The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/2040-8021.htm

How to engineer sustainability: from resource-wise manufacturing towards ecosystem-wide impacts

Sustainability Accounting, Management and Policy Journal

Julian M. Müller, Nikolai Kazantsev, Richard Allmendinger, Amirhossein Salehi-Amiri, Jacqueline Zonichenn Reis, Shaden Jaradat, Helena Bartolo and Paulo Jorge Da Silva Bartolo
(Author affiliations can be found at the end of the article)

Received 28 March 2024
Revised 19 July 2024
10 September 2024
24 October 2024
Accepted 8 November 2024

Abstract

Purpose – This conceptual paper aims to present a perspective on how to engineer sustainability through the prism of Industry 4.0 technologies and outline propositions to guide future research.

Design/methodology/approach – This study presents a literature review developing four research propositions, focusing on the nine leading technologies underpinning Industry 4.0 to engineer economic, environmental and social sustainability dimensions.

Findings – The authors derive benefits and challenges of Industry 4.0 technologies across all three business model elements: value creation, value delivery and value capture. The authors derive those for the economic, environmental and social dimensions of sustainability. Thereupon, we develop several propositions for future research.

Practical implications – The authors provide suggestions to practice how to better achieve value in all three sustainability dimensions through implementing a business model perspective, ecosystem thinking, societal demands and Data Governance and AI integration.

Social implications – By linking societal aspects of Industry 4.0 technologies with environmental, and economic aspects, the authors provide several suggestions how to implement Industry 4.0. For instance, policymakers are recommended to support entire ecosystems than isolated solutions.

Originality/value – The paper contributes to extant literature by conceptualising how Industry 4.0 can leverage value in reaching sustainability in all three dimensions and produce broader ecosystems-wide impacts.

Keywords Industry 4.0, Sustainability, Circular economy, Digital transformation, Ecosystems

Paper type Research paper

The second author acknowledges the EC/Horizon 2020 (grant agreement no. 723336), ESRC Made Smarter Network+ ("InterAct") Commissioned Research Programme, Early Career Researcher Fellowship number J17293/ES/W007231/1, and the community's role at Clare Hall College (Cambridge) in supporting his scientific work.

Sustainability Accounting, Management and Policy Journal
Emerald Publishing Limited
2040-8021
DOI 10.1108/SAMPJ-03-2024-0305

1. Introduction

By 2030, the implementation of the Circular economy is projected to provide a substantial $4.5tn increase in global GDP by generating jobs, improving the quality of life, reducing waste and creating growth opportunities in various sectors (BCG, 2023). Sustainable operations should be part of a company's holistic effort (Lerman *et al.*, 2024; Timmermans *et al.*, 2017). Digital technologies play a central enabling role through vertical and horizontal interconnection along value chains (Hofmann and Rüsch, 2017; Kagermann *et al.*, 2013). Digital technologies further enable new ways of organisation and control of entire value-adding systems, affecting entire product-service systems (PSS) - from order management, manufacturing, delivery and after-service to recycling (Bauernhansl *et al.*, 2014). Manufacturing systems undergo servitisation, increase operational efficiency and contribute to sustainable development (Kagermann *et al.*, 2013).

This work aims to contribute to engineering the desired sustainability changes in industrial value creation and outline propositions that will shape future research on this topic. Sustainability aims at meeting "today"s needs without compromising the ability of future generations to meet theirs' (WCED, 1987). Elkington (1998) suggested a holistic conceptualisation of sustainability, which recognises three pillars: The needs of society, responsible curation of the environment and strengthening of the economy. Adequate, sustainable development considers the intersection of interests between "business, environment and society" (Savitz and Weber, 2006; Wassmer *et al.*, 2014). Further, the term sustainability is used at the company and system level (Eccles, 2022). In this article, we address the difficulties of an entire system associated with insufficient visibility and traceability of data. This relates to inadequate data quality and level of detail, and the absence of automated and easily expandable methods for extracting data (Veile *et al.*, 2024).

While there is a broad consensus that digital technology is a crucial driver for increasing productivity and business transformation (Bessant, 2018), there is limited evidence of how these technologies can enable innovation into PSS, smart products and the circular economy (Findik *et al.*, 2023). For example, outdated machinery and equipment amount to about 40%–50% globally (McKinsey, 2015). By enabling shared information flow, Industry 4.0 (Kagermann *et al.*, 2013) attempts to highlight the critical societal challenges such as the attitudes towards consumption (e.g. higher demand for eco-transparency), ageing populations that impact the nature of the workforce and create new market opportunities for products and services, environmental challenges (e.g. climate change and resource efficiency); and economic challenges (e.g. higher productivity and cost-reduction).

While the impacts of digital technologies on operational efficiency have been investigated in the literature, their potential to engineer sustainable production in industries represents a remaining research gap. Particularly how Industry 4.0 pillars (Ghobakhloo, 2020; Majstorovic and Mitrovic, 2019) can support innovation towards net zero industrial value creation, which is currently under investigation. Although current literature states the requirement for technology-enabled sustainability of industrial value creation (Lerman *et al.*, 2024), more consideration should be given to how Industry 4.0 operation affects resources, raw materials, energy consumption and waste generation. In response to this research gap, we perform a literature review on the concept of Industry 4.0 to engineer sustainability, answering the following research question (RQ):

> *RQ1*. How can sustainability in its three dimensions be engineered using Industry 4.0 technologies?

In response, we perform a literature review of the technologies underpinning Industry 4.0 and conceptualise how they can align industrial value creation within Industry 4.0 with sustainability in all three dimensions. Thereupon, we develop four research propositions within a framework to engineer economic, environmental and social sustainability dimensions via Industry 4.0. We were particularly interested in Industry 4.0 as an enabling factor for sustainability inside and beyond the manufacturing system, differentiating our paper from extant publications.

We contribute to extant literature by showing that engineering for Industry 4.0 supports new strategies of distributed manufacturing and enables companies to operate near consumers, such as proximity to markets, reduced transportation costs, access to skilled workers and increased returns. In the future, we anticipate a growing convergence of biological principles with industrial digitisation principles to foster the advancement of sustainable and efficient industrial value generation. This encompasses the entirety of the manufacturing ecosystem, encompassing aspects such as factory layout and integration with the external environment, manufacturing processes, materials, product design, data storage and retrieval and the pursuit of zero-waste activities. Companies can create novel models of industrial value, such as new business models.

The subsequent sections of this article are organized as follows: Section 2 outlines the key technologies that enable the vision of Industry 4.0 and key features of sustainability. In Section 3, we present the findings of our literature review, presenting the economic, social and environmental pillars of sustainability. Section 4 develops four propositions based on our analysis in Section 3. Section 5 concludes the paper with implications for managerial practice, policy, limitations and future research suggestions.

2. Key technological elements of Industry 4.0 and their effects

The successful implementation of Industry 4.0 requires nine fundamental technologies to be part of the entire system (Hens *et al.*, 2018). They allow for the creation of *smart industries*, characterised by smart processes, producing smart products and implementing new business models and *smart and agile supply chains* through improved coordination, integration and real-time information exchange within entire value chains (Ghobakhloo, 2020; Majstorovic and Mitrovic, 2019).

Cyber-physical systems (CPS) refer to the integration of physical and virtual environments via the Internet of Things. This integration facilitates communication, system control and real-time decision-making (Zhou *et al.*, 2015). Combining these two realms enables "right the first time" manufacturing, enhancing safety measures and minimising waste (Cai *et al.*, 2017). CPS comprise intelligence, connectivity (the capacity to establish and use links among components of the production system) and adaptability to both external and internal fluctuations (Monostori *et al.*, 2016). The anticipated benefits of CPS include autonomous organisation, self-sustenance, remote analysis, live monitoring, transparency, security, effectiveness and predictability (Monostori *et al.*, 2016). CPS allow horizontal integration, vertical integration and comprehensive engineering that covers all stages of the value chain from start to finish (Wang *et al.*, 2016).

The *Internet of Things* (*IoT*) is essential for creating digital connections between physical things, devices and other settings (Almada-Lobo, 2016; Hermann *et al.*, 2016). The IoT network enables real-time and reliable information exchange of things and processes enabled by a wide range of product identification and localisation technologies, such as wireless sensors, actuators, radio frequency identification systems and information network technologies (De Sousa Jabbour *et al.*, 2018; Lopez *et al.*, 2017; Zhang *et al.*, 2017).

The *Internet of Services* (IoS) is a framework that enables service providers and users to work together across different businesses using the IoT. Within the IoS, service providers engage in collaborative efforts to create and implement services and digital business models.

A service-oriented value network may include the whole life cycle, spanning from research and development to operations and including design, marketing, sales, manufacturing and delivery. It is essential for all departments to collaborate across organisational boundaries to enhance the service's value (Cardoso *et al.*, 2009).

Cyber security refers to the security within cyberspace, aiming to cover a whole new set of threats and actors (Alguliyev *et al.*, 2018). Different approaches aim to mitigate these threats, thus improving data security and trust. A prominent example is Blockchain (Rüßmann *et al.*, 2015), a digital security system first used as a framework for establishing a decentralised public ledger for bitcoin transactions. The system is designed as a cohesive unit connected to earlier data sources and may be linked to subsequent data sources derived from current ones. Hence, the system functions as a linked sequence of transactions, where each data source has a mirrored representation of the preceding or subsequent associated records. The blockchain is a product of resilient methodologies drawn from dependable distributed computing, encryption and game theory (Reyna *et al.*, 2018).

Machine-to-machine (M2M) denotes the exchange of information between machines without any human involvement or interference. A programme may use and retain the transactional data to get valuable analytical conclusions (Lee *et al.*, 2015), such as descriptions, predictions and preventions.

Big data describes large amounts of high-velocity, unstructured multi-source, heterogeneous and real-time data (Santos *et al.*, 2017; Zhang *et al.*, 2017). Thus, data analytics considers extracting meaning from big data (Santos *et al.*, 2017). Relevant data-driven methods can be divided into two main groups: artificial intelligence (AI) and statistics (Gao *et al.*, 2015). AI, which aims to emulate human intelligence, includes machine learning (ML), deep learning and cognitive computing (Carvalho *et al.*, 2019).

