Driving smartness for organizational performance through Industry 4.0: a systems perspective

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Abstract

Purpose – The internationalization of business has grown the production value chains and created performance challenges for industrial production. Industry 4.0, the digital transformation of industrial processes, promises to deliver performance improvements through smart functionalities. This study investigates how digital transformation translates to performance gain by adopting a systems perspective to drive smartness.

Design/methodology/approach – This study uses qualitative research to collect data on the lived experiences of digital transformation practitioners for theory development. It uses semi-structured interviews with industry experts and applies the Gioia methodology for analysis.

Findings – The study determined that enterprise smartness is an organizational capability developed by digital transformation, it is a function of integration and the enabler of organizational performance gains in the Industry 4.0 context. The study determined that performance gains are experienced in productivity, sustainability, safety and customer experience, which represents performance metrics for Industry 4.0.

Research limitations/implications – This study contributes a model that inserts smartness in the linkage between digital transformation and organizational outcomes to the digital transformation and production management literature.

Practical implications – The study indicates that digital transformation programs should focus on developing smartness rather than technology implementations, which must be considered an enabling activity.

Originality/value – Existing studies recognized the positive impact of technology on performance in industrial production. The study addresses a missing link in the Industry 4.0 value creation process. It adopts a systems perspective to establish the role of smartness in translating technology use to performance outcomes. Smart capabilities have been the critical missing link in the literature on harnessing digital transformation in organizations. The study advances theory development by contributing an Industry 4.0 value model that establishes a link between digital technologies, smartness and organizational performance.

Keywords Digital transformation, Industry 4.0, Organizational performance

Paper type Article

1. Introduction

Production value chains have grown significantly as international business and globalization progress. This increased size and scope of production value chains have created a challenge for their performance. Performance considerations include concerns for production's social and environmental implications (Furstenau *et al.*, 2020), variability in the production environment (Dequeant *et al.*, 2016), the need for more resilience in supply chains (Ralston and Blackhurst, 2020), and the growing demand for custom products to meet unique needs of more diverse customers (Aheleroff *et al.*, 2019; Tseng and Jiao, 1997).

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Resilience in times of disruption is an important consideration for production value chain performance. Some studies have suggested that global value chains are more vulnerable to disruptions (Miroudot, 2020). Socio-economic and biological contagion plays important roles in global crises, as highlighted by the COVID-19 pandemic (Hansen, 2021; Hsiang *et al.*, 2020); thus, global value chains are both a risk and at risk. At the organizational level, variability in production parameters characterizes the expansive value chain and introduces uncertainty in production performance (Dequeant *et al.*, 2016; Smorodinskaya *et al.*, 2021). Industry 4.0, deploying cyber-physical systems to integrate the production value chain enables smartness in production systems to respond to this risk and optimizes the performance of production enterprises (Fragapane *et al.*, 2022). This smartness facilitates the flexibility of production systems, products and supply chains for addressing the variability challenge (Enrique *et al.*, 2022; Shahin *et al.*, 2020; Xie *et al.*, 2020).

Industry 4.0 has emerged as important to the productive capacity of organizations in uncertain environments (Lee and Trimi, 2021). The digital transformation literature has positioned Industry 4.0 as a technology-led value creation framework and focused the Industry 4.0 discourse predominantly around technology (Oztemel and Gursev, 2020), with several studies establishing the contribution of technologies to production performance (Büchi *et al.*, 2020; Dalenogare *et al.*, 2018; Lin *et al.*, 2019). The Industry 4.0 literature further discusses the expectation of smartness as a characteristic of transformation through which the enterprise optimizes outcomes (Adamik and Sikora-Fernandez, 2021; Chronopoulos *et al.*, 2020; Lichtblau *et al.*, 2015). The literature references the factory (Cheng *et al.*, 2018), supply chain (Tripathi and Gupta, 2021) and products (Nunes *et al.*, 2017; Salkin *et al.*, 2018) as elements of the production value chain through which smart capabilities materialize. Smartness is thus positioned as a link between technology and value realization.

However, the nuances of the relationships between smartness, technology and organizational performance are often overlooked, necessitating a more in-depth look at the holistic systems approach. From the above, two issues come to the fore. First, the performance of a value chain is multi-dimensional and not simply characterized by its throughput. The impact of value chain activities on its multiple stakeholders must drive the notion of performance, culminating in factors such as sustainability (Baier *et al.*, 2020). The literature remains limited in examining the impact of Industry 4.0 on broader organizational performance contexts such as customer experience, safety and sustainability. It follows that constructing an appropriate performance metric for the production firm must include a comprehensive understanding of its stakeholders and their interests in the enterprise. Secondly, the relationships between technology, smartness and performance highlight the role of smartness as the organizational capability emergent from end-to-end digital transformation of the production value chain, describes the Industry 4.0 value path and would benefit digital transformation strategy formulation.

Given such complexities, a systems perspective is needed to explore how inputs are converted to outcomes through smartness. Therefore, this study will improve the understanding of relationships between smartness, technology and organizational performance, to support manufacturing managers in developing Industry 4.0 strategy and harnessing the value from Industry 4.0 interventions.

