, connected customers, and the overall overconsumption and shorter product lifecycle intrinsic to the ongoing industrial revolution lead to the rebound in energy demand [52]. IEMS promotes energy efficiency through real-time monitoring and control of energy systems, enhancing the technical and commercial efficiency of energy production, assessing energy quality, and improving the reliability of energy systems [53]. IEMS and the complementing technologies such as cloud demand response systems, smart storage, intelligent charging technologies, microgrids, and blockchain-based peer-to-peer electricity trade help bridge the gap in developing renewable energy resources and integrating them into industrial and commercial operations [54,55].

Dynamic Simulation and Digital Twin (DSDT) technologies pair physical and virtual worlds, allowing proactive data analysis and monitoring of complex systems. DSDT technologies recreate digital representations of existing or impending physical systems such as products, processes, or an entire production line, which allows for tackling design inefficiencies, problems, performance concerns, and even future improvement planning, proactively and economically [56]. Mass personalization is indispensable to Industry 5.0, and DSDT allows for predicting and optimizing the effectiveness and performance of customizable products and reducing the complexity of the underlying manufacturing processes [57]. More importantly, DSDT is crucial to the sustainability objectives of Industry 5.0, as it allows businesses to simulate and predict the digital socio-environmental footprint of their products and services from design, prototyping, and development through end-user consumption and end-of-life-recovery [58]. DSDT technologies are data-driven and build on AI, the Internet of Everything (IoE), big data, and adaptive analytics to integrate historical and real-time data to construct the underlying complex virtual models [6].

Smart Product Lifecycle Management (SPLM) systems provide a more robust integration of processes across the value network, offering an all-inclusive product life coverage [59]. SPLM facilitates process integration and networking by creating digital models of product, service, manufacturing, and supply chain processes. SPLM also plays a critical role in materializing the smart product concept under Industry 5.0. Smart products are equipped with sensors, communication interfaces, processors, and embedded software to provide manufacturers and customers with added value.

SPLM can integrate with smart product embedded software, corporate backend systems, cloud service, and Internet of Services (IoS) to offer complete control of early-to-end stage product data [60]. Overall, smart and integrative SPLM critically contributes to the productivity, servitization, and product circularity objectives of Industry 5.0 by offering authoritative control over product and process data and improving manufacturing productivity, operational agility, environmental compliance, product quality, and end-of-life recovery [12].

3.2. Techno-functional principles of Industry 5.0

Techno-functional principles of Industry 5.0 (also known as design principles) concern the "how to achieve digital transformation" part of this phenomenon. Industry 5.0 design principles are the necessary conditions that allow Industry 5.0 components (e.g. adaptive smart factory and smart suppliers) to effectively leverage the enabling technologies and further contribute to the sustainable development objectives of Industry 5.0. The content-centric review of the literature identified eight techno-functional design principles for Industry 5.0, some of which root in the Industry 4.0 paradigm. These functions are briefly described in the following.

Decentralization entails having a more agile, flexible, and autonomous approach to production via decentralized intelligence to address the complexity of the integrated processes [14]. Under this principle, smart components of the Industry 5.0 ecosystem should operate autonomously and make independent yet informed decisions when necessary [61]. Decentralization relies on data transparency and the interconnectedness of objects and people across value chains. Thus, IoE, cloud data, and C-CPS are crucial to decentralization as they streamline the monitoring and control of the physical world based on which decentralized decisions are made [62].

Vertical Integration entails networking and integrating all processes and business units across an industrial organization, which involves integrating information, digital, and operations technologies, including equipment, machinery, legacy networks, smart material, and even human components [63]. The scope of vertical integration is not limited to the factory floor. It involves interdepartmental activity and process integration across different organizational and functional layers of an organization, from procurement to logistics, product development, manufacturing, and marketing and sale. Process efficiency, improved communications, and manufacturing productivity are the significant benefits of vertical integration [42].

Horizontal Integration involves integrating the internal operations of all value chain members, including suppliers, manufacturing chains, distribution channels, and customers [1]. For manufacturers with distributed production facilities or value networks with multiple manufacturing chains, horizontal integration further involves integrating all production facilities and seamless production data exchange across the manufacturing network [14]. Horizontal integration is considerably challenging due to cyber-security, data ownership, and trust concerns. Horizontal integration is closely tied to technological advancement in machine learning, blockchain, IoE, and cloud and edge computing technologies and significantly relies on developing new cooperation and business models across value network partners [64]. Horizontal integration offers many benefits, such as improved automation, lower production costs, product customization, and process visibility and flexibility [6,12].

The ***interoperability*** principle of Industry 5.0 concerns the ability of industrial systems and their micro components, such as tools, machines, humans, and processes, to meaningfully and reliably communicate with each other across lines of business and throughout the value network. Achieving interoperability is challenging since various operations and information technologies use proprietary communication protocols [16,65]. Within the Industry 5.0 paradigm, removing information silos within smart factories and across the value chain relies on the interoperability function to allow all business subcomponents to exchange and interpret each other's data [40]. Recent advancements in industrial automation solutions, such as smart Ethernet switches and multiprotocol I/O systems that support multiple IT/OP protocols, including SNMP, RESTful, Modbus, and EtherNet/IP, offer exciting opportunities for achieving interoperability under the Industry 5.0 agenda [66].

Modularity refers to the extent to which a complex value chain, including smart production facilities, upstream suppliers, and downstream distributors, can be decomposed into separate activity sub-systems, also known as modules [67]. Product customization, servitization, and more equitable distribution of value are among the fundamental objectives of Industry 5.0, and the modularity principle plays a crucial role in materializing these objectives [68]. Modularity provides businesses the necessary physical and managerial flexibility to re-configure their value chain modules innovatively and creatively and develop new business models and profit tools supporting Industry 5.0. Business model innovation, process flexibility, dynamic material flow systems, product adaptation, and circularity are among the properties of a modular value chain under Industry 5.0 [69].

Real-time Capability ensures that all smart objects and modules of an industrial ecosystem can communicate in real-time when necessary. Real-time capability is central to informed decision-making and selforganizing production consistent with the Industry 5.0 vision [70]. The real-time collection and analysis of production data at the smart factory level offer essential advantages such as more proactive approaches to operations and maintenance, production flexibility, improved energy consumption monitoring, responsive risk management, and failure prevention [14]. However, the value proposition of real-time capability is more salient at the value chain level since real-time insight into the value chain partners via Industry 5.0 technologies (e.g. SPLM) offers invaluable advantages such as value network visibility, supply chain agility, dynamic collaborative planning, emission monitoring, and customer satisfaction [5].

Technical Assistance entails the gradual transition of manual labor to decision-makers or problem-solvers by supplying them with visualized information in real-time and automating exhausting and unergonomic tasks [6]. Technical assistance entails the smartification of the human workforce, meaning new technologies such as ISWs are implemented to tailor industry workers' competencies to the requirements of rapidly evolving industrial systems while maintaining the workforce's rights to autonomy and privacy [13]. Technical assistance does not entail the replacement of the human workforce with autonomous machines. Instead, it promotes workforce-machine symbiosis and gives birth to emerging human-centric concepts such as the social or augmented operator [71].