Cloud computing universal and quick access to resources as needed (Wu *et al.*, 2017). Moreover, an ideal cloud should allow Cloud computing to enable universal and quick access to resources as needed. Cloud manufacturing, driven by cloud computing, allows on-demand manufacturing services from networked manufacturing resources (e.g. simulation tools, manufacturing equipment and testing capabilities) (De Sousa Jabbour *et al.*, 2018; Xu, 2012). The cloud has also been used for process planning, which considers and optimises all elements of a production process.

Simulation and Modelling include digital twin (DT), virtual reality (VR) and augmented reality (AR) (De Paula Ferreira *et al.*, 2020). A DT is a virtual representation of a manufacturing system, a production system or an organisation that allows for simulation, testing, predicting and anticipating scenarios and optimisation (Cimino *et al.*, 2019; Jones *et al.*, 2020; Lu *et al.*, 2020; Schleich *et al.*, 2017). VR provides fully immersed virtual environments to users, and AR, which enhances physical items by adding augmented information, uses a wide range of systems, such as handheld devices, head-mounted displays and smart glasses (Cipresso *et al.*, 2018).

Advanced automation and robotics include, for instance, intelligent, autonomous, flexible and cooperative robots that can safely interact with humans and learn from them (Rüßmann *et al.*, 2015). These robots act as critical enablers of Industry 4.0 due to their higher collaboration, flexibility and mobility levels than robots, allowing their use with humans and in changing environments. Thus, manufacturing parts that were not economically feasible before can be automated while supporting humans rather than replacing them (Frank *et al.*, 2019).

Additive manufacturing refers to a set of fabrication techniques that enable the rapid creation of actual products directly from digitally produced models. The fundamental principle of fabrication is the assembly of materials to create things based on three-dimensional (3D) data, often done in a sequential layer-by-layer manner (Mehrpouya *et al.*, 2019). This allows, among other advantages, waste reduction, new functional properties, spare parts supply without a supply chain and lightweight parts.

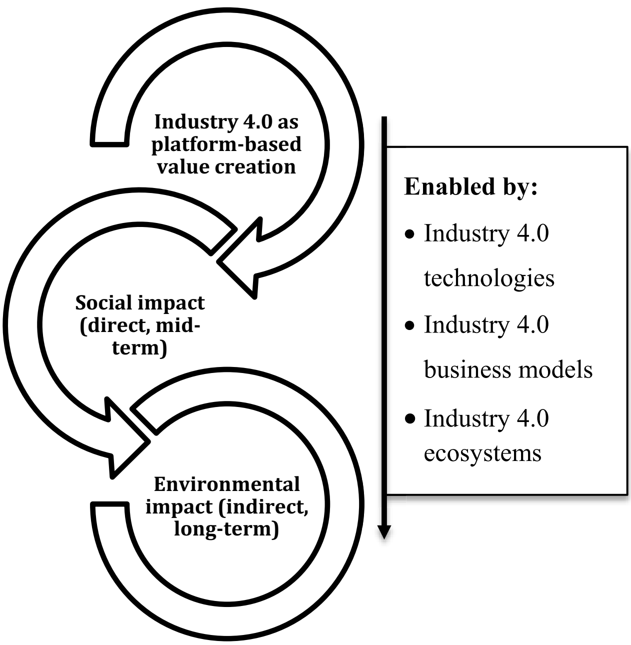
Conclusively, Industry 4.0 links to smart factories, where people, machines and resources communicate and interact autonomously using several technologies described above. As stated in Figure 1 below, Industry 4.0 firstly "engineers" society (i.e. production/supply chains that start working differently). Secondly, as an indirect impact, it produces environmental impacts over the long term.

Extrapolating Industry 4.0 beyond organisational borders and thus beyond smart factories described above by Hahn (2020) enables four main benefits for supply chains:

(1) *Scalability* (e.g. enhanced production ramp-up via capacity sharing with partners) and *flexibility* (e.g. enhanced reconfiguration). Scalability accelerates in the presence of transparency, quick adjustments and enhanced collaboration (Veile *et al.*, 2024).

(2) *A customer-driven approach* to collaborative manufacturing, moving order penetration points upstream, i.e. manufacturers can collaboratively adjust their production processes and supply chains to match client needs in Industry 4.0 business models (Müller *et al.*, 2024).

(3) *Platform-based manufacturing* enables on-demand provision of services from standardised processes. This concept refers to using digital platforms and advanced



Source: Authors' own work

Figure 1. Framework for Industry 4.0 social and environmental impacts enabled by specifically engineered technologies, business models and ecosystems

technologies to crowdsource standard processes from many participants and deliver flexible and scalable customised services (Liu *et al.*, 2022).

(4) *Reducing the number of stages in the supply chain* increases responsiveness and efficiency and reduces the need for logistics and handling processes (Holmström and Partanen, 2014; Leung *et al.*, 2023). Additive manufacturing, for example, allows the redesign of products with fewer components and production near consumers, while increased digital collaboration reduces the number of suppliers with enhanced buyer-supplier relationships. This could develop industrial supply chains into manufacturing ecosystems (Schmidt *et al.*, 2023).

Finally, Smit *et al.* (2016) conceptualise these changes as the main features of Industry 4.0:

- *Modularity*, which corresponds to the capability of system components to be added, rearranged or relocated in the production line on time;
- *Interoperability*, enabled by the use of standardised systems, corresponds to the ability of all elements of a company (e.g. people, machines, products) to communicate using dedicated networks and also to the ability of companies to communicate with other companies and customers;
- *Virtualisation*, which corresponds to the capability to create a virtual environment similar to the physical environment for monitoring and simulation of physical processes;
- *Service orientation*, which corresponds to the capability to integrate products and services, allowing companies to go from only selling things to offering a combination of products and services;
- *Decentralisation*, where decision-making and control are performed autonomously and in parallel;
- *Responsiveness* corresponds to a company's ability to respond to changes on time.

Industry 4.0 aims to achieve benefits in all three dimensions of sustainability (economic, ecological and social) by interconnection and integration of the entire value chain and the entire product lifecycle (Kagermann *et al.*, 2013). Although there might be secondary effects of getting value from each of the Industry 4.0 dimensions, we propose a direct mapping of:

- drivers of economic dimension from "vertical interconnection" within enterprises
- drivers of environmental dimension from "End-to-End interconnection" capturing the product life cycle
- drivers of social dimension from "Horizontal interconnection", integrating SMEs into demand-driven supply networks.

3. Literature review

3.1 Method

We conducted a literature review (Tranfield *et al.*, 2003) to better understand the contributing factors and sustainability dimensions. As a scientific database, we used Scopus due to its common usage in literature reviews and broad coverage of scientific literature while having the ability to filter per several criteria (Martín-Martín *et al.*, 2018).

To generate the initial set of results, we used the search string "Industry 4.0" AND "sustainab*" in the article title. We limited the search to the article tile since many articles use the terms Industry 4.0 or sustainable as keywords but are not actually related to them in a closer sense. A search using the search string "Industry 4.0" AND "sustainab*" in article title, abstract and keywords lead to nearly 4,000 initial results by December 2023 and was therefore regarded as too broad.

The search conducted in December 2023 was limited to academic journal articles in English language to ensure basic academic quality. Further, we limited the search to business and management disciplines to exclude purely technical papers. This initial selection yielded 92 results.

We further excluded journals that were not present in the Scimago Scientific Journal Ranking in Q1 and Q2 categories to ensure academic quality of articles. This left us with 86 articles.

We further examined the abstracts and full texts to determine if they fit our approach. This led us to exclude 15 articles, leaving us with 61 articles. For those, we analysed the literature sections to detect articles we might have missed (Tranfield *et al.*, 2003), adding 13 further articles. Hence, our initial literature sample consists of 74 articles. Those were complemented with papers published in 2024 on the same subject, adding 19 papers. Hence, we have a final sample of 93 papers that were further analysed in this section.

For an overview, we selected 19 articles which are summarised in Table 1 below. We further refer to economic, social and environmental dimensions in the following Sections 3.2–3.4.

According to Table 1, supply chains and manufacturing, Industry 4.0 technologies have a high impact to improve sustainability. According to extant literature, an advanced technology integration with process enhancements and sustainability concepts is essential to achieve this and organisations' present skills and their ability to integrate IoT is required for sustainable to determine their readiness for Industry 4.0.

However, small and micro-enterprises face significant challenges, like organisational barriers and ethical concerns, which need to be overcome for widespread adoption. These technologies boost production efficiency, support sustainable practices and enable new business models, though their impact on environmental and social metrics varies. The strong connection between Industry 4.0 and circular economy practices improves recycling, green manufacturing and overall company performance. Creating strategic plans and models to understand the broader impacts and guide the integration of these technologies is essential for achieving sustainable manufacturing and supply chains.

3.2 Economic impact

Contemporary production methods that include self-governing robots often use less resources and exhibit greater efficiency and cost-effectiveness (Huang and Rust, 2018). For example, Bosch-owned Rexroth [1] adopted Industry 4.0 technologies on its production line of hydraulic valves for mobile machinery, such as tractors.

Vertical integration within value chains increases opportunities for reducing overproduction, thus reducing costs. Industry 4.0 technologies promote multi-side data sharing and facilitate inter-organisational collaboration (Smit *et al.*, 2016; Sokolov and Ivanov, 2015). The ongoing technological transformations turn hierarchical supply structures into more distributed nascent ecosystems.