2. Literature review

2.1 Industry 4.0, systems theory and production performance

The value proposition of Industry 4.0 has been discussed extensively in academic literature. Many studies attribute Industry 4.0's value creation potential to a direct effect of *Industry 4.0 technologies* on aspects of the value chain, establishing a causal relationship between technology and performance. This approach translates to a reductionist view of the value-creation process as it focusses on siloed treatment of specific processes. Following this approach, Dalenogare *et al.* (2018), Qader *et al.* (2022) and Szász *et al.* (2020) explored the impact of Industry 4.0 technologies implementation on industrial performance metrics including product, supply chain performance, cost, quality, delivery and flexibility. Lin *et al.* (2019) identified drivers of Industry 4.0 strategy adoption, studying the relationship between these factors, adoption and performance (financial, innovation, stock market return and supply chain performance) and Büchi *et al.* (2020) considered technology from the perspective of the attitude toward adoption and established its impact on performance. Overall, these studies identified measures of Industry 4.0 technology adoption, implementation or application in production processes and established that Industry 4.0 technologies improve performance. Another approach considers the interactions between technology and organizational factors or management practices in the value-creation process. In addition to considering the causal relationship like the first school of thought, Szász *et al.* (2020) also determined that firm size positively influences adoption, thus, contributing to performance. Studies also found that Industry 4.0 enhances lean and JIT practices (Buer *et al.*, 2018; Lai *et al.*, 2019; Rosin *et al.*, 2020), eliminating waste and increasing productivity.

Fewer studies have considered Industry 4.0 as a systemic effect in investigating its value-creation process. Fatorachian and Kazemi (2021) and Ghadge *et al.* (2020) explored the impact of Industry 4.0 on the production supply chain performance using frameworks underpinned by systems theory. They examined the impact of Industry 4.0 on supply chain performance using frameworks that quantified the systemic impacts of Industry 4.0 on the production enterprise. Table 1 summarizes recent studies addressing the organizational value proposition of Industry 4.0. The measure of Industry 4.0 utility is indicative of the approach to value creation. While the studies with a holistic approach measured Industry 4.0 based on organizational capabilities created, the reductionist approach measured technology

Table 1. Industry 4.0 value creation in literature

Study	Industry 4.0 measurement	Performance metrics
Dalenogare *et al.* (2018)	Adoption of Industry 4.0 technologies	Product (innovation, customer), Operational (Cost, productivity, process efficiency), Side effects (sustainability, employee wellbeing)
Szász *et al.* (2020)	Adoption of Industry 4.0 technologies	Cost, quality, delivery and flexibility
Lin *et al.* (2019)	Industry 4.0 strategy adoption	Financial, innovation, stock market return and supply chain performance
Büchi *et al.* (2020)	Attitude towards Industry 4.0 based on the number of Industry 4.0 technologies adopted and the extent of their embeddeness in business operations	Six factors addressing productivity, product quality, resource utilization and product innovation
Rosin *et al.* (2020)	Adoption of Industry 4.0 technologies (IoT, Simulation, Autonomous Robots, Augmented Reality and Big Data and analytics)	JIT capability level
Lai *et al.* (2019)	Industry 4.0 technologies application	Waste reduction
Qader *et al.* (2022)	Technology implementation (IoT, Machine Learning and Blockchain)	Operational and financial performance of the supply chain
Fatorachian and Kazemi (2021)	Integration and transparency	Responsiveness, flexibility, dependability, product or service quality, efficiency and effectiveness
Ghadge *et al.* (2020)	Technology-enabled information transparency	Adaptability, agility and flexibility

Source(s): Authors work

implementations and management efforts. There does not appear to be adequate research exploring the performance impact of Industry 4.0 across the entire production value chain based on a holistic approach. A systems perspective is needed to advance the Industry 4.0 stream of literature beyond the predominant focus on reductionist values in the production organization. The influence of specific technologies on performance or practices like lean and Just in Time (JIT) does not consider end-to-end integration and the role of resultant information transparency on value creation.

Systems theory posits that a system can be optimized by eliminating reductionist approaches to its operation and management (Bar-Yam, 2018; Johnson *et al.*, 1964; Teece and Pisano, 1998). By integrating the value chain end-to-end (Bartodziej, 2017; Wang *et al.*, 2016), Industry 4.0 appeals to systems or holistic organization of the production enterprise rather than a reductionist approach to delivering value. However, many studies seek to explain the value proposition of Industry 4.0 by showing the impact of technology on aspects of the value chain, not the holistic effects of integrating the value chain. Furthermore, many technologies that are usually referenced, like sensors, robotics and automation, and their application in industrial production predates Industry 4.0 (Haidegger *et al.*, 2019; Lloyd Spetz *et al.*, 2001; Tantawi *et al.*, 2019).

This study applies systems theory in exploring the value creation potential of Industry 4.0 across broad performance metrics, modeling relationships between digital transformation, enterprise smartness and production performance. Therefore, the study addresses the key research question of "How does Industry 4.0 drive organizational performance, and how does smartness play a critical role in this process?"

The industrial production system comprises devices, materials, systems, processes, people and partnering organizations (Chukalov, 2017; Tabim *et al.*, 2021). Integrating them into a single system for holistic management creates a socio-technical system consisting of technical and non-technical parts (Sony and Naik, 2020). Socio-technical systems are characterized by extensive interactions among independent heterogeneous actors, resulting in highly volatile and unpredictable operating environments. The system must thus regulate agents' actions to optimize its function (Dalpiaz *et al.*, 2013). Industry 4.0 approaches this optimization challenge of the production system through smartness (Lichtblau *et al.*, 2015).

2.2 Smartness

Smartness is the characteristic of gaining optimization through the application of intelligence built on stimuli-responsiveness (Nguyen *et al.*, 2018; Samimi-Gharaie *et al.*, 2018; Zhao *et al.*, 2018). Smartness is linked to information transparency (Abiodun *et al.*, 2022; Wu *et al.*, 2021). Furthermore, information transparency is a function of integration (Guo *et al.*, 2022). It follows that the smartness potential of an enterprise or system depends on the quality of integration and is attributable to holistic approaches. The value-creation potential of digitalized industrial production systems is tied to information transparency (Flatt *et al.*, 2016). By integrating the value chain and enabling information transparency, Industry 4.0 facilitates smartness, including the smart factory (Radziwon *et al.*, 2014; Wang *et al.*, 2016), the smart supply chain (Wu *et al.*, 2016) and the smart product (Nunes *et al.*, 2017; Salkin *et al.*, 2018). Through real-time information on production elements, smart capabilities enhance autonomy, flexibility, decision-making and productivity (Alani and Alloghani, 2019; Barreto *et al.*, 2017; Cortés Serrano *et al.*, 2018).