*The**virtualization*** principle involves creating a digital replica of the business and industrial operations by merging sensor data collected from the physical equipment, assets, and processes across the value network [37]. Virtualization allows engineers and system analysts to structure, redesign, and optimize Industry 5.0 modules and components in complete isolation, thus, alleviating the risk of physical system design inefficiency and failure [23]. The digital replica of industrial operations further allows experts and managers to seamlessly oversee the complexity of business operations and monitor the efficiency and performance of machinery, equipment, processes, logistics infrastructure, and production facilities without disrupting their physical instances [6]. The virtualization principle is crucial to the productivity, profitability, and sustainability of business activities under the Industry 5.0 paradigm.

3.3. Industry 5.0 components

Industry 5.0 represents a paradigm shift involving the digital transformation of value-creating and delivery processes at the micro and macroscopic analysis levels [14]. Therefore, adaptive factories, logistics, suppliers, products, customers, and stakeholders are the major smart components that collectively constitute the hyper-connected socio-ecological value-creating ecosystem under Industry 5.0 [72,73].

Adaptive Smart Factory **(ASF)** concept refers to transitioning from a more traditional semi-automatic and rigid production system to a highly automated, flexible, digitalized, and resilient production system [74]. This concept centers around data-driven manufacturing, which entails system-wide and real-time data collection, integration, and analysis across all production and business functions [75]. The ASF is characterized by agile production processes, product customization capability, energy awareness, productivity, higher product and process innovation capacity, and production reliability [76] [77]. Compared to Industry 4.0, the smart factory under Industry 5.0 is associated with more disruptive technological innovations such as C-CPS, IIoT, IEMS, and CAI [78]. The SAF of Industry 5.0 takes a more human-centric approach to manufacturing and leverages technology to adapt the production processes to the benefit of the human workforce [42,79]. More importantly, the smart factory of Industry 5.0 is adaptive because it can adjust its elements (e.g. production systems or production scheduling) to meet structural shifts in consumer behavior or market dynamics [6,77].

Smart Products can communicate, store, and self-process data and have the necessary integrability to interact with and within the industrial ecosystem. Besides communicating their operational status in real-time, smart products can describe their entire usage and lifecycle history [80]. Under Industry 5.0, smart products are characterized by a wide range of technological properties, from being sensor-equipped and AI-driven to being built from smart or engineered living materials that offer significant self-regulation and environmental responsiveness functions [81]. By communicating the processing and assembly information at the production stage, usage behavior at the consumption stage, and end-of-life recovery information, smart products offer immense productivity, sustainable product innovation, and business model innovation opportunities under the Industry 5.0 agenda.

Smart Customers are at the heart of Industry 5.0, allowing businesses to offer data-driven services [82]. Although smart products can communicate valuable lifecycle data to the manufacturer, their implications for customer engagement and lifecycle management are somewhat limited [3]. Smart customers increasingly integrate with IoP and personal digital devices to interactively communicate with their digital selves and create a collective intelligence network at a global scale. Smart customers can digitally integrate and interact with other smart components of Industry 5.0, communicate their current and future preferences to the product and service provider, and contribute to realizing customer-driven and circular manufacturing under Industry 5.0 [4].

Smart Supply Chain transforms traditional, rigid, and linear supply chains into agile, modular, scalable, and highly interconnected digital supply networks [83]. Smart supply chains use Industry 5.0 technologies such as edge computing, CAI, C-CPS, and IIoT to establish dynamic digital threads between various supply nodes involving equipment, processes, delivery channels, planning platforms, and even customers. It acts on real-time data collection from sensors, connected resources, and distributed systems and uses cognitive computing and advanced data analytics to drive actionable insights [69]. Proactive risk mitigation, cost-effectiveness, asset efficiency, flexibility, and resilience to disturbances (e.g. global crises such as the COVID-19 pandemic) are among the advantages of smart supply chains [84] [83].

Smart Logistics component 5.0 involves adding the necessary autonomy and intelligence to logistics to meet the agility, interconnectedness, productivity, and efficiency requirements of the data-driven and real-time economy [85]. This process involves digitalizing various traditional components of logistics, including supply chain logistics (e.g. local and global operations structure), inbound logistics, outbound logistics (e.g. order-based delivery management), intralogistics (e.g. manual part feeding to production stations), and logistics routing. The smartification of logistics operations relies on the combination of advanced technologies such as IIoT, blockchain, and edge computing [86]. Predictive delivery management systems, autonomous transportation systems, smart warehousing, intelligent shelves, and smart containers are among the major components of smart logistics under Industry 5.0 [87].

The integrative and disruptive force of Industry 5.0 deeply concerns stakeholders all along the entire lifecycle of products and services [4,73]. Industry 5.0 and the underlying digital transformation are expected to impact consumer behavior, innovation lifecycle, employment market, distribution of wealth, workers' rights, and degradation of natural resources globally [88,89]. The smart stakeholder component describes the ability of all Industry 5.0 stakeholders, such as individual manufacturers, suppliers, distributors, technology providers, consultancy firms, universities, and governmental agencies, to interconnect and communicate seamlessly and align with the overall goal of digitalization for sustainable development. Recent technological advancements such as 5 G and upcoming 6 G networks, blockchain, IoE, satellite broadband, and cloud services play an essential role in developing the smart stakeholder component of Industry 5.0 [90].

3.4. Industry 5.0 strategic value

Overall, the content-centric analysis of eligible documents reveals many controversies regarding the expected outcomes of Industry 5.0. For example, Özdemir and Hekim [91], proposed that Industry 5.0 should address the asymmetrical innovation property of Industry 4.0 and further involve resilience to avoid the possible collapse of digital hyper-connectivity. Nahavandi [40] argued that Industry 4.0 and the underlying digitalization systemically disregard the human costs of automation. These scholars proposed that Industry 5.0 should develop smarter and more advanced technologies to facilitate human-centric automation. More advanced sensing and cognition technologies, AI, virtual training, and dynamic modeling and simulation are the necessary technological advancements to facilitate human-automation integration under the Industry 5.0 scenario [40,88]. For example, Javaid and Haleem [57] argue that besides human-centricity, globalization of manufacturing systems and product personalization are the central features of Industry 5.0. Javaid et al. [70] proposed that Industry 5.0 technologies can address the COVID-19 challenges by facilitating personalized therapy and treatment processes. Despite these controversies, the European Commission's most recent policy brief on Industry 5.0 99,100 Empowered scholars to develop a unified perspective on this agenda's drivers and core objectives. Indeed, recent studies such as the work of Goloviankoet al. [62], Ghobakhloo et al. [92], Huang et al. [73], and Leng et al. [93] collectively acknowledge that the driving force behind Industry 5.0 involves integrating inclusive sustainability objectives into the ongoing digital industrial transformation [94].