Unlike supply chains, ecosystems evolve around product development (Beuren *et al.*, 2013; Mont, 2002; Tukker, 2004) by introducing new service systems and increasing supplier interdependencies towards manufacturing ecosystems (Schmidt *et al.*, 2023). Ecosystems represent a vibrant, often fragile network dependent on cooperative partners (Hannah and Eisenhardt, 2018; Reeves *et al.*, 2019). These ecosystems represent networks of interdependent firms that collectively deliver the product despite inter-firm competition

Table 1. Literature review of the recent works using Industry 4.0 in various associated domains

Author	Industry 4.0 Focus IoT	AAR	DA\BD	CC	CS	AR\VR	AM	DT	ML	AI	Key finding regarding sustainability
Kamble *et al.* (2018)	■	■	■	■	■						Researchers propose a sustainable Industry 4.0 framework with three key components: Industry 4.0, process integration, and sustainability
Salah *et al.* (2019)						■					Proposal to use virtual reality to improve student training in Industry 4.0 and reconfigurable manufacturing systems (RMS)
Tang and Veelenturf (2019)	■		■							■	Strategic role of logistics and transportation services in creating economic, environmental, and social values in Industry 4.0
Manavalan and Jayakrishna (2019)	■										Proposal for assessing supply chain organisations' Industry 4.0 readiness, with a focus on IoT-embedded sustainable supply chains
Hidayatno *et al.* (2019)			■							■	Development of a conceptual model, represented as a causal loop diagram, that illustrates the systemic impact of Industry 4.0
Tiwari and Khan (2020)				■						■	Development of an empirical formulation that maps the attributes of Industry 4.0 in Indian industry
Yadav *et al.* (2020)		■					■				Through Industry 4.0 technologies, managerial, economic, and environmental enablers help manufacturing companies adopt sustainability
Kumar *et al.* (2020)							■			■	Identification/analysis of challenges that impact the application of Industry 4.0 in small/medium enterprises (SMEs) for ethical and sustainable operations
Bai *et al.* (2020)	■	■	■	■	■	■	■				Industry 4.0 technologies have the potential to significantly impact sustainability across various industries
Ghobakhloo (2020)	■		■	■	■	■		■	■	■	Production efficiency and business model innovation, are found to be more immediate outcomes of Industry 4.0

(*continued*)

Table 1. Continued

Author	Industry 4.0 Focus										Key finding regarding sustainability
	IoT	AAR	DA\BD	CC	CS	AR\VR	AM	DT	ML	AI	
Enyoghasi and Badurdeen (2021)	■	■		■	■	■					Industry 4.0 technologies can facilitate or enhance sustainable manufacturing practices
Khanzode *et al.* (2021)					■						Identification and analysis of barriers to implementing Industry 4.0 for sustainable production in Indian Micro, Small and Medium Enterprise
Nara *et al.* (2021)	■		■	■	■						Industry 4.0 technologies improve sustainable plastics industry economic metrics; however, environmental and social metrics are less affected
Javaid *et al.* (2022)	■		■						■	■	Industry 4.0 technologies have significant benefits for creating a sustainable environment, particularly in the manufacturing and related industries
Ching *et al.* (2022)		■	■				■				Development of a roadmap that outlines how Industry 4.0 technologies can enable and support sustainable manufacturing
Toktaş-Palut (2022)	■									■	Combination of Industry 4.0 technologies and coordination has a significant impact on the sustainability of supply chains
Tang *et al.* (2022)							■				Industry 4.0 and blockchain technology have a positive impact on circular economy practices, particularly in the context of green manufacturing and recycling
Verma *et al.* (2022)								■		■	Organisational impediments are the most prominent barriers to the adoption of Industry 4.0 technologies for sustainable digital manufacturing
Yu *et al.* (2022)		■									Industry 4.0 promotes circular economy and supply chain capability, improving firm performance
Alkaraan *et al.* (2023)							■				Significant synergy between Industry 4.0 (I4.0) technologies and Circular Economy

Notes: IoT = internet of things; AAR = advanced automation and robotics; DA = data analytics; BD = big data; CC = cloud computing; CS = cybersecurity; AR = augmented reality; VR = virtual reality; AM = additive manufacturing; DT = digital twins; ML = machine learning; AI = artificial intelligence
Source: Authors' own work

(Adner, 2017; Adner and Kapoor, 2010). As an enabler, digital platforms share information between participants and coordinate product development processes (MacCarthy *et al.*, 2016; Schmidt *et al.*, 2019). Including new innovative suppliers in collaborative environments will fill the bottlenecks in nascent ecosystems (Batz *et al.*, 2018; Hannah and Eisenhardt, 2018).

The majority of European enterprises are represented by Small and Medium-sized Enterprises (SMEs) and provide specialised knowledge and expertise relevant to industrial supply chains (Müller *et al.*, 2024). Unlike larger enterprises, SMEs have limited resources and often do not directly supply Original Equipment Manufacturers (OEMs) or customers. Therefore, collaboration is critical and a fruitful path for SMEs to adopt Industry 4.0 (Smit *et al.*, 2016). Although SMEs are more flexible than larger enterprises, they operate in niche-oriented markets and have fewer potential uses for Industry 4.0 technologies (Mittal *et al.*, 2018; Müller *et al.*, 2024). Therefore, SMEs try to find complementary partners and cooperate to fit tenders. Research in the domain of aerospace and automotive supply chains has recognised further barriers that impede collaborations between SMEs, examples of challenges include opaque markets, lack of trust among small and medium enterprises, significant opportunistic behaviour, worries about sharing data, insufficient collaborative skills and a lack of external coordination (Kazantsev *et al.*, 2023; Kazantsev, 2022).

Industry 4.0 technologies allow suppliers to engage in virtual organisations (Ricci *et al.*, 2002). Existing practices of virtual collaboration, such as the Virtuelle Fabrik (Katzy and Crowston, 2008), suggest that suppliers located closely share the entrepreneurial mindset and shared practices, increasing the chances of forming collaborations (Mehandjiev *et al.*, 2007). Industry 4.0 thus enables a new inter-organisational infrastructure that increases preparedness of the existing "virtual organisation breeding environments" (Camarinha-Matos *et al.*, 2017) and facilitates new collaborative links between SMEs.

Business models describe "the rationale of how an organisation creates, delivers and captures value" (Osterwalder and Pigneur, 2010). Industry 4.0 introduces new features to re-construct the business models of existing organisations using principles of interoperability, virtualisation, decentralisation, modularity and service orientation in real-time, service orientation (Smith *et al.*, 2016). Firstly, Industry 4.0 is regarded as an opportunity for companies to generate, access and analyse more data for predictive and prescriptive analytics (Lepenioti *et al.*, 2020; Menezes *et al.*, 2019). Secondly, Industry 4.0 provides technological opportunities for manufacturing companies to adopt a service mindset (Ibarra *et al.*, 2020; Iivari *et al.*, 2016). Servitisation transforms product-specific companies with smaller margins on cost-efficiency and loose customer relationships into service-oriented companies. This transformation provides new revenue streams through maintenance, updates and enhancement of products during their utilisation (Baines *et al.*, 2009; Raddats *et al.*, 2017). Industry 4.0 thus enables a more efficient customer-oriented mix of products and services as the entire product lifecycle is interconnected. Thirdly, Industry 4.0 provides more opportunities to access wider supply networks and further specialisation of products, reducing the cost of mass customisation (Smith *et al.*, 2016). Fourthly, Industry 4.0 allows real-time simulations, process planning, logistics and monitoring, enabling the development of new cloud-based strategies and business models (Leung *et al.*, 2023; Müller *et al.*, 2024).

Table 2 subsumes benefits and challenges across the three business model elements of value creation, delivery and capture.

3.3 Social impact

Horizontal interconnection, facilitated by digital connectivity between enterprises, enables the incorporation of smaller, more creative companies (Kagermann *et al.*, 2013). The

Table 2. Industry 4.0 benefits and challenges across all three business model elements in economic dimension of sustainability

Business model dimension	Benefits	Challenges
Value creation	Interconnection between companies; Transparency of information; Decentralisation of production and decision-making; Real-time human or machine assistance	The implementation of Industry 4.0 is subject to substantial short-term organisational and financial efforts, while the benefits are only expected in the medium to short-term plan horizon; Economic uncertainty
Value delivery	New customer interfaces; Customer proximity; Product/service personalisation	Converting data into commercial use; Overwhelming customer demand hampers internal standardisation and, with it, the cost efficiency of Industry 4.0-related solutions
Value capture	More efficient processes that lead to cost optimisation and new revenue streams	Companies often fear losing their existing customers as they become more aware of price fluctuations and switch to more cost-efficient alternatives; Market uncertainty

Source: Authors' own work

COVID-19 outbreak has triggered multiple cooperations around local demand for social and healthcare products across supply chains. Responding to the demand for various medical and personal protective equipment (PPEs), SMEs from various industries cooperated to manufacture them locally. An example was the Ventilator Challenge UK [2], a cross-industrial initiative that embraced automotive, aerospace and electronics suppliers to design, develop and ramp up production of locally demanded ventilators. The strong demand for such products eliminated inter-firm collaboration barriers, such as network distrust, partner opportunism and intellectual property concerns (Kazantsev *et al.*, 2022).

Industry 4.0 also enables the development of innovative and safe products with improved performance by adding sensors, connectivity and advanced materials to existing products. It enhances user experience through sensor-enabled applications or using data to track product conditions and system failures to predict customer needs, offering better services Ghisellini *et al.* (2016). Industry 4.0 technologies further facilitate cost-effective mass customisation and personalisation, i.e. changing, assembling or modifying a product or service according to customer's needs and desires by, e.g. additive manufacturing technologies and data transparency from customers all across the supply chain (Kagermann *et al.*, 2013). Industry 4.0 technologies, mainly additive manufacturing, IoT, modelling and simulation, have also been used for humanitarian causes. An example is the Humanitarian Makers, a global online community of volunteer experts who can assist remotely with challenging designs and activities. Projects include spare parts to repair baby incubators, 3D printed tourniquets or local 3D printed natural latex shoe manufacturing [3].

VR and AR systems allow the development of flexible and adaptive training programs aiming to speed up the reconfiguration of production lines, improve the cooperation between humans and machines, provide virtual training for assembling parts, develop more ergonomic machines or working environments, training workers on complex tasks to improve productivity and support advanced diagnostics (Damiani *et al.*, 2018). Industry 4.0 also enables smart and autonomous production systems to support workers' health and safety by replacing workers in monotonous and repetitive tasks, reducing workload and improving standard operating conditions (Sartal *et al.*, 2020) See Table 3. CPS enable the development of user-friendly human-machine interactions, improving workers' manufacturing decisions and safety, while autonomous robots can perform risky tasks or operate in extreme environments (Kumar *et al.*, 2020; Sartal *et al.*, 2020). Technological unemployment, observed in routine and non-routine manufacturing tasks, with high potential for social disruptions, is considered the negative aspect of Industry 4.0 (Brynjolfsson and McAfee, 2011). However, it simultaneously opens new opportunities for skilled and knowledge-based jobs.