The smart factory is a network of devices, systems and processes for production, implementing an automation pyramid from ground-level devices with sensing and actuation functionalities to enterprise information systems like enterprise resource planning (ERP) (Zuehlke, 2010). Smart factories have smart systems characteristics, including intelligence, awareness and environmental interaction (Chen *et al.*, 2018;

Radziwon *et al.*, 2014). The smart factory is underpinned by cyber-physical integration. The physical elements are instrumented with sensing and actuation, allowing them to integrate with the virtual elements and interact with their environment. The smart factory aims to engender flexibility in the production enterprise and enable agility in product development and resilience to variability in the operating environment (Bortolini *et al.*, 2018; Chen *et al.*, 2018).

The smart supply chain can enable flexibility of the production value chain through autonomous recovery from disruptions and optimization of logistical functions (Wu *et al.*, 2016). The problem statement for the classic supply chain is optimizing the cost of having items at the right place and time (Mallik, 2010). Industry 4.0 uses smart system functionalities to optimize supply chain management goals. Through horizontal integration, the participating entities in a supply chain are integrated with interoperable business functions. The integration can facilitate real-time information about articles traversing through the chain, enabling autonomous logistic functionalities based on optimal decision-making (Gupta *et al.*, 2019; Sodhi and Tang, 2019).

The smart product can automate embedding customer experience, feedback and requirements into production. In the reverse direction, it can automate maintenance and continual improvement of products and services, creating a dynamic product lifecycle loop designed to optimize customer experience and manufacturers' productivity (Nunes *et al.*, 2017; Salkin *et al.*, 2018). The smart product builds on the end-to-end engineering integration in the production value chain and sensing and actuation features on the product (Romero and Noran, 2017).

2.3 Industry 4.0 performance metrics

A clear value proposition is necessary to drive the vision of Industry 4.0 and digital transformation (Rupp *et al.*, 2021). The value proposition would be informed by its implication to stakeholders for performance outcomes (Baier *et al.*, 2020). In designing systems, there is a tendency to focus on functional relevance, leading to specifications narrowly constrained within the system's technical boundaries and insufficient consideration for its wider implications (Coakes and Elliman, 2002). This narrow view of systems design translates to a constraint on its ability to fulfill its purpose. Similarly, a holistic view of business performance requires an understanding of its implication for its stakeholders – those it impacts and those that impact it (Parmar *et al.*, 2010). The organizational performance context thus encompasses notions of sustainability and factors aligned to the interests of other stakeholders, in addition to the financial success of the enterprise (Baier *et al.*, 2020; Harrison and Wicks, 2013; Laplume *et al.*, 2008). Determining performance objectives is therefore linked to identifying stakeholders.

The pattern of Industry 4.0's emergence provides some insight into its stakeholders and performance considerations. Specific concurrent shifts in the global socio-economic landscape were very influential in its development and raised the significance of stakeholders, beyond shareholders, to the production enterprise (Lasi *et al.*, 2014). Its key characteristics, including, mass product customization, optimization of resource use, reduction of environmental impact and flexibility of production systems (BMBF, 2014; Ghobakhloo, 2020; Jiao *et al.*, 2021; Prause, 2015; Tripathi *et al.*, 2021) address the interests of these stakeholders.

Connections have been made between globalization, global governance and digital technologies (Voronkova *et al.*, 2020). The value proposition of digitally integrating the value chain is increased as it grew in scope due to globalization and the internationalization of business. These transnational value chains have some challenges, including sustainability due to increasing socio-economic impact on the environment and people not involved in the business (Prause, 2015; Zhu *et al.*, 2018) and new operational challenges to productivity due to size and complexity (Strange and Zucchella, 2017). Variability is challenging for production, and the increased complexity of value chains introduces more variability to the supply chain and production processes (Núñez-Merino *et al.*, 2020). Furthermore, small and medium enterprises (SMEs) are part of complex supply chains. Their success increasingly requires functional and process integration within the supply chain networks based on digital technologies (Türkeş *et al.*, 2019).

A regime of customer influence is also emerging from changing customer behavior (Jiang *et al.*, 2006). The Henry Ford notion of customers adjusting their tastes to the product is no longer feasible; products must be flexible and fit with the customer (Lasi *et al.*, 2014). The demands of this change are beyond new products. A paradigm shift to customer-centric production is necessary (Guo *et al.*, 2020).

The increasing scope of the production value chain creates challenges for production performance. Industry 4.0 seeks to respond to these challenges through digital transformation. It integrates the value chain to enable functioning and optimization as a holistic system. The optimization is through the development of smart functionalities. This study uses qualitative research to determine the relationships between digital technologies, smartness and organizational performance. It uses the research process to determine the performance metrics for Industry 4.0 and creates an Industry 4.0 business capability model to reflect its value-creation process.