Figure 2 offers the evidence map for the expected strategic value of Industry 5.0, as the eligible documents propose. This figure draws on the content-centric review results and provides the visual classification of Industry 5.0 expected values based on the analysis and impact levels. The size of each circle in this figure represents the strength of evidence on each value within the literature. Figure 2 categorizes the expected values of Industry 5.0 at three analysis levels (microscopic, mesoscopic, and macroscopic) and within the triple bottom line context (at the economic, environmental, and social sustainability contexts). Results in Figure 2 show that Industry 5.0 is expected to offer a variety of economic values at various analysis levels. For example, manufacturing resilience and business model innovation are among the most expected economic sustainability values that Industry 5.0 delivers at the firm (microscopic) level [93,95]. Supply chain resilience and industrial productivity growth are expected meso-economic outcomes of Industry 5.0 [64,92]. This phenomenon is also believed to offer implications for macro-regional economic development (Renda et al., 2022).

Scholars also believe that Industry 5.0 would lead to several environmental sustainability values. At the firm level, material flow and energy efficiency are among the most acknowledged values of Industry 5.0 [6]b). This framework is also believed to significantly boost sustainability values, such as sectorial waste management at the mesoscopic level [38,96]. Boosting the circular economy and introducing more environmental-friendly products within the global market are among the expected environmental values of Industry 5.0 at the macroscopic level [68,78].

The evidence synthesis of Industry 5.0 literature reveals that this phenomenon does not merely build on technological development for the sole purpose of industrial productivity and profitability [89]. Industry 5.0 is believed to offer various social sustainability values, such as a safer work environment at the firm (microscopic) level [73,97] or employment growth at the regional/global (macroscopic) level [4,98]. Overall, Industry 5.0 promises important implications for sustainable development under the modern manufacturing economy via equitably controlling and managing the economic, environmental, and social bottom line[99].

4. Results and discussion

The study draws on the results of the content-centric literature review and develops the architectural design of Industry 5.0, as shown in Figure 3. This architectural design aims to provide a holistic but detailed overview of the Industry 5.0 concept and its underlying technologies, design principles, components, and strategic values. The developed architectural design proposes that Industry 5.0 is not replacing the Industry 4.0 paradigm chronologically. Instead, it should be regarded as the logical continuation of the existing digital industrial transformation, which can systematically address Industry 4.0 shortcomings in empowering societal and ecological values. Although Industry 5.0 is centered around socio-environmental values, it builds on many features of Industry 4.0, including the idea of merging the physical and virtual worlds through innovative technologies, integrating humans and machines, pushing technological development, and contributing to a more competitive industry. Industry 5.0 covers many technologies, principles, and components associated with Industry 4.0 while shifting from a technological perspective to a human-centered one [96].

Figure 3 illustrates the logical interactions between Industry 5.0 technologies, principles, components, and values discussed in the previous sections. The architectural design builds on technological determinism and proposes that Industry 5.0 is a socio-technological phenomenon, meaning technological advancement under Industry 5.0 will inevitably determine the socio-cultural values and economic structures of the new manufacturing economy. Thus, the enabling technologies constitute the primary building block of the Industry 5.0 archetype in Figure 3. Industry 5.0 builds on widely commercialized facilitating and disruptive emerging technologies to develop essential techno-functional design principles. Industry 5.0 adapts many of its design principles from Industry 4.0 but takes them to the next level. For example, Industry 5.0 extends the concept of modularity to the supply

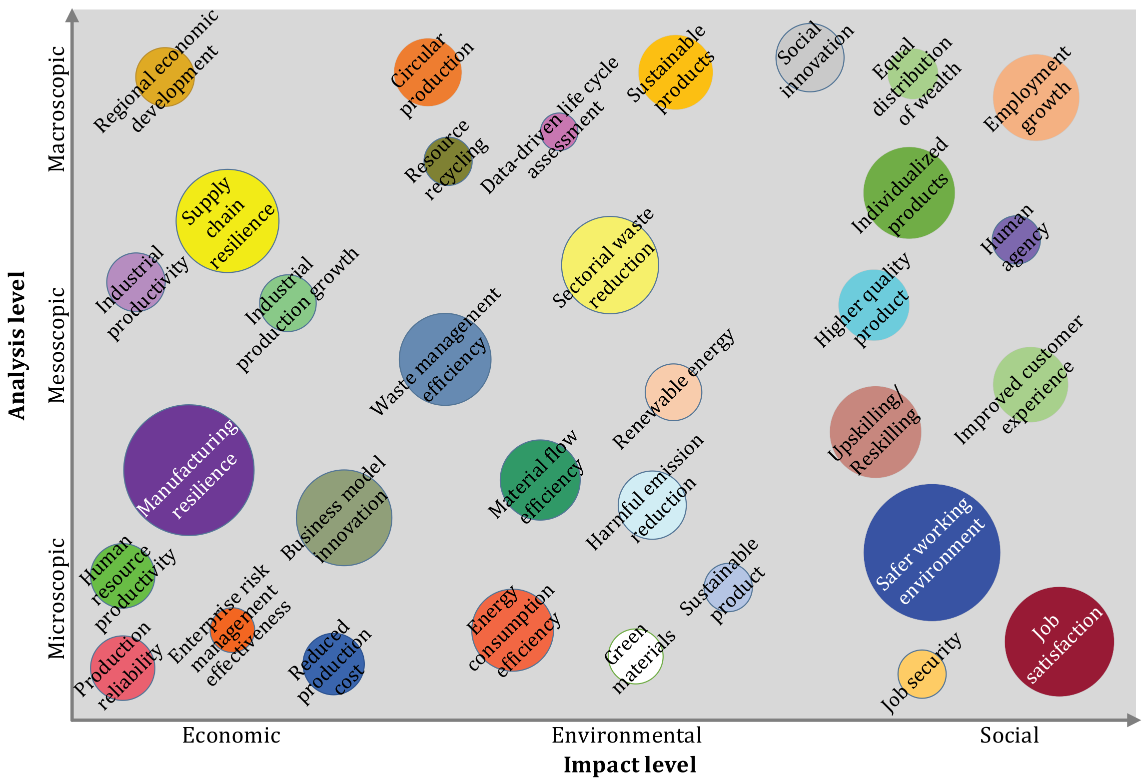

Figure 2. The evidence map of Industry 5.0 expected values.