Digital tools and technologies that enable Industry 4.0 will also enable the development of novel urban manufacturing strategies, addressing a critical demographic challenge as the proportion of the global population residing in urban areas is steadily increasing (Mulligan and Crampton, 2005). Cities represent important markets and knowledge-intensive spaces, with universities and research centres. Therefore, a future avenue could be producing close to the clients and thus taking advantage of reduced transportation costs, access to highly skilled workers and opportunities to form smart grids between cities and industrial manufacturing. Within these ecosystems, industrial enterprises will seamlessly merge with the urban surroundings, using symbiotic approaches to exchange resources and energy with other firms, homes and infrastructures. They will also embrace eco-efficient manufacturing methods (Herrmann *et al.*, 2014).

We anticipate a greater incorporation of biological principles into industrial digitisation concepts to cultivate manufacturing organisations that are more sustainable, intelligent, efficient and productive. This notion may be extended to include the whole manufacturing ecosystem, including aspects such as factory design, layout and integration with the external environment, production processes, materials, product design, management strategies, data

Table 3. Industry 4.0 benefits and challenges across all three business model elements in social dimension of sustainability

Business model dimension	Benefits	Challenges
Value creation	Enhancing the user experience by developing innovative, personalised and safe products. Improving access to healthcare services and promoting smart agriculture, providing the growing population with a food security	Ethical implications associated with robots and AI technologies replacing humans in work, which shows high potential for social disruptions. IA algorithms can inherit biases from the data they are trained on, resulting in biased decision-making and unfair outcomes
Value delivery	Greater control and visibility over the supply chain by using data to track product conditions and monitor system failures to predict customer needs, meaning companies can deliver products and services faster and with better quality	Data collection and analysis raises concerns about individuals' privacy and data protection. Organisations must prioritize ethical data practices, ensuring that consent is obtained, data is securely stored and used for legitimate purposes
Value capture	New revenue streams through innovative products and subscriptions of digital services. Lower costs through greater automation and better visibility allow savings to be passed on to customers	Balancing the technological unemployment in manufacturing routine and non-routine tasks, and start investing on high skill education for more knowledge-based jobs is a long-term investment

Source: Authors' own work

storage and retrieval and the pursuit of zero-waste activities (Byrne *et al.*, 2018). It includes new bio-inspired industrial processes, new models for production organisations including manufacturing systems and supply chains, emerging new chemistry, new materials and new products using biomaterials and bio-integration and bio-intelligent strategies for design, process and equipment, manufacturing, system and organisation. Some authors refer to the concept of Industry 5.0 for this, although disputed as a term and differentiation from Industry 4.0 (Müller, 2020). Leng *et al.* (2022) explains that Industry 4.0 integrates Information Technology (IT) and Operational Technology (OT) to facilitate mass customisation and personalisation with advanced intelligence, while Industry 5.0 synergizes human cognitive capabilities and intelligence with the efficiency, AI and precision of machines in industrial production. This approach emphasises human-centric values, fostering the development of a symbiotic ecosystem.

3.4 Environmental impact

End-to-end engineering interconnects an entire lifecycle of a product, which can be used to optimise production loads. Manufacturers have defined their Industry 4.0 strategies to position themselves ahead of competitors. They are prepared to transition into the next generation of manufacturing and logistics with modular, efficient automation systems optimised through data analytics, ensuring comprehensive control over supply chain dynamics and material flow management. The integration of socially responsible and environmentally sustainable practices is imperative for manufacturing, resulting in substantial positive impacts on global health. When sustainability efforts are aligned with addressing business challenges, they can yield significant economic and environmental benefits. Embedding sustainable development as a core philosophy, rather than a secondary consideration, could fundamentally transform corporate operations (Javaid *et al.*, 2022).

To effectively address environmental challenges like waste management, resource optimisation, carbon neutrality and water conservation, advanced technologies such as AI and ML can be used (Tiwari and Khan, 2020).

As Davenport and Ronanki (2018) discussed, digital technologies provide can help to better understand customer demands, thus reducing overproduction and waste. Moreover, Yigitcanlar *et al.* (2020) highlighted that AI optimises energy production and consumption in conjunction with industrial value creation (Kanemura *et al.*, 2013). Industry 4.0 allows companies to implement intelligent energy systems, becoming part of a smart grid (Gabriel and Pessl, 2016; Tao *et al.*, 2016). The adoption of novel energy utilisation technologies, such as electric heating systems, electrified rail transit and electric vehicles, creates opportunities for innovative business models. Companies are increasingly harnessing various forms of renewable energy, facilitated by cutting-edge technologies See Table 4.

Further, additive manufacturing offers significant environmental advantages compared to conventional manufacturing technologies (Faludi *et al.*, 2015). It significantly reduces material consumption and waste creation, does not require using tools and coolants, and causes less pollution (Huang *et al.*, 2013). According to Cardeal *et al.*, 2020, one of the most frequently cited advantages of additive manufacturing is the potential for distributed production. Distributed manufacturing shifts production from large, centralised facilities to smaller, localised mini-factories nearer to the consumer. Additive manufacturing enables companies to substitute central warehouses with central data repositories, thereby facilitating distributed manufacturing. This transition can significantly reduce inventory costs and streamline supply chains by enhancing logistics and minimising transportation needs, ultimately lowering environmental impacts. Moreover, a key attribute of additive manufacturing is its capacity to fabricate complex components with fewer design limitations compared to traditional

Table 4. Industry 4.0 benefits and challenges across all three business model elements in environmental dimension of sustainability

Business model dimension	Benefits	Challenges
Value creation	Cognitive digital technologies provide insights into customer demands, eliminating overproduction; Maximise the energy utilisation, sharing resources through circular economy;	Resource efficiency and waste management, since a higher customisation, which is one of the Industry 4.0 main drivers, on the other hand, can create more energy consumption and waste material
Value delivery	Collaborative tools and sustainable practices, engaging customer and partners in a collective approach for exchange of materials, energy, water and products	Integrating sustainable practices into production processes, ensuring the entire chain adheres to environmental regulations can be costly and complex to implement and maintain
Value capture	New opportunities to trade/share resources by closing the loop of waste-to-resource streams within networks and create economic value from waste material	The initial investment required for adopting Industry 4.0 technologies can be high, and it can be challenging to balance these costs with the need to deliver environmental benefits

Source: Authors' own work

manufacturing processes. This attribute is crucial as it allows designers to optimise their designs, thereby enhancing performance. Indeed, numerous studies emphasise the use of additive manufacturing to reengineer components, such as reducing the weight of aircraft, which in turn decreases fuel consumption. This technological advancement offers substantial benefits to society from both economic and environmental perspectives (Cardeal *et al.*, 2020).

The Circular Economy concept aims to reduce waste's environmental impact through recovery, reuse and recycling, reduce greenhouse gas emissions from raw material extraction and create economic value from waste material. It can be significantly enhanced through digital tools and technologies that characterise Industry 4.0 (Awan *et al.*, 2021). Embracing the circular economy requires collaboration among individual consumers, suppliers and manufacturers. The synergy between technological integration and the circular economy can enhance the efficiency and environmental sustainability of recycling and recovery processes. The adoption of smart technologies within the framework of the circular economy will foster trust, reliability, visibility and traceability among all stakeholders (Tang *et al.*, 2022).

Conclusively, Industry 4.0 allows the development of an integrated sustainable manufacturing approach engaging traditionally separate companies in a collective approach to share resources by closing the loop of waste-to-resource streams within industrial value creation (Stock *et al.*, 2018). For Tang *et al.* (2022), the integration of Industry 4.0 technologies will facilitate sustained technological advancement within organisations, yielding numerous benefits in environmental conservation.

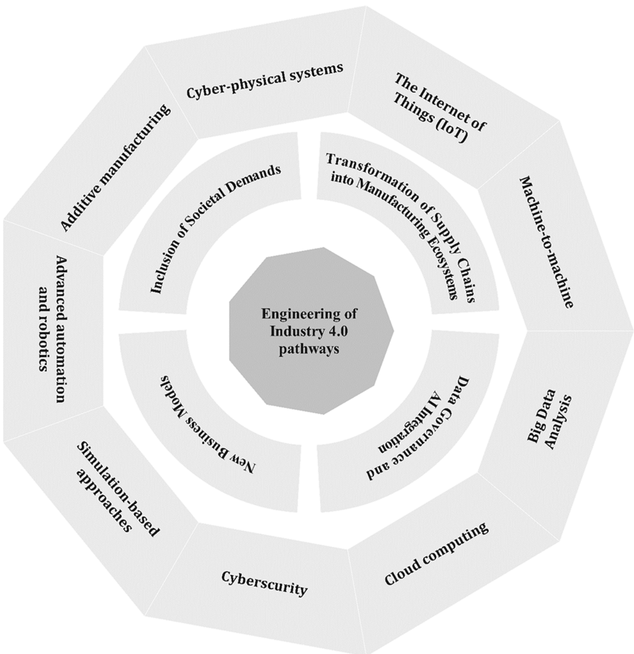
4. Contribution to literature and proposition development

Based on the literature review described in Section 3.1, we contribute to extant literature by providing the following analysis: Sections 3.2–3.2 present a perspective on engineering sustainability through the prism of Industry 4.0 technologies. After reviewing the nine leading technologies underpinning Industry 4.0 in the extant literature, we describe their current impact on economic, environmental and social sustainability dimensions.

Based on this literature review, we develop four propositions for the future of Industry 4.0 to engineer sustainability potentials to extend extant research. These propositions are envisioned to go beyond the research of Industry 4.0 in the last decade, extending beyond industrial manufacturing and towards a potential yet disputed concept of Industry 5.0 (Müller, 2020) and realising the perspective of industrial value creation (Kagermann *et al.*, 2013) towards societal demands into manufacturing ecosystems (Kazantsev *et al.*, 2023). Further, the propositions can be combined as well as regarded individually. Figure 2 below summarises the nine technological pillars of Industry 4.0 and the four propositions:

P1. The Further Development of Industry 4.0 Towards Societal Demands.