3. Methodology

This study aims to formulate theory from practice and generate insight with practical usefulness. Industry 4.0 emerged and developed largely through the effort of industry actors (Verhoef *et al.*, 2021). The industry has also outpaced academia in the digital transformation sphere resulting in theoretical gaps in support of industry practices. Furthermore, an analysis of existing literature revealed insufficient coverage of socio-technical systems in digital transformation (Liere-Netheler *et al.*, 2018). As this study aims to explore existential phenomenology, the approach of exploring lived experiences of a relevant group to capture knowledge for theory development is justifiable (Collingridge and Gantt, 2008; Wang, 2022). Qualitative methodology is appropriate because it is effective for theory formulation to bridge gaps in the literature (Edmondson and McManus, 2007). Qualitative approaches are also useful for exploring experiences using natural language for data capture and translation to theory (Levitt *et al.*, 2018); in this instance, a semi-structured interview of industry experts was employed. The interview framework is presented in Appendix 1. The semi-structured interview provided the flexibility to explore each expert's unique experiences and insights while maintaining the same breadth of questions and similar depths of exploration across the interviewees (Saunders *et al.*, 2009). Semi-structured interviews are also appropriate where the respondent's expertise is material (McIntosh and Morse, 2015).

The study aimed to access practitioners' deep industrial digital transformation knowledge bases. Thus, senior personnel of global technology firms who provide key technologies and services to global industrial organizations was targeted for participation. Sixteen respondents from seven organizations participated as convergence was achieved at 16 interviews when no new concepts were observed. The smallest of these organizations by revenue had over USD 30B in revenue in 2021. The participants had a minimum of 21 years of relevant experience in digital transformation and belonged to the senior management cadre. Snowballing sampling technique was employed to facilitate triangulation (cross-checking responses among participants from the same organizations and similar industry affiliations) and enhance research validity (Etikan *et al.*, 2016; Kitto *et al.*, 2008). An overview of the respondents' profiles is presented in Appendix 3 – Participant profiles.

Coding and analysis followed the Gioia methodology (Gioia *et al.*, 2013). The Gioia methodology builds perspectives on a subject matter through an iterative contextual analysis process that develops higher-order concepts from lower-order ones. It is effective for navigating diverse concepts to develop a data structure for understanding a subject matter in relatively short iterations (Gehman *et al.*, 2017). The methodology consists of three stages through which the researcher applies consistent treatment to interview responses to arrive at a reliable outcome. The first stage is the first-order analysis. The principles of open coding (Strauss and Corbin, 1998) are applied, extracting concepts that preserve the original thought of research participants (Gioia *et al.*, 2013). Open coding principles align with grounded theory methodology (Strauss and Corbin, 1994). The researcher extracts theory from data rather than imposing existing theory on the data, facilitating the original objective of existential phenomenology. The first-order analysis stage generates a lot of concepts that feed the second stage, the second-order analysis phase. In this phase, the researcher identifies emerging concepts based on logical associations among the first-order concepts. This is achieved by applying the researcher's conceptual perspectives on the first-order concepts (Shkedi, 2004), including consideration of the contexts in which the concepts were discussed. This study's conceptual perspective relates to performance and value creation. The final phase of analysis involves another iterative cycle through the second-order concepts, this time applying applicable theoretical lens to identify aggregate dimensions that define a data structure for the subject matter. Systems theory is the overarching theoretical foundation for this study. The model of systems presented by Dutta *et al.* (2005) provides a guide, identifying inputs, capability as the intermediate outcome with enabling functionality and system outputs.

To illustrate the application of the Gioia methodology in this study as an example, we consider the respondents' references to enhanced collaboration between man and machines as a feature of Industry 4.0 and the identification of collaborative robots as its key enabler. The first-order concepts capture the respondents' thoughts as natively and verbatim as possible, identifying man-machine collaboration and cobots as concepts. To derive the second-order concepts, the researchers apply the lenses of performance and value creation to the first-order concepts. These are the conceptual perspectives of the study. They enable the second-order concepts to answer the question, "How do the respondents attribute value creation to the first-order concept?" It results in *Digital Technology* and *Task Transformation* as second-order concepts. To derive the aggregate dimensions, the researchers explore the second-order concepts from the lenses of the study's theoretical basis, systems theory and the specific system model presented by Dutta *et al.* (2005), situating the emergent concept as input, output or intermediate capability. It identifies *Digital Technology*, *Productivity* and *Safety* as aggregate dimensions.

Appendix 2 presents the emergent data structure from the analysis.

The validity of the research is important to achieve its objectives (Golafshani, 2003; Rolfe, 2006). The research employed an initial expert validation by research colleagues (Straub, 1989) consisting of researchers with expertise in digital transformation and qualitative methodologies. They provided inputs into the construction of the interview guide. The study also employed triangulation in the data collection, analysis and interpretation process (Kitto *et al.*, 2008), recruiting multiple respondents from each industry segment covered by respondents. Three researchers reviewed the coding, analysis and final data structure.

4. Results

The first-order concepts derived from analyzing responses to the question "What is Industry 4.0?" are documented in Appendix 2. The Appendix also documents the second-order concepts and the aggregate dimensions derived through further iterative analysis of the concepts from the lenses of their functional contribution to the production organization. Six aggregate dimensions, discussed in the following sections, are identified in the study. The first is the digital technologies that enable Industry 4.0. The second dimension is the capabilities of Industry 4.0 that while the last four dimensions address the value propositions of Industry 4.0, productivity, customer experience, sustainability and safety.