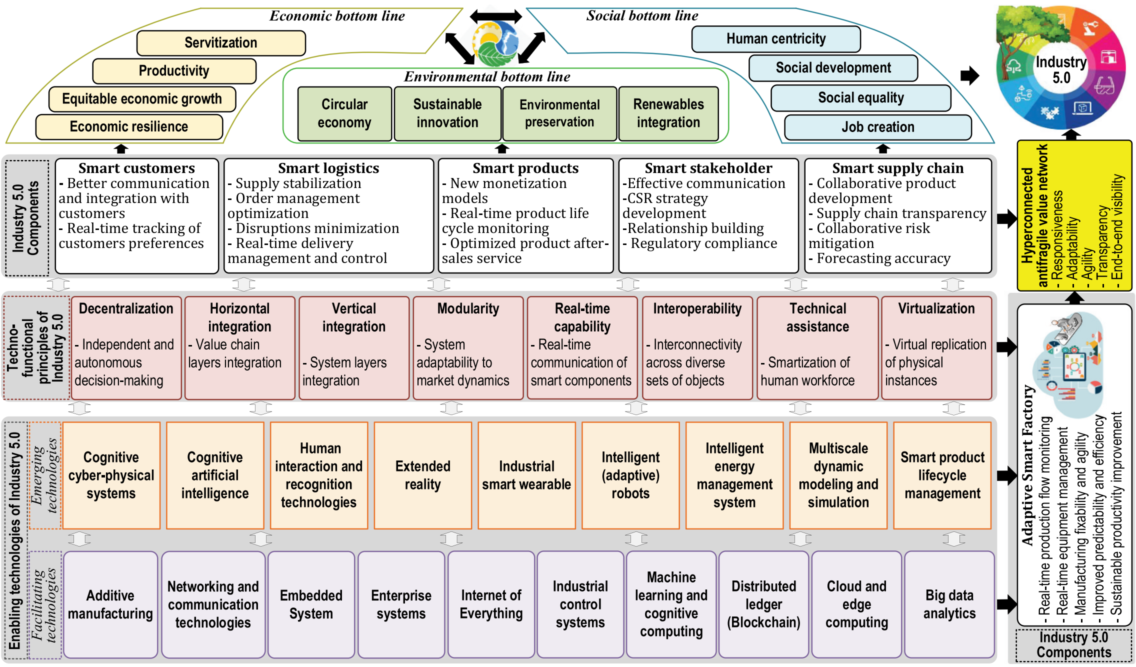

Figure 3. The architectural design of Industry 5.0.

network level, where modular system design offers supply chain agility and resilience toward disruptions. Industry 5.0 entails transitioning from shareholder value to stakeholder value, which requires integrating its various smart components such as supply partners, logistics, customers, and stakeholders interested in the outcomes of Industry 5.0 digitalized business ecosystem. The stakeholder-level integration of Industry 5.0 allows regulatory bodies such as government agencies, labor unions, or international associations to legally regulate the digitalization aspects of Industry 5.0 to mitigate the negative implication of digital industrial transformation and ensure the fair distribution of underlying benefits.

The enabling technologies and techno-functional principles of Industry 5.0 allow its components to integrate into a hyperconnected antifragile value network that draws on the complementarity among unique features of each smart component to deliver the strategic values of Industry 5.0. This value network is antifragile because Industry 5.0 allows the stakeholder to build the necessary collaboration, adaptability, innovation, and responsiveness competencies to turn ongoing and forthcoming disruptions into value gain while alleviating any traces of human injustice. Industry 5.0 strategic values maintain a healthy balance in promoting the triple bottom line. Industry 5.0 is adequately productivity-driven, focusing on increasing the efficiency and productivity of industrial operations and value-creation activities while valuing resilience and equitable economic development. Industry 5.0 draws on circularity, sustainable innovation, and renewables to prevent ever-worsening environmental degradation. This phenomenon shares many grounds with the Society 5.0 concept in prioritizing human-centricity at the firm and societal levels – Industry 5.0 values social development and equal opportunities for rights to jobs, income, and autonomy.

Industry 5.0 and the emerging new manufacturing economy recognize the potential of digital industrial transformation to achieve sustainable development goals and address the socio-environmental concerns of Industry 4.0. The architectural design in Figure 3 explains that economic, environmental, and social sustainability values are equitably valued under Industry 5.0. Regarding the *economic sustainability* bottom line, Industry 5.0 aims to improve the productivity and scalability of individual and networked businesses so that value chain members can maintain profitability and efficiency while growing production and sales. Industry 5.0 also aims to increase the capacity of the regional economies to resist unforeseen crises and recover more rapidly to reach the desired growth level. In addition, it strives to introduce the healthy distribution of added value and corporate equality to the industry.

Results imply that the *environmental bottom line* of Industry 5.0 involves preserving Earth's biosphere and natural resources by breaking the linear take-make-waste economic model, promoting a circular economy, introducing sustainable innovation into products and processes, and facilitating the integration of renewable resources. Industry 5.0 takes a more holistic approach toward environmental sustainability. Besides addressing waste reduction, emission reduction, resource efficiency, and renewables integration at the manufacturing and distribution levels, Industry 5.0 also addresses the ever-increasing global sustainability challenges such as shortening product life cycles, product recyclability, and rebound effects.

Scholars widely believe that human and social centricity is the primary differentiating feature of Industry 5.0. The *social bottom line* of this phenomenon involves many goals and functions. At the industrial level, Industry 5.0 promotes human-centricity via re/up-skilling of the workforce, tailoring technological development based on human needs, and improving the safety and ergonomics of the industrial working environment. At the socio-political level, it involves promoting social protection to enhance social welfare via minimizing labor market disruptions and preventing polarization of the labor force. More importantly, and drawing on the adverse socio-economic effects of the COVID-19 pandemic, the socio-centricity of Industry 5.0 involves enhancing social resilience using technology and data sources to prevent or manage the impact of human-caused and natural crises. The social resilience goal of Industry 5.0 also involves digitalizing the healthcare systems under Healthcare 5.0 agenda and strengthening public health.

Industry 5.0 relies on the synergies among its technological constituents and design principles to deliver the intended sustainability values. We believe the underlying technologies and design principles are complementary, synergistically contributing to inclusive sustainability. For example, C-CPS, adaptive robots, and ISWs are designed to work together, leveraging the power of vertical integration and real-time communication to establish a more efficient and effective working environment focused on human workers' needs. While adaptive robots draw on CAI to optimize interaction and integration with the human workforce and improve physical and psychological well-being, ISWs and C-CPS can provide the operators with real-time data on their physical performance, empowering them to enhance well-being on the job while maximizing productivity and efficiency.

Overall, the review of Industry 5.0 literature and the resulting archetype presented in Figure 3 reveals notable similarities and differences between Industry 5.0 and its predecessor. Both concepts share similar hallmark features in being technology-driven, improving industrial productivity, and promoting a data economy. However, Industry 5.0 differs from Industry 4.0 in terms of the following three unique features:

(1) The socio-environmental values and priorities pull Industry 5.0, whereas Industry 4.0 has predominantly been a technology push and productivity-driven phenomenon. Industry 5.0 also concerns macro socio-environmental priorities such as responsible consumption and production, promoting renewables, inclusive growth, and social protection;
(2) Human-centric technological innovations are key to Industry 5.0. For example, adaptive robots can better adapt to human worker behavior and offer a safer and more reliable working environment while accomplishing more complex tasks. Emerging human interaction and recognition technologies under Industry 5.0 can optimize human-machine integration and interaction, thus, providing the human workforce with more pleasant and safer cognitive and physical tasks.
(3) Industry 5.0 emphasizes generating value for all stakeholders instead of maximizing shareholder value. More importantly, Industry 5.0 recognizes the importance of the fair and more equitable distribution of value across regional and global industrial value networks.

5. Contributions

The study showed that contrary to Industry 4.0, Industry 5.0 appears to be pulled by socio-environmental values and needs. Industry 5.0 is the logical continuation of Industry 4.0 that draws on commercially mature digital and operations technologies and emerging disruptive technologies such as CAI and adaptive robots to promote human-centricity, resilience, and sustainable development. Industry 5.0 is expected to address the pressing sustainable development concerns by introducing circularity into industrial operations, enhancing synergy between autonomous machines and humans, and regulating the pace and quality of digital industrial transformation.