The key technologies enabling Industry 4.0 facilitate a paradigm shift from mass production to mass customisation of products and services, thus addressing customer expectations and societal needs directly (Dahmani *et al.*, 2021). For example, companies like Adidas are using 3D printing to create custom shoes tailored to individual customers' foot shapes and preferences. Further digitalisation will extend its impact on social and environmental areas, such as smart cities and smart societies (Chauhan *et al.*, 2021). Smart cities are leveraging IoT and AI to optimise traffic flow, reduce energy consumption and enhance public safety. This encompasses renewable energy production and consumption, urban production, and the



Source: Authors' own work

Figure 2. Nine technological pillars of Industry 4.0 and summary of propositions

relocalisation of manufacturing to consumption sites. By intertwining Industry 4.0 and societal demands, further exploration should include smart energy, smart health and smart mobility (Vasconcellos *et al.*, 2023). For instance, telemedicine platforms enabled by Industry 4.0 technologies are expanding healthcare access, especially in remote areas. This vision, placing people and society at its centre, promises significant progress for the economy and society.

This transition closely aligns with the concept of Industry 5.0, which places humans and societal needs at the forefront of technological advancements, but is yet debated as a concept (Müller, 2020). Industry 5.0 extends Industry 4.0's digital innovations by integrating human-centric approaches, promoting collaboration between humans and machines to achieve greater personalisation and sustainability. This synergy aims to create a balanced relationship between technology, societal well-being and environmental stewardship, suggesting that Industry 5.0 could be a natural progression from the advanced capabilities developed during Industry 4.0 (Leng *et al.*, 2022). Future research must determine if this represents an extension of Industry 4.0 technologies with a broader focus or a new conceptual framework altogether:

P2. Industry 4.0 will Gradually Transform Supply Chains into Manufacturing Ecosystems.

Industry 4.0 supports new strategies of distributed manufacturing, enabling manufacturing ecosystems to emerge (Kazantsev *et al.*, 2023). Traditional value chains will be replaced by modular, reconfigurable networks of providers and consumers (Veile *et al.*, 2024), allowing each client to act as a platform operator. Companies like Amazon Web Services provide cloud-based platforms that allow businesses to use and repurpose resources dynamically. This transformation increases the need for compatibility and seamless operation across various systems, devices and processes, from the factory floor to enterprise business systems and the entire ecosystem (Givehchi *et al.*, 2017).

Ecosystems foster collaboration, innovation, capacity sharing and bottleneck avoidance (Benitez *et al.*, 2020; Kazantsev *et al.*, 2023; Schmidt *et al.*, 2023). For example, Siemens' MindSphere platform enables different manufacturers to share data and insights, fostering innovation. Future research should focus on the emergence and evolution of these manufacturing ecosystems driven by Industry 4.0 technologies:

P3. The Sustainability Impact of Industry 4.0 will depend on Data Governance and AI Integration.

Despite the numerous benefits of Industry 4.0, companies face high risks related to data sharing due to security concerns, data leaks and the potential vulnerability of know-how and intellectual property (Müller *et al.*, 2024). For example, the healthcare sector, which increasingly relies on AI and big data, faces significant challenges in maintaining patient confidentiality. Data sharing and transparency in Industry 4.0 supply chains are critical, necessitating further research on AI and data governance in manufacturing (Veile *et al.*, 2024). Additionally, balancing social motivations with data security compliance poses a significant challenge (Yavuz *et al.*, 2023). In response, companies are developing blockchain solutions to enhance data transparency while ensuring security (Lohmer *et al.*, 2024).

Thus, societal readiness to share meaningful data will impact the efficiency of emerging AI applications, which offer vast potential but also raise ethical concerns (Ahmed *et al.*, 2022; Jan *et al.*, 2023). The future sustainability impact of Industry 4.0 will depend on robust data governance frameworks and responsible AI integration (Lohmer *et al.*, 2024):

P4. Engineering Sustainability via Industry 4.0 requires New Business Models.

Industry 4.0 presents significant challenges to companies, necessitating new business models that consider these risks (Müller *et al.*, 2024) and the new value emerging from impacts on value creation, but especially social aspects. As customer expectations shift from merely purchasing products to seeking solutions that address specific issues and provide tangible value, companies may need to adopt service-oriented and sustainability-oriented business models (Gebauer *et al.*, 2021). For instance, performance in terms of environmental or social value could be valued directly, besides an economic value generated (Lerman *et al.*, 2024).

Sustainable business models are essential for supporting sustainability engineering, raising questions about integrating environmental or social value into business model logic (Khan *et al.*, 2021; Luthra *et al.*, 2021). However, the paradox of firms investing in digital business models and servitisation without achieving positive results persists (Gebauer *et al.*, 2021). Research could examine how companies like Philips have successfully transitioned to circular economy models by refurbishing and reselling medical equipment. Future research should explore generating value from digital business models across all dimensions using Industry 4.0 technologies, particularly considering systems level view on business model innovation (Velu, 2017).

5. Conclusion

5.1 Practical implications

The progression of Industry 4.0 towards addressing societal demands holds significant practical implications for businesses and communities. For managers, they must adapt their manufacturing processes to be more flexible and responsive to individual customer needs. This requires investments in advanced technologies such as 3D printing, robotics and IoT, which can facilitate on-demand production and enhance product personalisation.

Practitioners must further introduce data analytics, AI and ML into their operations to optimise efficiency and innovation. The development of smart factories, where machines and systems are interconnected and communicate seamlessly, will be crucial for staying competitive. This also entails significant changes in supply chain management as traditional linear supply chains evolve into dynamic, reconfigurable ecosystems.

From a societal perspective, the implementation of smart city initiatives, driven by Industry 4.0 technologies, promises to improve urban living conditions through enhanced energy management, transportation systems and healthcare services. Practical applications include deploying smart grids for efficient energy distribution, intelligent traffic management systems to reduce congestion and telemedicine platforms to expand healthcare access.

Managers must also consider the workforce implications. Employees will need reskilling and upskilling to handle new technologies and processes. Continuous professional development and training programs will be essential to equip workers with the necessary skills.

Finally, strategic investments must be made into adaptive Industry 4.0 business models that develop towards the transition value creation into of Industry 4.0 ecosystems while addressing societal demands.

5.2 Policy implications

The advancements in Industry 4.0 and its transition towards addressing societal demands necessitate proactive and adaptive policy frameworks. Governments must create supportive regulatory environments encouraging innovation while ensuring ethical standards and data security. Policies should promote investment in digital infrastructure, such as high-speed internet and IoT technologies, foundational to Industry 4.0 advancements. Furthermore, regulatory frameworks must address the interoperability of systems and standards to facilitate seamless integration across various platforms and industries.

Policymakers should also consider incentives for sustainable practices within Industry 4.0, such as tax breaks or subsidies for companies adopting renewable energy technologies or engaging in urban production and relocalisation efforts. These incentives could drive the shift towards smart cities and societies, contributing to broader environmental goals and connecting to the objectives of the Industry 5.0 concept.

Data governance and security are critical areas where robust policies are needed to protect intellectual property and personal data while fostering a culture of transparency and trust. This includes developing international standards for data sharing and AI ethics and ensuring that advancements in AI and ML are aligned with societal values and privacy concerns.

Additionally, education and workforce development policies must evolve to address the skills gap in Industry 4.0 technologies. Governments should foster education and continuous learning programs to prepare the workforce for new roles in Industry 4.0 ecosystems.

Finally, policies should support collaborative research and development initiatives, facilitating partnerships between academia, industry and government to drive innovation and address the complex challenges posed by integrating Industry 4.0 technologies. By aligning policies with the goals of Industry 4.0, governments can help ensure that technological advancements lead to sustainable economic growth and societal well-being. This also includes merging different research disciplines better.

5.3 Limitations

Literature reviews are not without limitations. A significant issue is the quality and heterogeneity of the included studies. Studies may vary in their design, methodology and execution quality, which can lead to inconsistencies. This heterogeneity can complicate the synthesis process.

Further, the search strategy used in literature reviews can introduce a selection bias. If the search is not exhaustive or uses overly restrictive criteria, important studies might be missed. This problem is compounded by the reliance on specific databases and search terms, which may not capture all relevant literature. Subjective decisions in study selection, data extraction and interpretation can further influence the findings.

5.4 Future research

Firstly, future research should investigate several key areas to fully realise the potential of Industry 4.0 in addressing societal demands. One crucial area is the development and refinement of DT technologies. Researchers should explore how DTs can be effectively integrated across various industries and connect better to recent concepts introduced, such as the industrial metaverse.

Secondly, another promising research avenue is the ethical and societal implications of AI and ML within Industry 4.0. Studies should focus on developing robust frameworks for AI governance that balance innovation with ethical considerations, privacy concerns and data security. This includes investigating the societal readiness for AI integration and the willingness to share data in a secure and transparent manner.

Thirdly, the intersection of Industry 4.0 and the Circular Economy warrants further exploration. Research should examine how digital manufacturing technologies can contribute to circular economy models, reducing waste and promoting resource efficiency. Investigating the role of Industry 4.0 in supporting renewable energy adoption and smart energy management systems can be of further interest in this regard.

Fourthly, future research should address the challenges and opportunities of workforce transformation in the context of Industry 4.0. This involves studying effective strategies for reskilling and upskilling the workforce, assessing the impact of new technologies on job roles and exploring the socio-economic implications of widespread automation.

Fifthly, the evolution of business models in the digital age is a critical area for investigation. Researchers should analyse how businesses can successfully transition to service-oriented and sustainability-oriented models, identifying best practices for different industries. This includes evaluating the effectiveness of different business models in generating value from specific digital technologies individually. Thus, future research should aim to better connect Industry 4.0, sustainability, and associated topics with relevant theories and theoretical concepts.

Notes

1. www.boschrexroth.com/en/gb/manufacture-likeabosch/ (accessed 20 September 2023).
2. The Manufacturer. www.themanufacturer.com/articles/ventilatorchallengeuk-takes-abreath-afterdelivering-almost-13500-units-to-nhs (accessed 20 September 2023).
3. Humanitarian Makers. www.humanitarianmakers.org (accessed 22 December 2020).

References

Adner, R. (2017), "Ecosystem as structure", *Journal of Management*, Vol. 43 No. 1, pp. 39-58.

Adner, R. and Kapoor, R. (2010), "Value creation in innovation ecosystems: how the structure of technological interdependence affects firm performance in new technology generations", *Strategic Management Journal*, Vol. 31 No. 3, pp. 306-333.

Ahmed, I., Jeon, G. and Piccialli, F. (2022), "From artificial intelligence to explainable artificial intelligence in industry 4.0: a survey on what, how, and where", *IEEE Transactions on Industrial Informatics*, Vol. 18 No. 8, pp. 5031-5042.