4.1 Technology use

The value of Industry 4.0 is attributable to emergent properties of the confluence of increasing maturities of many digital technologies, which enabled interoperability across the production value chain (Respondent 1). Twelve respondents (1, 3, 4, 5, 6, 7, 8, 9, 11, 13, 14 and 16) identified the role of digital technologies in Industry 4.0. They identified digitalization and integration as the primary objectives of applying digital technologies and information transparency as result of digitalizing and integrating. Respondent 3 stated that industrial production had experienced pockets of gains from automation and computing prior to Industry 4.0. It is noted, however, that the value of Industry 4.0 is in the utilization of technologies to achieve cyber-physical systems (cps):

> It is revolutionary, resulting in efficiency and effectiveness gains through cps. (Respondent 3)

Respondents 4 and 10 similarly attributed the Industry 4.0 value to using digital technologies to create cps. They approached cyber-physical integration from the IT-OT integration perspective:

> Industry 4.0 is the extension of digitalization principles from IT to OT. IT has long transformed the business technology space of the enterprise. Now the OT space is being similarly transformed and integrated, creating a single digital enterprise. This transformation is dependent on advanced technologies, particularly sensors, robotics, virtual reality, and artificial intelligence. (Respondent 4)

Other respondents viewed the resulting integration from applying advanced technologies from different lenses. Respondent 8 focused on enabling the end-to-end integration of the enterprise, while respondents 5 and 7 linked the end-to-end integration to Industry 4.0 capabilities development. Respondent 9 focused on linking the technology-enabled integrations to production value stating that:

> Industry 4.0 is about integrating the physical and virtual worlds for the purpose of production processes advancement. . . . In the Industry 4.0 context, production systems can attain super efficiency. (Respondent 9)

Respondent 7 summarized the use of technology in Industry 4.0. They identified the link between technologies and capabilities development and value creation. According to the interviewee:

> Industry 4.0 is a series of layered capabilities that deliver optimal socio-economic outcomes in industrial production. The layered capabilities are facilitated by advanced technologies that enable stimuli responsiveness, artificial intelligence, data processing, visualization, and robotic actuation. (Respondent 7)

4.2 Enterprise smartness

According to Respondent 5, Industry 4.0's resultant enterprise capability for value delivery is smartness built on value chain integration:

> The implementation of these technologies enables the integration of the value chain and the factory elements resulting in three capabilities, smart products, smart factory, and smart supply chain.(Respondent 5)

Respondent 11 corroborates the link between integration and smartness and established the Industry 4.0 value path from technology to smartness through digitization, integration, data capability and information transparency:

> Industry 4.0 is the digitization of all aspects of production processes, the vertical integration of the factory, and horizontal integration of the production ecosystem with IoT, Enterprise Information Systems, and autonomous functionalities. Digitization provides the platform for integration, while integration creates the capability for smart characteristics. The horizontal integration connects the entire value chain from suppliers to the consumers while the vertical integration connects the processes within the production enterprise.
>
> Data is an important part of the Industry 4.0 idea; it is the lifeblood of Industry 4.0. Data related to all aspects of the production enterprise operations covering planning, production, and maintenance are made available in real-time, powering analytics and providing the intelligence required for smart operations. (Respondent 11)

Respondent 7 provides more context to creating the Industry 4.0 smart capabilities, indicating that Industry 4.0 technologies produce stimuli-responsiveness, intelligence and enhanced data functionalities to facilitate the capabilities which deliver optimal socio-economic outcomes in industrial production.

> Industry 4.0 is a series of layered capabilities that deliver optimal socio-economic outcomes in industrial production. The layered capabilities are facilitated by advanced technologies that enable stimuli responsiveness, artificial intelligence, data processing, visualization, and robotic actuation. (Respondent 7)

Respondent 2 describes Industry 4.0 as the use of smartness to address key challenges of industrial production, namely the requirement for mass product customization, variability in the production environment and sustainability challenges:

> Industry 4.0 emerged as a systemic response to fundamental challenges facing production enterprises because of evolving socio-economic realities over a period. First is the increasing demand to customize or individualize products and services to satisfy the changing needs of consumers. The second is the evolving challenge of energy and resource utilization in response to environmental requirements. The third is the volatility of production parameters requiring a higher capacity for flexibility in production enterprises. Industry 4.0 uses smart solutions to address the challenges. (Respondent 2)

Respondent 2 puts smartness central to Industry 4.0 as its core value-creating capability. According to Respondent 12, Industry 4.0 goes beyond employing smartness internally, but the organization becomes a smart entity, reflected in its external interaction with its customers.

The smart factory, supply chain and product are Industry 4.0 capabilities developed by the digital transformation of the production enterprise. They address challenges of the variability of production parameters, the need for mass product customization and increased sensitivity to production's environmental impacts, providing the enterprise with the capacity for flexible and autonomous functioning. Through vertical, horizontal and engineering integrations, sufficient information transparency is achieved to make the enterprise smart (Respondents 2, 10, 11, 12 and 16).

The respondents presented Industry 4.0 as a value-creation mechanism. According to Respondent 16:

> Industry 4.0 is about the creation of fully connected production value chains. The idea thus is to better the capabilities of linear value chain constructs. (Respondent 6)

The study identified four lenses for Industry 4.0 value creation, seen from stakeholders' viewpoints, Productivity, Sustainability, Safety and Customer experience.

4.3 Productivity

According to Respondent 16, the integrated, nonlinear value chains created by Industry 4.0 is more productive than their linear predecessor. The research identified productivity from four stakeholder perspectives, Employees, Government, Partners and Shareholders. Task-level productivity impacts Employees and Shareholders. Respondents 5 and 9 identified improvement of work tasks through enhanced man-machine interactions, and Respondents 6, 7 and 12 identified the impact of autonomous actuation on work tasks. According to Respondent 1, Industry 4.0 has implications beyond the firm at the national and international levels. It impacts economic growth, sovereign manufacturing capability and job creation with implications for Government. Respondent 1 stated:

> We will experience the classic hype cycle effect. The level of investment required to drive it to fruition will be difficult to achieve at this point. It will improve manufacturing in first-world countries because of lower cost manufacturing. It will push the pursuit of more sustainable supply chain arrangement, away from the constant pursuit of lower costs. (Respondent 1)

Industry 4.0 impacts enterprise (organizational) production capabilities (Respondents 2, 3, 8, 12 and 16). Respondent 2 identified that Industry 4.0 develops organizational capabilities that deliver outcomes for the firm. Respondents 3, 8, 9 and 12 identified organizational level productivity impact of the Industry 4.0 capabilities. Respondent 9 stated, *"in the Industry 4.0 context, production systems can attain super efficiency."*

4.4 Customer experience

Respondent 6 puts the value delivery to the customer as important to Industry 4.0, stating, "the basic business value of Industry 4.0 is customer, the ability to anticipate customer needs and deliver them rapidly."