The findings reveal that Industry 4.0 and Industry 5.0 share similarities but have notable differences. For example, both frameworks emphasize horizontal integration, which involves integrating different parts of the production process across the manufacturing supply chains to improve productivity and reduce costs. Nonetheless, horizontal integration under Industry 5.0 goes beyond just integrating various parts of the manufacturing value network. It integrates all stakeholders, including technology providers, labor unions, and government regulators, to create a seamless and collaborative network to govern technological advancement. Another significant difference between the two frameworks concerns the technological focus. Although Industry 4.0 was pushed by emerging technologies such as the internet of things and cloud computing, these technologies are now commonplace and considered standard in Industry 5.0. Instead, Industry 5.0 is associated with the emergence of cognitive technologies that support human-machine symbioses, such as artificial general intelligence, cognitive cyber-physical systems, and adaptive robots. These technologies enable greater collaboration between humans and machines, and they have the potential to revolutionize the way we work and live. Overall, the findings imply that the critical difference between Industry 4.0 and Industry 5.0 lies in the scope and nature of integration and the technological properties that drive innovation and economic values in each framework. While Industry 4.0 is merely focused on economic performance, Industry 5.0 seeks to balance triple bottom-line considerations by harnessing technology-driven productivity to enhance societal values.

Results showed that Industry 5.0 is a novel concept that is continually evolving, and the literature does not provide a detailed and widely accepted definition. Following the conceptualization of Industry 5.0 offered by the European Commission and drawing on the existing literature, the present study developed and introduced the Industry 5.0 archetype to better explain the mechanism through which this phenomenon may contribute to sustainability under the new manufacturing economy. Manufacturers should be aware that Industry 5.0 builds on technological advancements to deliver its intended values. Thus, manufacturers should constantly increase their technological competencies to adopt emerging disruptive technologies and integrate them into their business operations. Industry 5.0 does not contradict manufacturing-economic productivity. Instead, it strives to balance economic productivity gains and socio-environmental development.

Industry 4.0 has already shown promising contributions to sustainability at the corporate level. Thus, policymakers need to note that developing a resilient, innovation-driven, and prosperous society and economy appears to be the focus of Industry 5.0 supportive policies for regulating the digital industrial transformation. It is imperative to note that Industry 5.0 is not the sequential continuation of Industry 4.0. Instead, it extends the Industry 4.0 paradigm, an evolutionary step that places environmentalism, human centricity, and resilience among major industrial transformation principles. Industry 5.0 delivers this role by promoting the integration of cognitive technologies and involving the stakeholders in the technology governance process.

The archetype developed in this study recognizes the potential of digital industrial transformation to achieve sustainable development goals and address the socio-environmental concerns of Industry 4.0. Scholars believe that Industry 5.0 values are vital for the future industry to remain relevant and constructive in the new economic reality. Although Industry 5.0 has emerged from societal changes, needs, and realities, it cannot be self-propelled. Indeed, Industry 5.0 advancement relies on stakeholders, particularly policy-making bodies, to collaborate closely and facilitate the transition toward this phenomenon. Policymakers need to note that promoting industrial awareness, facilitating technological advancement, open innovation and research, developing technology-innovation roadmaps, and supportive multilateral policies (addressing taxation, education, labor, employment, trade, income, industrial relationships, and energy) are among the much-needed enablers of Industry 5.0 transformation.

6. Conclusions

While many businesses struggle to digitalize and develop the necessary interconnectedness to improve productivity under the Industry 4.0 paradigm, the next phase of digital industrial transformation, known as Industry 5.0, is already being pulled. Leading policy-making and academic institutions, such as the European Union, argue that technological advancement is unstoppable, yet social and ecological needs must be integrated into the ongoing techno-industrial revolution. The present study took a systemic approach and integrated different perspectives to develop the architectural design of Industry 5.0 and address the vagueness surrounding its technologies, design principles, components, and values.

The results reveal that Industry 4.0 has been primarily driven and pushed by technological advancements and the ever-increasing need to boost industrial productivity. Our observations show that Industry 4.0 has been an overall successful experience in the sense that it has delivered the intended productivity-based values. Nonetheless, Industry 4.0 does not systematically value social and environmental sustainability, despite inadvertently boosting some micro-societal values, such as resource efficiency or workplace safety. The literature acknowledges that Industry 4.0 has adversely affected various social and human-centric values, mainly because social actors have failed to manage and govern the pace of technology integration actively. Examples of such adverse effects include undermining the autonomy and dignity of the workforce, causing income inequality on a firm and regional scale, intensifying the skill gap crisis, and causing significant job displacement. The socially disruptive digital transformation under Industry 4.0 has been severely felt globally, particularly within Europe and most Western economies, explaining why the social actors radically promote the Industry 5.0 framework.

6.1. Future research directions

Although Industry 5.0 is closer than expected, this phenomenon is in its infancy, and the mechanisms through which the enabling technologies can promote human and socio-centricity are empirically ill-defined. In reality, emerging technologies such as CAI can be a double-edged sword when touching upon the concept of human centricity. For instance, if regulated improperly, self-conscious AI can replace human-occupied professions that are extraordinarily difficult to automate. Thus, a question remains who will push human centricity under Industry 5.0? If governments intend to push for human-centric technological advancements, what legislative framework should be created, and what support programs should be developed? More importantly, how can human-centricity and sustainability be pushed uniformly worldwide to avoid cross-regional competitiveness imbalances? Addressing these questions opens an exciting and vital avenue for future research. In this vein, it is logical to believe that inclusive technology governance can be a critical success factor for implementing the Industry 5.0 framework. Consistently, future research is invited to outline how Industry 5.0 actors can govern technological advancement and ensure that the development and deployment of emerging technologies under this framework would prioritize including diverse stakeholders and their perspectives, particularly those historically marginalized or underrepresented under the digital industrial transformation.

The archetype developed holds a supply network perspective in defining the scope of Industry 5.0 impacts. However, the archetype mainly exemplified the implications of Industry 5.0 transformation for manufacturing value networks, emphasizing the central role of adaptive smart factories. Like Industry 4.0, the ripple effects of Industry 5.0 will reach beyond the manufacturing industry, impacting other business sectors such as healthcare, transportation, construction, and energy. Future research is encouraged to expand the proposed archetype to the industry-specific roadmaps of Industry 5.0 transformation, identifying enabling technologies, principles, values, and components unique to each industry. Accordingly, researchers and practitioners are invited to develop industry-specific Industry 5.0 transformation roadmaps that outline the essential steps, technologies, and strategies required for each business sector to achieve sustainable transformation goals. This could include conducting case studies and analyzing best practices to identify each industry's unique challenges and opportunities.

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Data availability statement

The data that support the findings of this study are available from the corresponding author, [Morteza Ghobakhloo], upon reasonable request.