Alguliyev, R., Imamverdiyev, Y. and Sukhostat, L. (2018), "Cyber-physical systems and their security issues", *Computers in Industry*, Vol. 100, pp. 212-223.

Alkaraan, F., Elmarzouky, M., Hussainey, K. and Venkatesh, V.G. (2023), "Sustainable strategic investment decision-making practices in UK companies: the influence of governance mechanisms on synergy between industry 4.0 and circular economy", *Technological Forecasting and Social Change*, Vol. 187, p. 122187.

Almada-Lobo, F. (2016), "The industry 4.0 revolution and the future of manufacturing execution systems (MES)", *Journal of Innovation Management*, Vol. 3 No. 4, pp. 16-21.

Awan, U., Sroufe, R. and Shahbaz, M. (2021), "Industry 4.0 and the circular economy: a literature review and recommendations for future research", *Business Strategy and the Environment*, Vol. 30 No. 4, pp. 2038-2060.

Bai, C., Dallasega, P., Orzes, G. and Sarkis, J. (2020), "Industry 4.0 technologies assessment: a sustainability perspective", *International Journal of Production Economics*, Vol. 229, pp. 1-15.

Baines, T.S., Lightfoot, H.W., Benedettini, O. and Kay, J.M. (2009), "The servitisation of manufacturing", *Journal of Manufacturing Technology Management*, Vol. 20 No. 5, pp. 547-567.

Batz, A., Kunath, M. and Winkler, H. (2018), "Discrepancies between cluster services and SMEs' needs constraining the creation of a culture of innovation amidst industry 4.0", *Logforum*, Vol. 14 No. 3, pp. 387-405.

Bauernhansl, T., Ten Hompel, M. and Vogel-Heuser, B. (2014), *Industrie 4.0 in Produktion, Automatisierung Und Logistik: Anwendung-Technologien-Migration*, Springer, Wiesbaden.

BCG (2023), "Climate action starts with supply chains", available at: www.bcg.com/publications/2023/climate-change-starts-with-supply-chains (accessed 20 October 2023).

Benitez, G.B., Ayala, N.F. and Frank, A.G. (2020), "Industry 4.0 innovation ecosystems: an evolutionary perspective on value cocreation", *International Journal of Production Economics*, Vol. 228, pp. 107713-107735.

Bessant, J. (2018), *The Great Transformation*, Routledge.

Beuren, F.H., Gomes Ferreira, M.G. and Cauchick Miguel, P.A. (2013), "Product-service systems: a literature review on integrated products and services", *Journal of Cleaner Production*, Vol. 47, pp. 222-231.

Brynjolfsson, E. and McAfee, A. (2011), *Race against the Machine: How the Digital Revolution is Accelerating Innovation, Driving Productivity, and Irreversibly Transforming Employment and the Economy*, Cambridge, USA.

Byrne, G., Dimitrov, D., Monostori, L., Teti, R., Van Houten, F. and Wertheim, R. (2018), "Biologicalisation: biological transformation in manufacturing", *CIRP Journal of Manufacturing Science and Technology*, Vol. 21, pp. 1-32.

Cai, Y., Starly, B., Cohen, P. and Lee, Y.-S. (2017), "Sensor data and information fusion to construct digital-twins virtual machine tools for cyber-physical manufacturing", *Procedia Manufacturing*, Vol. 10, pp. 1031-1042.

Camarinha-Matos, L.M., Fornasiero, R. and Afsarmanesh, H. (2017), "Collaborative networks as a core enabler of industry 4.0", *Working Conference on Virtual Enterprises*, pp. 3-17.

Cardeal, G., Höse, K., Ribeiro, I. and Götze, U. (2020), "Sustainable business models–canvas for sustainability, evaluation method, and their application to additive manufacturing in aircraft maintenance", *Sustainability*, Vol. 12 No. 21, p. 9130.

Cardoso, J., Voigt, K. and Winkler, M. (2009), "Service engineering for the internet of services", *Enterprise Information Systems*, Berlin, Heidelberg, pp. 15-27.

Carvalho, T.P., Soares, F.A.A.M.N., Vita, R., Francisco, R.D.P., Basto, J.P. and Alcalá, S.G.S. (2019), "A systematic literature review of machine learning methods applied to predictive maintenance", *Computers and Industrial Engineering*, Vol. 137, pp. 1-10.

Chauhan, A., Jakhar, S.K. and Chauhan, C. (2021), "The interplay of circular economy with industry 4.0 enabled smart city drivers of healthcare waste disposal", *Journal of Cleaner Production*, Vol. 279, p. 123854.

Ching, N.T., Ghobakhloo, M., Iranmanesh, M., Maroufkhani, P. and Asadi, S. (2022), "Industry 4.0 applications for sustainable manufacturing: a systematic literature review and a roadmap to sustainable development", *Journal of Cleaner Production*, Vol. 334, p. 130133.

Cimino, C., Negri, E. and Fumagalli, L. (2019), "Review of digital twin applications in manufacturing", *Computers in Industry*, Vol. 113, pp. 1-15.

Cipresso, P., Giglioli, I.A.C., Raya, M.A. and Riva, G. (2018), "The past, present, and future of virtual and augmented reality research: a network and cluster analysis of the literature", *Frontiers in Psychology*, Vol. 9 No. 2086, pp. 1-10.

Dahmani, N., Benhida, K., Belhadi, A., Kamble, S., Elfezazi, S. and Jauhar, S.K. (2021), "Smart circular product design strategies towards eco-effective production systems: a lean eco-design industry 4.0 framework", *Journal of Cleaner Production*, Vol. 320, p. 128847.

Damiani, L., Demartini, M., Guizzi, G., Revetria, R. and Tonelli, F. (2018), "Augmented and virtual reality applications in industrial systems: a qualitative review towards the industry 4.0 era", *IFAC-PapersOnLine*, Vol. 51 No. 11, pp. 624-630.

Davenport, T.H. and Ronanki, R. (2018), "Artificial intelligence for the real world", *Harvard Business Review*, Vol. 96 No. 1, pp. 108-116.

De Paula Ferreira, W., Armellini, F. and De Santa-Eulalia, L.A. (2020), "Simulation in industry 4.0: a state-of-the-art review", *Computers and Industrial Engineering*, Vol. 149, pp. 1-17.

De Sousa Jabbour, A.B.L., Jabbour, C.J.C., Foropon, C. and Godinho Filho, M. (2018), "When titans meet – can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors", *Technological Forecasting and Social Change*, Vol. 132, pp. 18-25.

Eccles, R.G. (2022), available at: https://impactalpha.com/cant-tell-the-players-without-a-scorecard-sorting-out-esg-impact-and-sustainability/

Elkington, J. (1998), "Partnerships from cannibals with forks: the triple bottom line of 21st-century business", *Environmental Quality Management*, Vol. 8 No. 1, pp. 37-51.

Enyoghasi, C. and Badurdeen, F. (2021), "Industry 4.0 for sustainable manufacturing: opportunities at the product, process, and system levels", *Resources, Conservation and Recycling*, Vol. 166, p. 105362.

Faludi, J., Bayley, C., Bhogal, S. and Iribarne, M. (2015), "Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment", *Rapid Prototyping Journal*, Vol. 21 No. 1, pp. 14-33.

Findik, D., Tirgil, A. and Özbuğday, F.C. (2023), "Industry 4.0 as an enabler of circular economy practices: evidence from European SMEs", *Journal of Cleaner Production*, Vol. 410, p. 137281.

Frank, A.G., Dalenogare, L.S. and Ayala, N.F. (2019), "Industry 4.0 technologies: implementation patterns in manufacturing companies", *International Journal of Production Economics*, Vol. 210, pp. 15-26.

Gabriel, M. and Pessl, E. (2016), "Analysis of environmental potential by implementing", *Industry 4.0. Industry 4.0*, Vol. 1 No. 2, pp. 141-144.

Gao, R., Wang, L., Teti, R., Dornfeld, D., Kumara, S., Mori, M. and Helu, M. (2015), "Cloud-enabled prognosis for manufacturing", *CIRP Annals*, Vol. 64 No. 2, pp. 749-772.

Gebauer, H., Paiola, M., Saccani, N. and Rapaccini, M. (2021), "Digital servitisation: crossing the perspectives of digitisation and servitisation", *Industrial Marketing Management*, Vol. 93, pp. 382-388.

Ghisellini, P., Cialani, C. and Ulgiati, S. (2016), "A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems", *Journal of Cleaner Production*, Vol. 114, pp. 11-32.

Ghobakhloo, M. (2020), "Industry 4.0, digitisation, and opportunities for sustainability", *Journal of Cleaner Production*, Vol. 252, pp. 1-21.

Givehchi, O., Landsdorf, K., Simoens, P. and Colombo, A.W. (2017), "Interoperability for industrial Cyber-Physical systems: an approach for legacy systems", *IEEE Transactions on Industrial Informatics*, Vol. 13 No. 6, pp. 3370-3378.

Hahn, G.J. (2020), "Industry 4.0: a supply chain innovation perspective", *International Journal of Production Research*, Vol. 58 No. 5, pp. 1425-1441.

Hannah, D.P. and Eisenhardt, K.M. (2018), "How firms navigate cooperation and competition in nascent ecosystems", *Strategic Management Journal*, Vol. 39 No. 12, pp. 3163-3192.

Hens, L., Block, C., Cabello-Eras, J.J., Sagastume-Gutierez, A., Garcia-Lorenzo, D., Chamorro, C., Herrera Mendoza, K., Haeseldonckx, D. and Vandecasteele, C. (2018), "On the evolution of 'cleaner production' as a concept and a practice", *Journal of Cleaner Production*, Vol. 172, pp. 3323-3333.

Hermann, M., Pentek, T. and Otto, B. (2016), "Design principles for industrie 4.0 scenarios", *2016 49th HI international conference on system sciences (HICSS)*, pp. 3928-3937.

Herrmann, C., Schmidt, C., Kurle, D., Blume, S. and Thiede, S. (2014), "Sustainability in manufacturing and factories of the future", *International Journal of Precision Engineering and Manufacturing-Green Technology*, Vol. 1 No. 4, pp. 283-292.