According to Respondents 2 and 8, product customization is one of the key objectives of Industry 4.0 and a major way through which it influences customer experience (Respondents 2 and 8). Respondent 2 identified the customer and the enterprise (shareholders) as beneficiaries of the customer experience value, stating, *"Industry 4.0 enables mass product customization, simultaneously delivering value to the producer and consumer as productivity and superior customer experience."*

Respondents 8, 12 and 16 further reiterated the significance of mass product customization in Industry 4.0 through the enterprise transformations initiated to facilitate it, including product lifecycle transformation and persistent engagement of the customer.

4.5 Sustainability

Sustainability concern is one of the key factors that necessitated Industry 4.0. According to Respondent 2, three challenges necessitated Industry 4.0, and one was:

> The evolving challenge of energy and resource utilization in response to environmental requirements. Through smartness, Industry 4.0 addresses the challenges that necessitated it. . . . It optimizes resource utilization and environmental interaction of production systems. (Respondent 2)

Industry 4.0's sustainability impact includes socio-economic growth (Respondent 2), resource utilization in production processes (Respondents 5, 9, 12, 13, 15 and 16), environmental impacts of production processes (Respondents 5, 6, 7, 9, 10, 11, 12, 13, 15 and 16) and facilitation of social equity through consumptive business models which reduces setup costs for lower resourced producers by converting capital costs to operating costs (Respondent 14).

The study identified unique sustainability impacts through sovereign manufacturing capability Respondent 1 linked the emergent sovereign manufacturing capability from

Industry 4.0 and sustainable supply chains. According to the interviewee, the impact on outsourcing dynamics between well-developed and lesser-developed nations will create sustainable supply chain arrangements, stating, *"it will push the pursuit of more sustainable supply chain arrangement, away from the constant pursuit of lower costs."*

Respondent 14 identified the similarity between cloud factories for manufacturing and cloud computing for digital infrastructure. According to the interviewee, cloud technologies enable consumptive business models. It facilitates social equity and democratizes access to opportunities, stating, *"Industry 4.0 actualizes the cloud factory concept which democratizes production infrastructure in the same way cloud computing does for digital infrastructure." (Respondent 14).*

4.6 Safety

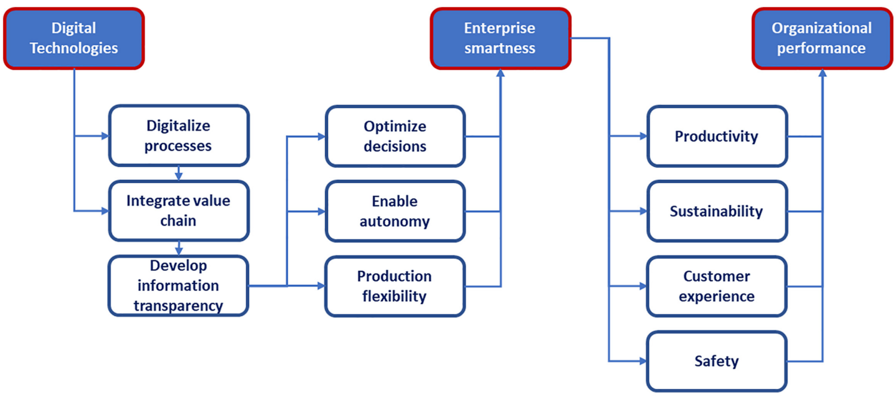
According to Respondents 3 and 15, worker safety is a value proposition of Industry 4.0. Respondent 3 stated, *"Industry 4.0 increases productivity, product and process quality, cost optimization, product innovation, and employee safety." Respondent 15 stated,* "The value created by the integrated intelligent systems include organizational and occupational safety and productivity."

Work process transformation (Respondents 12 and 13) eliminates hazards, making them safer. Enhanced man-machine collaboration reduces physical and cognitive loads on workers (Respondents 5 and 9), and it introduces technologies with safety-enhancing functionalities (Respondents 2, 7 and 12). Respondent 3 stated that they had witnessed Industry 4.0 save a worker's life through tracking technologies that monitor the status of workers in real-time and reported an isolated worker who had collapsed, stating, *"I have witnessed a worker's life saved by Industry 4.0 technology with a man-down alarm going off."*

4.7 Conceptual framework

Based on the results, Figure 1 depicts conceptual model arising from this study, revealing the progression of utility from technologies to value creation.

Respondent 3 established a foundation for the thought process on Industry 4.0 value creation by stating that performance gains related to automation predated Industry 4.0. As such, the value proposition of Industry 4.0 is not in the application of technologies to automate processes. Respondent 14 reiterates the existence of automation and its application



Source(s): Authors work

Figure 1.
Industry 4.0 conceptual model for organizational performance enhancement

in industrial production before Industry 4.0. Respondents 3, 4, 9, 10 and 14 posited that the value is tied to cyber-physical integration built on digitization, which Respondent 9 characterized as *integrating the physical and virtual worlds*. They positioned information transparency as an additional layer of value on automation brought on by Industry 4.0. Respondents 5 and 11 progressed the thought processes by arguing that producers create value by exploiting the data and information resources presented by integration to generate smartness. According to respondent 11, contextual data about all production elements facilitated by end-to-end value chain integration are the basis for smartness. The value creation process of Industry 4.0 thus involves the derivation of information transparency from integration and smartness from information transparency. Beyond real-time information, transparency enables information flexibility, providing access to information beyond real-time through simulation, extended reality (Respondents 4 and 11) and predictive analytics (Respondents 5, 11 and 13).