Nomenclature

AI	Artificial Intelligence
ASF	Adaptive Smart Factory
CAI	Cognitive Artificial Intelligence
C-CCP	Cognitive Cyber-Physical Systems
CPS	Cyber-Physical Systems
DSDT	Dynamic Simulation and Digital Twin
HIRT	Human interaction and recognition technologies
IEMS	Intelligent Energy Management System
IIoT	Industrial Internet of Things
IoS	Internet of Services
ISW	Industrial Smart Wearable
IT/OP	Information Technology/Operational Technology
SNMP	Simple Network Management Protocol
SPLM	Smart Product Lifecycle Management
XR	Extended reality

References

[1] Ghobakhloo M, Fathi M, Iranmanesh M, et al. Industry 4.0 Ten Years On: a Bibliometric and Systematic Review of Concepts, Sustainability Value Drivers, and Success Determinants. J Clean Prod. 2021;302:127052.

[2] Baig MI, Yadegaridehkordi E. Exploring moderating effects of industry 4.0 adoption on sustainable performance of Malaysian manufacturing organizations. J Ind Prod Eng. 2023;40(4):271–286.

[3] Sindhwani R, Afridi S, Kumar A, et al. Can industry 5.0 revolutionize the wave of resilience and social value creation? A multi-criteria framework to analyze enablers. Technol Soc. 2022;68:101887.

[4] Breque M, De Nul L, Petridis A (2021). Industry 5.0, R&I Paper Series, European Commission, Retrieved fromhttps://op.europa.eu/flexpaper/common/view.jsp?doc=468a892a-5097-11eb-b59f-01aa75ed71a1.en.PDF.pdf&user=&format=pdf&page=[*,0].

[5] Saniuk S, Grabowska S, Straka M. Identification of Social and Economic Expectations: contextual Reasons for the Transformation Process of Industry 4.0 into the Industry 5.0 Concept. Sustainability. 2022;14(3):1391.

[6] Xu X, Lu Y, Vogel-Heuser B, et al. Industry 4.0 and Industry 5.0—Inception, conception and perception. J Manuf Syst. 2021a;61:530–535.

[7] Ghobakhloo M, Iranmanesh M. Digital transformation success under Industry 4.0: a strategic guideline for manufacturing SMEs. J Manuf Technol Manage. 2021;32(8):1533–1556.

[8] Silva RL, Junior OC, Rudek M. A road map for planning-deploying machine vision artifacts in the context of Industry 4.0. J Ind Prod Eng. 2022;39(3):167–180.

[9] Fernando Y, Tseng M-L, Wahyuni-Td IS, et al. Cyber supply chain risk management and performance in industry 4.0 era: information system security practices in Malaysia. J Ind Prod Eng. 2023;40(2):102–116.

[10] Kianpour P, Gupta D, Krishnan KK, et al. Automated job shop scheduling with dynamic processing times and due dates using project management and industry 4.0. J Ind Prod Eng. 2021;38(7):485–498.

[11] Liu Y, Ma X, Shu L, et al. From Industry 4.0 to Agriculture 4.0: current Status, Enabling Technologies, and Research Challenges. IEEE Trans Ind Inform. 2021a;17(6):4322–4334.

[12] Fatima Z, Tanveer MH, Waseemullah W, Zardari S, Naz LF, Khadim H, Noorah A, and Tahir M. Production Plant and Warehouse Automation with IoT and Industry 5.0. Appl Sci. 2022;12(4):2053.

[13] Lu Y, Zheng H, Chand S, Xia W, Liu Z, Xu X, Wang L, Qin Z, and Bao J. Outlook on human-centric manufacturing towards Industry 5.0. J Manuf Syst. 2022;62:612–627.

[14] Sharma M, Sehrawat R, Luthra S, Daim, T, Bakry, D, et al. Moving Towards Industry 5.0 in the Pharmaceutical Manufacturing Sector: Challenges and Solutions for Germany. IEEE Transactions on Engineering Management. 2022; 1–18. doi:10.1109/TEM.2022.3143466.

[15] Chen N, Okada M. Towards 6G Internet of Things and the Convergence with RoF System. IEEE Int Things J. 2020;8(11):8719–8733.

[16] Xu L, Zhou X, Tao Y, et al. AF Relaying Secrecy Performance Prediction for 6G Mobile Communication Networks in Industry 5.0. IEEE Trans Ind Inform. 2021b;18(8):5485–5493.

[17] Broo DG, Kaynak O, Sait SM. Rethinking engineering education at the age of industry 5.0. J Ind Inf Integr. 2022;25:100311.

[18] Dautaj M, Rossi M (2022) Towards a New Society: solving the Dilemma Between Society 5.0 and Industry 5.0. *Vol. 639 IFIP. 18th IFIP WG 5.1 International Conference on Product Lifecycle Management, PLM 2021*; Curitiba (pp. 523–536): Springer Science and Business Media Deutschland GmbH.

[19] Mukherjee AA, Raj A, Aggarwal S. Identification of barriers and their mitigation strategies for industry 5.0 implementation in emerging economies. Int J Prod Econ. 2023;257:108770.

[20] Wang H, Lv L, Li X, et al. A safety management approach for Industry 5.0′ s human-centered manufacturing based on digital twin. J Manuf Syst. 2023;66:1–12.

[21] Watson RT, Webster J. Analysing the past to prepare for the future: writing a literature review a roadmap for release 2.0. J Decis Syst. 2020;29(3):129–147.

[22] Carayannis EG, Morawska-Jancelewicz J. The Futures of Europe: society 5.0 and Industry 5.0 as Driving Forces of Future Universities. J Knowl Econ. 2022;13(4):3445–3471.

[23] Müller J (2020). Enabling technologies for Industry 5.0, *Directorate-General for Research and Innovation, European Commission*. Retrived from https://op.europa.eu/o/opportal-service/download-handler?identifier=8e5de100-2a1c-11eb-9d7e-01aa75ed71a1&format=pdf&language=en&productionSystem=cellar&part=

[24] Mahood Q, Van Eerd D, Irvin E. Searching for grey literature for systematic reviews: challenges and benefits. Res Synth Methods. 2014;5(3):221–234.

[25] Tseng M-L, Tran TPT, Ha HM, et al. Sustainable industrial and operation engineering trends and challenges Toward Industry 4.0: a data driven analysis. J Ind Prod Eng. 2021;38(8):581–598.

[26] Cañas H, Mula J, Díaz-Madroñero M, et al. Implementing industry 4.0 principles. Comput Ind Eng. 2021;158:107379.

[27] Masood T, Sonntag P. Industry 4.0: adoption challenges and benefits for SMEs. Comput Ind. 2020;121:103261.

[28] Longo F, Nicoletti L, Padovano A. New perspectives and results for Smart Operators in industry 4.0: a human-centered approach. Comput Ind Eng. 2022;163:107824.

[29] Brough P, Ed. Advanced Research Methods for Applied Psychology: design, Analysis and Reporting. 1st ed. Oxfordshire: Routledge; 2018.