Hidayatno, A., Destyanto, A.R. and Hulu, C.A. (2019), "Industry 4.0 technology implementation impact to industrial sustainable energy in Indonesia: a model conceptualisation", *Energy Procedia*, Vol. 156, pp. 227-233.

Hofmann, E. and Rüsch, M. (2017), "Industry 4.0 and the current status as well as future prospects on logistics", *Computers in Industry*, Vol. 89, pp. 23-34.

Holmström, J. and Partanen, J. (2014), "Digital manufacturing-driven transformations of service supply chains for complex products", *Supply Chain Management: An International Journal*, Vol. 19 No. 4, pp. 421-430.

Huang, S.H., Liu, P., Mokasdar, A. and Hou, L. (2013), "Additive manufacturing and its societal impact: a literature review", *The International Journal of Advanced Manufacturing Technology*, Vol. 67 Nos 5/8, pp. 1191-1203.

Huang, M.-H. and Rust, R.T. (2018), "Artificial intelligence in service", *Journal of Service Research*, Vol. 21 No. 2, pp. 155-172.

Ibarra, D., Bigdeli, A.Z., Igartua, J.I. and Ganzarain, J. (2020), "Business model innovation in established SMEs: a configurational approach", *Journal of Open Innovation: Technology, Market, and Complexity*, Vol. 6 No. 3, pp. 1-22.

Iivari, M.M., Ahokangas, P., Komi, M., Tihinen, M. and Valtanen, K. (2016), "Toward ecosystemic business models in the context of industrial internet", *Journal of Business Models*, Vol. 4 No. 2, pp. 42-59.

Jan, Z., Ahamed, F., Mayer, W., Patel, N., Grossmann, G., Stumptner, M. and Kuusk, A. (2023), "Artificial intelligence for industry 4.0: systematic review of applications, challenges, and opportunities", *Expert Systems with Applications*, Vol. 216, p. 119456.

Javaid, M., Haleem, A., Singh, R.P., Suman, R. and Gonzalez, E.S. (2022), "Understanding the adoption of industry 4.0 technologies in improving environmental sustainability", *Sustainable Operations and Computers*, Vol. 3, pp. 203-217.

Jones, D., Snider, C., Nassehi, A., Yon, J. and Hicks, B. (2020), "Characterising the digital twin: a systematic literature review", *CIRP Journal of Manufacturing Science and Technology*, Vol. 29, pp. 36-52.

Kagermann, H., Helbig, J., Hellinger, A. and Wahlster, W. (2013), *Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0: Securing the Future of German Manufacturing Industry, Industrie 4.0 Working Group, Issue.*

Kamble, S.S., Gunasekaran, A. and Gawankar, S.A. (2018), "Sustainable industry 4.0 framework: a systematic literature review identifying the current trends and future perspectives", *Process Safety and Environmental Protection*, Vol. 117, pp. 408-425.

Kanemura, A., Morales, Y., Kawanabe, M., Morioka, H., Kallakuri, N., Ikeda, T., Miyashita, T., Hagita, N. and Ishii, S. (2013), "A waypoint-based framework in brain-controlled smart home environments: brain interfaces, domotics, and robotics integration", IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 865-870.

Katzy, B.R. and Crowston, K. (2008), "Competency rallying for technical innovation–the case of the virtuelle fabrik", *Technovation*, Vol. 28 No. 10, pp. 679-692.

Kazantsev, N. (2022), *Supporting SME Collaborations in Low-Volume High-Variability Manufacturing*, The University of Manchester (United Kingdom), Manchester.

Kazantsev, N., Petrovskyi, O. and Müller, J.M. (2023), "From supply chains towards manufacturing ecosystems: a system dynamics model", *Technological Forecasting and Social Change*, Vol. 197, p. 122917.

Kazantsev, N., Pishchulov, G., Mehandjiev, N., Sampaio, P. and Zolkiewski, J. (2022), "Investigating barriers to demand-driven SME collaboration in low-volume high-variability manufacturing", *Supply Chain Management: An International Journal*, Vol. 27 No. 2, pp. 265-282.

Khan, I.S., Ahmad, M.O. and Majava, J. (2021), "Industry 4.0 and sustainable development: a systematic mapping of triple bottom line, circular economy and sustainable business models perspectives", *Journal of Cleaner Production*, Vol. 297, p. 126655.

Khanzode, A.G., Sarma, P.R.S., Mangla, S.K. and Yuan, H. (2021), "Modeling the industry 4.0 adoption for sustainable production in micro, small and medium enterprises", *Journal of Cleaner Production*, Vol. 279, p. 123489.

Kumar, R., Singh, R.K. and Dwivedi, Y.K. (2020), "Application of industry 4.0 technologies in SMEs for ethical and sustainable operations: analysis of challenges", *Journal of Cleaner Production*, Vol. 275, pp. 1-13.

Lee, J., Bagheri, B. and Kao, H.-A. (2015), "A cyber-physical systems architecture for industry 4.0-based manufacturing systems", *Manufacturing Letters*, Vol. 3, pp. 18-23.

Leng, J., Sha, W., Wang, B., Zheng, P., Zhuang, C., Liu, Q. and Wang, L. (2022), "Industry 5.0: prospect and retrospect", *Journal of Manufacturing Systems*, Vol. 65, pp. 279-295.

Lepenioti, K., Bousdekis, A., Apostolou, D. and Mentzas, G. (2020), "Prescriptive analytics: literature review and research challenges", *International Journal of Information Management*, Vol. 50, pp. 57-70.

Lerman, L.V., Benitez, G.B., Müller, J.M., de Sousa, P.R. and Frank, A.G. (2024), "When digital transformation meets supply chain needs in emerging markets: contributions for social and economic performance", *Supply Chain Management: An International Journal, in Press*, Vol. 29 No. 6.

Leung, T.C.H., Guan, J. and Lau, Y.Y. (2023), "Exploring environmental sustainability and green management practices: evidence from logistics service providers", *Sustainability Accounting, Management and Policy Journal*, Vol. 14 No. 3, pp. 461-489.

Liu, Z., Sampaio, P., Pishchulov, G., Mehandjiev, N., Cisneros-Cabrera, S., Schirrmann, A., Jiru, F. and Bnouhanna, N. (2022), "The architectural design and implementation of a digital platform for industry 4.0 SME collaboration", *Computers in Industry*, Vol. 138, p. 103623.

Lohmer, J., Birkel, H. and Müller, J.M. (2024), "The internet of value: towards a definition, framework, and understanding of its sustainability implications", *Technological Forecasting and Social Change*, Vol. 206, p. 123466.

Lopez, J., Rios, R., Bao, F. and Wang, G. (2017), "Evolving privacy: from sensors to the internet of things", *Future Generation Computer Systems*, Vol. 75, pp. 46-57.

Lu, Y., Liu, C., Wang, K.I.K., Huang, H. and Xu, X. (2020), "Digital twin-driven smart manufacturing: connotation, reference model, applications and research issues", *Robotics and Computer-Integrated Manufacturing*, Vol. 61, pp. 1-26.

Luthra, S., Mangla, S.K., Lopes de Sousa Jabbour, A.B. and Huisingh, D. (2021), "Industry 4.0, cleaner production, and circular economy: an important agenda for improved ethical business development", *Journal of Cleaner Production*, Vol. 326, p. 129370.

McKinsey (2015), *Industry 4.0 How to Navigate Digitisation of the Manufacturing Sector*, Detroit, MI.

MacCarthy, B.L., Blome, C., Olhager, J., Srai, J.S. and Zhao, X. (2016), "Supply chain evolution– theory, concepts and science", *International Journal of Operations and Production Management*, Vol. 36 No. 12, pp. 1696-1718.

Majstorovic, V.D. and Mitrovic, R. (2019), "Industry 4.0 programs worldwide", Springer International Publishing, Basel, pp. 78-99.

Manavalan, E. and Jayakrishna, K. (2019), "A review of internet of things (IoT) embedded sustainable supply chain for industry 4.0 requirements", *Computers and Industrial Engineering*, Vol. 127, pp. 925-953.

Martín-Martín, A., Orduna-Malea, E., Thelwall, M. and López-Cózar, E.D. (2018), "Google scholar, web of science, and scopus: a systematic comparison of citations in 252 subject categories", *Journal of Informetrics*, Vol. 12 No. 4, pp. 1160-1177.

Mehandjiev, N.D., Stalker, I.D. and Carpenter, M.R. (2007), "Activity coordination for flexible processes in instant virtual enterprises", pp. 1-2.

Mehrpouya, M., Dehghanghadikolaei, A., Fotovvati, B., Vosooghnia, A., Emamian, S.S. and Gisario, A. (2019), "The potential of additive manufacturing in the smart factory industrial 4.0: a review", *Applied Sciences*, Vol. 9 No. 18, pp. 1-34.

Menezes, B.C., Kelly, J.D., Leal, A.G. and Le Roux, G.C. (2019), "Predictive, prescriptive and detective analytics for smart manufacturing in the information age", *IFAC-PapersOnLine*, Vol. 52 No. 1, pp. 568-573.

Mittal, S., Khan, M.A., Romero, D. and Wuest, T. (2018), "A critical review of smart manufacturing and industry 4.0 maturity models: implications for small and medium-sized enterprises (SMEs)", *Journal of Manufacturing Systems*, Vol. 49, pp. 194-214.

Monostori, L., Kádár, B., Bauernhansl, T., Kondoh, S., Kumara, S., Reinhart, G., Sauer, O., Schuh, G., Sihn, W. and Ueda, K. (2016), "Cyber-physical systems in manufacturing", *CIRP Annals*, Vol. 65 No. 2, pp. 621-641.

Mont, O.K. (2002), "Clarifying the concept of product–service system", *Journal of Cleaner Production*, Vol. 10 No. 3, pp. 237-245.

Müller, J.M. (2020), *Enabling Technologies for Industry 5.0 – Results of a Workshop with Europe's Technology Leaders.*

Müller, J.M., Islam, N., Kazantsev, N., Romanello, R., Olivera, G., Das, D. and Hamzeh, R. (2024), "Barriers and enablers for industry 4.0 in SMEs: a combined integration framework", *IEEE Transactions on Engineering Management*, *in Press.*

Mulligan, G.F. and Crampton, J.P. (2005), "Population growth in the world's largest cities", *Cities*, Vol. 22 No. 5, pp. 365-380.