Respondents identified value attributes of smartness to include autonomous functionalities (Respondents 12 and 13), optimized actions (responses, decisions and actuations) (Respondents 2 and 13) and flexibility of processes (Respondent 13).

Sections 4.3 to 4.6 established that smart functionalities in production organizations improve the performance related to productivity, sustainability, customer experience and safety resulting in the framework described in Figure 1.

5. Discussion and conclusion

The study examined how to drive organizational performance through Industry 4.0 and identified smartness as a critical link. It examined the value creation process of Industry 4.0. Integrating the value chain enables it to function as a single system that can provide better utilities than its parts could do on a reductionist basis. The results confirmed that integrating the value chain using digital technologies develops smart capabilities that optimize its operations and create performance enhancements. The study identified the performance impacts of Industry 4.0. Driving the holistic approach to value realization.

The premise of Industry 4.0 value creation is based on the relationships between the degree of integration, the quality of information transparency and the amount of smartness. Smartness is indicated by the quality of decision-making and actuation (including speed and accuracy) and the flexibility of processes.

The study provides additional context to existing studies that established Industry 4.0 as a performance improvement mechanism for industrial production through the application of technology (Dalenogare *et al.*, 2018; Ghadge *et al.*, 2020; Szász *et al.*, 2020). Dutta *et al.* (2005) describe capability as a system's capacity to translate inputs into outputs. This study identified smartness as the capability in the Industry 4.0 context, translating digital transformation into performance gains. Smartness has been identified in studies as a feature of Industry 4.0 (Radziwon *et al.*, 2014; Sjödin *et al.*, 2018; Wu *et al.*, 2016; Zawadzki and Żywicki, 2016) describing the functionality of operational characteristics of the factory, supply chain and products in the Industry 4.0 paradigm. This study identified the role of smartness in the value creation process and a product of a holistic design and operations framework for industrial production.

Furthermore, studies have predominantly quantified Industry 4.0 development by measuring aspects such as strategy, organizational culture and technology (Kırmızı and Kocaoglu, 2022; Lassnig *et al.*, 2021; Ramanathan and Samaranayake, 2021; Santos and Martinho, 2020; Veile *et al.*, 2019). Existing trends associate digital maturity with the scope and scale of implemented technologies (Tutak and Brodny, 2022). Such efforts represent inputs into the digital transformation process and are not automatically reflective of outcomes; smartness is the organizational capability that effectively reflects value creation.

Managers thus must target digital transformation efforts to improve enterprise smartness which would also be an appropriate measure of digital transformation maturity.

The study made a theoretical contribution to the manufacturing technology management literature by providing an Industry 4.0 systems model that established a relationship between technology, enterprise smartness and organizational performance.

Despite its contribution, future research should involve quantitative studies to provide further empirical validation of its relationship with organizational performance and test the model quantitatively. Future studies could also focus on particular industries where trends across various industries can increase the generalizability of findings. It can also span various countries and involve cross-comparisons between countries at different levels of development to explore the impact of industry 4.0 on the smartness and performance of their organizations.

5.1 Managerial implications

The findings of this study provide implications for managers. According to the findings, these actions would be vital to driving organizational performance through Industry 4.0.

Respondents opined, *"Data is an important part of the Industry 4.0 idea; it is the lifeblood of Industry 4.0"*. Therefore, executing the Industry 4.0 paradigm implies that production organizations must uplift their data capability. Managers must ensure that key aspects of data capability, including data asset capture, governance and utilization for developing autonomous functionalities and improved decision-making. Furthermore, the study identified information transparency, the ubiquitous availability of contextual information on all aspects of production, as central functionality to Industry 4.0 value creation. Developing the organizational data capability involves technology implementation, new management processes and culture change. Managers must ensure that data capability uplift is well-resourced and driven with senior leadership support for Industry 4.0 success.

Competition for scarce investment resources will pressure managers to pursue short-term reductionist approaches. Respondents argued that "*the level of investment required to drive it to fruition will be difficult to achieve at this point*". Investments must be initially channeled to aspects of Industry 4.0 that contributed to smartness and those that delivered the quickest. To actualize the holistic systems approach, managers must take a more nuanced approach to end-to-end value chain transformation by dividing the value chain and prioritizing aspects that deliver quicker and more significant returns on transformation investments.

For example, the automotive industry started its digital transformation journey with factory autonomous functionalities before progressing to address smartness opportunities in the supply chain and products (Lee *et al.*, 2023). Factory smartness delivered business gains through production efficiencies and product quality, enabling investments in more sustainable and feature-rich supply chains and products in subsequent investment cycles.

Respondents posited, *"Industry 4.0 will push the pursuit of more sustainable supply chain arrangement, away from the constant pursuit of lower costs"*. The study's outcome implies that managers have more opportunities to pursue sustainability and long-term value for the broad stakeholder base under the Industry 4.0 paradigm and should utilize it. The study determines that Industry 4.0 will help optimize production costs and lessen the influence of cost pressures on ecosystem arrangements, leaving room for managers to pursue longer-term value realization. For example, managers will no longer feel pressured to outsource aspects of production to factories in places with poorer protections for workers or the environment due to cost considerations.

The study identified IT–OT integration as an underpinning structure for the end-to-end value chain integration and a running theme for Industry 4.0. IT and OT are historically siloed structures, representing separate people organizations, business processes, systems and thought processes. Technology alone will not achieve the needed integration. To facilitate this integration, managers must devise organizational structures, management frameworks and culture change programs. For instance, agile methodologies in project organizations have been identified as helpful in breaking existing silo walls between IT and business units (Colavita, 2016).