[30] Choi TM, Kumar S, Yue X, et al. Disruptive Technologies and Operations Management in the Industry 4.0 Era and Beyond. Prod Oper Manage. 2022;31(1):9–31.
[31] John A, Mohan S, Vianny DMM. Cognitive Cyber-Physical System Applications. In: Prakash KB, Kanagachidambaresan GR, Srikanth V, and Vamsidhar E, editors. Cognitive Engineering for Next Generation Computing: a Practical Analytical Approach. Beverly: Scrivener Publishing LLC; 2021. pp. 167–187.
[32] Wiedermann J, van Leeuwen J (2021). *Towards Minimally Conscious Cyber-Physical Systems: a Manifesto*. Paper presented at the SOFSEM 2021: Theory and Practice of Computer Science, Cham.
[33] Saadati Z, Barenji RV. Toward Industry 5.0: cognitive Cyber-Physical System. In: Azizi A, and Barenji RV, editors. Industry 4.0: technologies, Applications, and Challenges. Singapore: Springer Nature Singapore; 2023. pp. 257–268.
[34] Rahman SM (2019). () *Cognitive cyber-physical system (C-CPS) for human-robot collaborative manufacturing*. Paper presented at the 2019 14th Annual Conference System of Systems Engineering (SoSE); Anchorage.
[35] Maier M, Ebrahimzadeh A, Beniiche A, et al. The Art of 6G (TAO 6G): how to wire Society 5.0 [Invited]. J Opt Commun Networking. 2022;14(2):A101–112.
[36] Reggia JA, Katz GE, Davis GP. Artificial conscious intelligence. J Artif Intell Conscious. 2020;7(01):95–107.
[37] Ghosh S, Dagiuklas T, Iqbal M, et al. A Cognitive Routing Framework for Reliable Communication in IoT for Industry 5.0. IEEE Trans Ind Inform. 2022;18(8):5446–5457.
[38] Maddikunta PKR, Pham Q-V, Prabadevi B, et al. Industry 5.0: a survey on enabling technologies and potential applications. J Ind Inf Integr. 2022;26:100257.
[39] Ye Q, Zhong H, Qu C, et al. Human Interaction Recognition Based on Whole-Individual Detection. Sensors. 2020;20(8):2346.
[40] Nahavandi S. Industry 5.0—A human-centric solution. Sustainability. 2019;11(16):4371.
[41] Gong L, Fast-Berglund Å, Johansson B. A Framework for Extended Reality System Development in Manufacturing. IEEE Access. 2021;9:24796–24813.
[42] Longo F, Padovano A, Umbrello S. Value-oriented and ethical technology engineering in Industry 5.0: a human-centric perspective for the design of the Factory of the Future. Appl Sci. 2020;10(12):4182.
[43] Martynov VV, Shavaleeva DN, Zaytseva AA (2019). *Information Technology as the Basis for Transformation into a Digital Society and Industry 5.0*. Paper presented at the 2019 International Conference"Quality Management, Transport and Information Security, Information Technologies"(IT&QM&IS); Sochi.
[44] Siriwardhana Y, Porambage P, Liyanage M, et al. A survey on mobile augmented reality with 5G mobile edge computing: architectures, applications and technical aspects. IEEE Commun Surv Tutorials. 2021;23(2):1160–1192.
[45] Niknejad N, Ismail WB, Mardani A, et al. A comprehensive overview of smart wearables: the state of the art literature, recent advances, and future challenges. Eng Appl Artif Intell. 2020;90:103529.
[46] Jan MA, Khan F, Khan R, et al. Lightweight Mutual Authentication and Privacy-Preservation Scheme for Intelligent Wearable Devices in Industrial-CPS. IEEE Trans Ind Inform. 2020;17(8):5829–5839.
[47] Pérez L, Rodríguez-Jiménez S, Rodríguez N, et al. Symbiotic human–robot collaborative approach for increased productivity and enhanced safety in the aerospace manufacturing industry. Int J Adv Manuf Technol. 2020;106(3–4):851–863.
[48] Schneider S, Kummert F. Comparing robot and human guided personalization: adaptive exercise robots are perceived as more competent and trustworthy. Int J Social Rob. 2020;13(2):169–185.
[49] Taniguchi T, El Hafi L, Hagiwara Y, et al. Semiotically adaptive cognition: toward the realization of remotely-operated service robots for the new normal symbiotic society. Adv Rob. 2021;35(11):664–674.
[50] Coronado E, Kiyokawa T, Ricardez GAG, et al. Evaluating quality in human-robot interaction: a systematic search and classification of performance and human-centered factors, measures and metrics towards an industry 5.0. J Manuf Syst. 2022;63:392–410.
[51] Kent MD, Kopacek P (2020). *Do We Need Synchronization of the Human and Robotics to Make Industry 5.0 a Success Story?* Paper presented at The International Symposium for Production Research; Turkey.
[52] Safarzadeh S, Rasti-Barzoki M, Hejazi SR. A review of optimal energy policy instruments on industrial energy efficiency programs, rebound effects, and government policies. Energy Policy. 2020;139:111342.
[53] Kermani M, Adelmanesh B, Shirdare E, et al. Intelligent energy management based on SCADA system in a real Microgrid for smart building applications. Renewable Energy. 2021;171:1115–1127.
[54] ElFar OA, Chang C-K, Leong HY, et al. Prospects of Industry 5.0 in algae: customization of production and new advance technology for clean bioenergy generation. Energy Convers Manage: X. 2021;10:100048.
[55] Kim H, Choi H, Kang H, et al. A systematic review of the smart energy conservation system: from smart homes to sustainable smart cities. Renew Sust Energ Rev. 2021;140:110755.
[56] Liu M, Fang S, Dong H, et al. Review of digital twin about concepts, technologies, and industrial applications. J Manuf Syst. 2020;58(Part B):346–361.
[57] Javaid M, Haleem A. Critical components of Industry 5.0 towards a successful adoption in the field of manufacturing. J Ind Integration Manage. 2020;5(03):327–348.
[58] Kaewunruen S, Lian Q. Digital twin aided sustainability-based lifecycle management for railway turnout systems. J Clean Prod. 2019;228:1537–1551.
[59] Liu Y, Zhang Y, Ren S, et al. How can smart technologies contribute to sustainable product lifecycle management? J Clean Prod. 2020b;249:119423.
[60] Lim KYH, Zheng P, Chen C-H. A state-of-the-art survey of Digital Twin: techniques, engineering product lifecycle management and business innovation perspectives. J Intell Manuf. 2019;31(6):1313–1337.
[61] Paschek D, Mocan A, Draghici A (2019). *Industry 5.0-The expected impact of next Industrial Revolution*. Paper presented at the Thriving on Future Education, Industry, Business, and Society, Proceedings of the MakeLearn and TIIM International Conference, Piran, Slovenia.
[62] Golovianko M, Terziyan V, Branytskyi V, et al. Industry 4.0 vs. Industry 5.0: co-existence, Transition, or a Hybrid. Procedia Comput Sci. 2023;217:102–113.
[63] Jabrane K, Bousmah M. A New Approach for Training Cobots from Small Amount of Data in Industry 5.0. Int J Adv Comput Sci Appl. 2021;12(10):634–646.
[64] Ivanov D. The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human-centricity perspectives. Int J P Res. 2023;61(5):1683–1695.