Nara, E.O.B., da Costa, M.B., Baierle, I.C., Schaefer, J.L., Benitez, G.B., do Santos, L.M.A.L. and Benitez, L.B. (2021), "Expected impact of industry 4.0 technologies on sustainable development: a study in the context of Brazil's plastic industry", *Sustainable Production and Consumption*, Vol. 25, pp. 102-122.

Osterwalder, A. and Pigneur, Y. (2010), *Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers*, Vol. 1, John Wiley and Sons, Hoboken.

Raddats, C., Zolkiewski, J., Story, V.M., Burton, J., Baines, T. and Ziaee Bigdeli, A. (2017), "Interactively developed capabilities: evidence from dyadic servitisation relationships", *International Journal of Operations and Production Management*, Vol. 37 No. 3, pp. 382-400.

Reeves, M., Lotan, H., Legrand, J. and Jacobides, M.G. (2019), "How business ecosystems rise (and often fall)", *MIT Sloan Management Review*, Vol. 60 No. 4, pp. 1-6.

Reyna, A., Martín, C., Chen, J., Soler, E. and Díaz, M. (2018), "On blockchain and its integration with IoT. challenges and opportunities", *Future Generation Computer Systems*, Vol. 88, pp. 173-190.

Ricci, A., Omicini, A. and Denti, E. (2002), "Virtual enterprises and workflow management as agent coordination issues", *International Journal of Cooperative Information Systems*, Vol. 11 No. 3n4, pp. 355-379.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P. and Harnisch, M. (2015), "Industry 4.0: the future of productivity and growth in manufacturing industries", *Boston Consulting Group*, Vol. 9 No. 1, pp. 54-89.

Salah, B., Abidi, M.H., Mian, S.H., Krid, M., Alkhalefah, H. and Abdo, A. (2019), "Virtual reality-based engineering education to enhance manufacturing sustainability in industry 4.0", *Sustainability*, Vol. 11 No. 5, pp. 1477.

Santos, M.Y., Oliveira E Sá, J., Andrade, C., Vale Lima, F., Costa, E., Costa, C., Martinho, B. and Galvão, J. (2017), "A big data system supporting bosch braga industry 4.0 strategy", *International Journal of Information Management*, Vol. 37 No. 6, pp. 750-760.

Sartal, A., Bellas, R., Mejías, A.M. and García-Collado, A. (2020), "The sustainable manufacturing concept, evolution and opportunities within industry 4.0: a literature review", *Advances in Mechanical Engineering*, Vol. 12 No. 5, pp. 1-17.

Savitz, A. and Weber, K. (2006), *The Triple Bottom Line: how Todays Best Run Companies Are Achieving Economic, Social and Environmental Success–and How You Can Too*, John Wiley and Sons, Hoboken.

Schleich, B., Anwer, N., Mathieu, L. and Wartzack, S. (2017), "Shaping the digital twin for design and production engineering", *CIRP Annals*, Vol. 66 No. 1, pp. 141-144.

Schmidt, M.-C., Veile, J.W., Müller, J.M. and Voigt, K.I. (2019), "Kick-start for connectivity: how to implement digital platforms successfully in industry 4.0", *Technology Innovation Management Review*, Vol. 9 No. 10.

Schmidt, M.-C., Veile, J.W., Müller, J.M. and Voigt, K.-I. (2023), "Industry 4.0 implementation in the supply chain: a review on the evolution of buyer-supplier relationships", *International Journal of Production Research*, Vol. 61 No. 17, pp. 6063-6080.

Smit, J., Kreutzer, S., Moeller, C. and Carlberg, M. (2016), *Industry 4.0 – Study for the ITRE Committee*, European Parliament, Brussels.

Smith, G., Ofe, H.A. and Sandberg, J. (2016), "Digital service innovation from open data: exploring the value proposition of an open data marketplace", *2016 49th HI International Conference on System Sciences (HICSS)*, pp. 1277-1286.

Sokolov, B. and Ivanov, D. (2015), "Integrated scheduling of material flows and information services in industry 4.0 supply networks", *IFAC-PapersOnLine*, Vol. 48 No. 3, pp. 1533-1538.

Stock, T., Obenaus, M., Kunz, S. and Kohl, H. (2018), "Industry 4.0 as enabler for a sustainable development: a qualitative assessment of its ecological and social potential", *Process Safety and Environmental Protection*, Vol. 118, pp. 254-267.

Tang, C.S. and Veelenturf, L.P. (2019), "The strategic role of logistics in the industry 4.0 era", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 129, pp. 1-11.

Tang, Y.M., Chau, K.Y., Fatima, A. and Waqas, M. (2022), "Industry 4.0 technology and circular economy practices: business management strategies for environmental sustainability", *Environmental Science and Pollution Research*, Vol. 29 No. 33, pp. 49752-49769.

Tao, F., Wang, Y., Zuo, Y., Yang, H. and Zhang, M. (2016), "Internet of things in product life-cycle energy management", *Journal of Industrial Information Integration*, Vol. 1, pp. 26-39.

Timmermans, J., Yaghmaei, E., Stahl, B.C. and Brem, A. (2017), "Research and innovation processes revisited–networked responsibility in industry", *Sustainability Accounting, Management and Policy Journal*, Vol. 8 No. 3, pp. 307-334.

Tiwari, K. and Khan, M.S. (2020), "Sustainability accounting and reporting in the industry 4.0", *Journal of Cleaner Production*, Vol. 258, pp. 1-14.

Toktaş-Palut, P. (2022), "Analysing the effects of industry 4.0 technologies and coordination on the sustainability of supply chains", *Sustainable Production and Consumption*, Vol. 30, pp. 341-358.

Tranfield, D., Denyer, D. and Smart, P. (2003), "Towards a methodology for developing evidence-informed management knowledge by means of systematic review", *British Journal of Management*, Vol. 14 No. 3, pp. 207-222.

Tukker, A. (2004), "Eight types of product–service system: eight ways to sustainability? Experiences from suspronet", *Business Strategy and the Environment*, Vol. 13 No. 4, pp. 246-260.

Vasconcellos, L., Ferreira, F.C. and Sakuramoto, C. (2023), "A life-saving collaborative network: repairing ventilators in Brazil", *Revista de Gestão*, Vol. 31 No. 4.

Veile, J.W., Schmidt, M.C., Müller, J.M. and Voigt, K.I. (2024), "The transformation of supply chain collaboration and design through industry 4.0", *International Journal of Logistics Research and Applications*, Vol. 27 No. 6, pp. 986-1014.

Velu, C. (2017), "A systems perspective on business model evolution: the case of an agricultural information service provider in India", *Long Range Planning*, Vol. 50 No. 5, pp. 603-620.

Verma, P., Kumar, V., Daim, T., Sharma, N.K. and Mittal, A. (2022), "Identifying and prioritising impediments of industry 4.0 to sustainable digital manufacturing: a mixed method approach", *Journal of Cleaner Production*, Vol. 356, p. 131639.

Wang, S., Wan, J., Li, D. and Zhang, C. (2016), "Implementing smart factory of industrie 4.0: an outlook", *International Journal of Distributed Sensor Networks*, Vol. 12 No. 1, pp. 1-10.

Wassmer, U., Paquin, R. and Sharma, S. (2014), "The engagement of firms in environmental collaborations", *Business and Society*, Vol. 53 No. 6, pp. 754-786.

Wced, S.W.S. (1987), "World commission on environment and development", *Our Common Future*, Vol. 17 No. 1, pp. 1-91.

Wu, D., Liu, X., Hebert, S., Gentzsch, W. and Terpenny, J. (2017), "Democratising digital design and manufacturing using high performance cloud computing: performance evaluation and benchmarking", *Journal of Manufacturing Systems*, Vol. 43, pp. 316-326.

Xu, X. (2012), "From cloud computing to cloud manufacturing", *Robotics and Computer-Integrated Manufacturing*, Vol. 28 No. 1, pp. 75-86.

Yadav, G., Kumar, A., Luthra, S., Garza-Reyes, J.A., Kumar, V. and Batista, L. (2020), "A framework to achieve sustainability in manufacturing organisations of developing economies using industry 4.0 technologies' enablers", *Computers in Industry*, Vol. 122, p. 103280.

Yavuz, O., Uner, M.M., Okumus, F. and Karatepe, O.M. (2023), "Industry 4.0 technologies, sustainable operations practices and their impacts on sustainable performance", *Journal of Cleaner Production*, Vol. 387, p. 135951.

Yigitcanlar, T., Desouza, K.C., Butler, L. and Roozkhosh, F. (2020), "Contributions and risks of artificial intelligence (AI) in building smarter cities: insights from a systematic review of the literature", *Energies*, Vol. 13 No. 6, pp. 1-38.

Yu, Z., Khan, S.A.R. and Umar, M. (2022), "Circular economy practices and industry 4.0 technologies: a strategic move of automobile industry", *Business Strategy and the Environment*, Vol. 31 No. 3, pp. 796-809.

Zhang, Y., Ren, S., Liu, Y. and Si, S. (2017), "A big data analytics architecture for cleaner manufacturing and maintenance processes of complex products", *Journal of Cleaner Production*, Vol. 142, pp. 626-641.

Zhou, K., Taigang, L. and Lifeng, Z. (2015), "Industry 4.0: towards future industrial opportunities and challenges", *Proceedings of 12th International Conference on Fuzzy Systems and Knowledge Discovery*.

Author affiliations

Julian M. Müller, Friedrich-Alexander-Universität Erlangen-Nürnberg, Nürnberg, Germany and Private University Schloss Seeburg, Seekirchen am Wallersee, Austria

Nikolai Kazantsev, Institute for Manufacturing (IfM), Cambridge University, Cambridge, UK

Richard Allmendinger and Amirhossein Salehi-Amiri, Alliance Manchester Business School, The University of Manchester, Manchester, UK

Jacqueline Zonichenn Reis, Universidade Paulista, Sao Paulo, Brazil

Shaden Jaradat, Faculty of Science and Engineering, The University of Manchester, Manchester, UK

Helena Bartolo, Department of Civil Engineering, Polytechnic Institute of Leiria, Leiria, Portugal, and

Paulo Jorge Da Silva Bartolo, Singapore Centre for 3D Printing, Nanyang Technological University, Singapore, Singapore

Corresponding author
Julian M. Müller can be contacted at: julian.mueller@fau.de