[65] Sarma SS, Hazra R, Mukherjee A. Symbiosis between D2D communication and Industrial IoT for Industry 5.0 in 5G mm-Wave cellular network: an interference management approach. IEEE Trans Ind Inform. 2021;18 (8):5527–5536.
[66] Kang S, Chung K. IoT Framework for Interoperability in the oneM2M Architecture. Adv Electr Comput Eng. 2020;20(2):11–18.
[67] Shao Y, Zavala VM. Modularity measures: concepts, computation, and applications to manufacturing systems. AIChE J. 2020;66(6):e16965.
[68] Dwivedi A, Agrawal D, Jha A, et al. Studying the interactions among Industry 5.0 and circular supply chain: towards attaining sustainable development. Comput Ind Eng. 2023;176:108927.
[69] Dolgui A, Ivanov D, Sokolov B. Reconfigurable supply chain: the X-network. Int J P Res. 2020;58(13):4138–4163.
[70] Javaid M, Haleem A, Singh RP, et al. Industry 5.0: potential applications in COVID-19. J Ind Integration Manage. 2020;5(4):507–530.
[71] Romero D, Stahre J (2021). *Towards the Resilient Operator 5.0: the Future of Work in Smart Resilient Manufacturing Systems*. Paper presented at the 54th CIRP Conference on Manufacturing Ssystems, CMS 2021; virtual conference.
[72] Cillo V, Gregori GL, Daniele LM, et al. Rethinking companies' culture through knowledge management lens during Industry 5.0 transition. J Knowl Manage. 2022;26(10):2485–2498.
[73] Huang S, Wang B, Li X, et al. Industry 5.0 and Society 5.0—Comparison, complementation and co-evolution. J Manuf Syst. 2022;64:424–428.
[74] Destouet C, Tlahig H, Bettayeb B, et al. Flexible job shop scheduling problem under Industry 5.0: a survey on human reintegration, environmental consideration and resilience improvement. J Manuf Syst. 2023;67:155–173.
[75] Büchi G, Cugno M, Castagnoli R. Smart factory performance and Industry 4.0. Technol Forecasting Social Change. 2020;150:119790.
[76] Aslam F, Aimin W, Li M, et al. Innovation in the era of IoT and industry 5.0: absolute innovation management (AIM) framework. Information. 2020;11(2):124.
[77] Jerman A, Pejić Bach M, Aleksić A. Transformation towards smart factory system: examining new job profiles and competencies. Syst Res Behav Sci. 2020;37 (2):388–402.
[78] Fraga-Lamas P, Lopes SI, Fernández-Caramés TM. Green IoT and edge AI as key technological enablers for a sustainable digital transition towards a smart circular economy: an industry 5.0 use case. Sensors. 2021;21(17):5745.
[79] Hein-Pensel F, Winkler H, Brückner A, et al. Maturity assessment for Industry 5.0: a review of existing maturity models. J Manuf Syst. 2023;66:200–210.
[80] Lenz J, MacDonald E, Harik R, et al. Optimizing smart manufacturing systems by extending the smart products paradigm to the beginning of life. J Manuf Syst. 2020;57:274–286.
[81] Li CZ, Chen Z, Xue F, et al. A blockchain-and IoT-based smart product-service system for the sustainability of prefabricated housing construction. J Clean Prod. 2021;286:125391.
[82] Bhat SA, Huang NF, Sofi IB, et al. Agriculture-Food Supply Chain Management Based on Blockchain and IoT: a Narrative on Enterprise Blockchain Interoperability. Agric. 2022;12(1):40.
[83] Nasiri M, Ukko J, Saunila M, et al. Managing the digital supply chain: the role of smart technologies. Technovation. 2020;96-97:102121.
[84] Modgil S, Singh RK, Agrawal S. Developing human capabilities for supply chains: an industry 5.0 perspective. Ann Oper Res. 2023;1–31. DOI:10.1007/s10479-023-05245-1
[85] Humayun M, Jhanjhi N, Hamid B, et al. Emerging smart logistics and transportation using IoT and blockchain. IEEE Internet Things Mag. 2020;3(2):58–62.
[86] Guo Z, Zhang Y, Zhao X, et al. CPS-based self-adaptive collaborative control for smart production-logistics systems. IEEE Trans Cybern. 2020;51(1):188–198.
[87] Ding Y, Jin M, Li S, et al. Smart logistics based on the internet of things technology: an overview. Int J Logist. 2021;24(4):323–345.
[88] Bednar PM, Welch C. Socio-technical perspectives on smart working: creating meaningful and sustainable systems. Inform Syst Front. 2019;22(2):1–18.
[89] Ghobakhloo M, Iranmanesh M, Morales ME, et al. Actions and approaches for enabling Industry 5.0-driven sustainable industrial transformation: a strategy roadmap. Corp Soc Resp Environ Manage. 2022a;30(3):1–22.
[90] Allam Z, Jones DS. Future (post-COVID) digital, smart and sustainable cities in the wake of 6G: digital twins, immersive realities and new urban economies. Land Use Policy. 2021;101:105201.
[91] Özdemir V, Hekim N. Birth of Industry 5.0: making Sense of Big Data with Artificial Intelligence, "the Internet of Things" and Next-Generation Technology Policy. OMICS. 2018;22(1):65–76.
[92] Ghobakhloo M, Iranmanesh M, Mubarak MF, et al. Identifying industry 5.0 contributions to sustainable development: a strategy roadmap for delivering sustainability values. Sustainable Prod Consumption. 2022b;33:716–737.
[93] Leng J, Sha W, Wang B, et al. Industry 5.0: prospect and retrospect. J Manuf Syst. 2022;65:279–295.
[94] Alexa L, Pîslaru M, Avasilcăi S. From Industry 4.0 to Industry 5.0—An Overview of European Union Enterprises. In: Draghici A Ivascu L, editors. Sustainability and Innovation in Manufacturing Enterprises: indicators, Models and Assessment for Industry 5.0. Springer Singapore; 2022. pp. 221–231.
[95] Cimino A, Elbasheer M, Longo F, et al. Empowering Field Operators in Manufacturing: a Prospective Towards Industry 5.0. Procedia Comput Sci. 2023;217:1948–1953.
[96] Carayannis EG, Christodoulou K, Christodoulou P, et al. Known Unknowns in an Era of Technological and Viral Disruptions—Implications for Theory, Policy, and Practice. J Knowl Econ. 2022;13(1):587–610.
[97] Rožanec JM, Novalija I, Zajec P, et al. Human-centric artificial intelligence architecture for industry 5.0 applications. Int J P Res. 2022;1–26. DOI:10.1080/00207543.2022.2138611
[98] Doyle-Kent M, Kopacek P (2020). Industry 5.0: is the Manufacturing Industry on the Cusp of a New Revolution? Proceedings of the International Symposium for Production Research 2019, Cham.
[99] Renda A, et al. Industry 5.0, a transformative vision for Europe – Governing systemic transformations towards a sustainable industry. Publications Office of the European Union; 2022. https://data.europa.eu/doi/10.2777/17322
[100] Ghobakhloo M, Fathi M. Industry 4.0 and opportunities for energy sustainability. J Clean Prod. 2021;295:126427.