Product transformation through smartness is a core part of the Industry 4.0 value creation process. It leverages persistent customer integration to connect products' production and operations contexts into a cyclic lifecycle. Managers must facilitate the product lifecycle transformation through enhanced customer and product lifecycle management functionalities. This typically involves implementing better customer relationship management (CRM) and project lifecycle management (PLM) systems. It also involves developing better processes and aligning organizational structures to support the new product lifecycle paradigm.

This study has presented a unique framework for achieving organizational performance through Industry 4.0 by adopting a systems perspective for generating smartness as an organizational capability.

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Appendix 1
Semi-structured interview guide

(1) What is Industry 4.0?

(2) Which technologies are important for Industry 4.0 and why?

(3) Which management competencies are important for Industry 4.0 and why?

(4) Which business factors have driven the adoption of Industry 4.0 capabilities? (productivity, safety, etc.)

(5) Which business factors have hindered the adoption of Industry 4.0 technologies? (Cost, complexity, etc.)

(6) What role do environmental factors play in the adoption of these technologies? (Competition, Regulation, etc.)

(7) What role do organizational factors play in the adoption of these technologies? (Size, complexity)

(8) What role do technological factors play in the adoption of these technologies? (Exiting technology investments, implementation, integration, management capabilities, etc.)

(9) How does Industry 4.0 influence organizational performance?

(10) What is smartness, and how is it related to Industry 4.0?

Source(s): Authors work.

Appendix 2

First-order concepts	Second-order concepts	Aggregate dimensions
Artificial intelligence	Digital Technology	Digital Technology
Autonomy	Resource and Process Optimization	Productivity Sustainability
Cloud computing	Digital Technology	Digital Technology
Cloud factory	Economic transformation Smart factory Social value creation	Productivity Capability Sustainability
Cobots	Digital Technology	Digital Technology
Computing infrastructure	Digital Technology	Digital Technology
Connected enterprise	Supply chain optimization/ Interoperability	Productivity
Connectivity	Resource and Process Optimization	Productivity
Cost-effectiveness	Economic transformation	Productivity
Data acquisition	Data Capability	Capability
Data Analytics	Data Capability	Capability
Data Capability	Data Capability	Capability
Data processing	Data Capability	Capability
Digital Enterprise	Supply chain optimization/ Interoperability	Productivity
Digital Fabrication	Resource and Process Optimization	Productivity
Digitization	Resource and Process Optimization	Productivity
Digitization of Shopfloor processes	Resource and Process Optimization	Productivity
Edge computing	Digital Technology	Digital Technology
Emergence (System of Systems)	Supply chain optimization/ Interoperability	Productivity
Enhanced Manufacturing capabilities	Resource and Process Optimization	Productivity
Enhanced Operating and production processes	Resource and Process Optimization Task transformation	Productivity Safety
Enterprise Information Systems	Supply chain optimization/ Interoperability	Productivity
Extended reality	Digital Technology	Digital Technology
Flexibility	Resource and Process Optimization	Productivity
Flexible production systems	Resource and Process Optimization	Productivity Sustainability
Holistic Enterprise transformation	Supply chain optimization/ Interoperability	Productivity
Hyperconnectivity	Resource and Process Optimization	Productivity
Improved production capabilities	Resource and Process Optimization	Productivity
Information and data transparency	Data Capability	Capability
Integrated production enterprise	Supply chain optimization/ Interoperability	Productivity
Integrated systems and processes	Resource and Process Optimization	Productivity
Integrated value chain	Supply chain optimization/ Interoperability	Productivity
Intelligent actions	Resource and Process Optimization	Productivity Sustainability
IoT	Digital Technology	Digital Technology
Live virtual construct	Digital Technology	Digital Technology
Machine Learning	Digital Technology	Digital Technology

(*continued*)

Table A1.
First-order concepts – aggregate dimensions map

First-order concepts	Second-order concepts	Aggregate dimensions
Man-machine collaboration	Task transformation	Productivity Safety
Manufacturing cost optimization	Economic transformation	Productivity
Mass Product Customization	Mass Product Customization	Customer experience
	Product lifecycle transformation	Productivity
New customer experience capabilities	Product lifecycle transformation	Customer experience
Nextgen Communication	Digital Technology	Digital Technology
Optimal socio-economic value	Economic transformation	Productivity Sustainability
	Social value creation	Sustainability
OT (Operating technologies) Digitization	Resource and Process Optimization	Productivity
OT-IT Integration	Resource and Process Optimization	Productivity
Persistent customer engagement	Customer engagement	Customer experience
Physical virtual information loop	Data Capability	Capability
Physical virtual integration	Supply chain optimization/ Interoperability	Productivity
Process digitization	Resource and Process Optimization	Productivity
Process Efficiency	Resource and Process Optimization	Productivity
Process Flexibility	Resource and Process Optimization	Productivity Sustainability
Product development capability	Product lifecycle transformation	Customer experience Productivity
Product lifecycle integration	Resource and Process Optimization	Productivity
Production capability transformation	Resource and Process Optimization	Productivity
	Task transformation	Safety
Production ecosystems	Supply chain optimization/ Interoperability	Productivity
Rapid delivery of customer requirements	Product lifecycle transformation	Customer experience Productivity
Real-time business intelligence	Data Capability	Capability
Boundary removal	Resource and Process Optimization	Productivity
Robotics	Digital Technology	Digital Technology
Sensors	Digital Technology	Digital Technology
Smart capability technologies	Resource and Process Optimization	Productivity Sustainability
	Technology features	Safety
Smart enterprise	Resource and Process Optimization	Productivity
Smart factory	Smart factory	Capability
Smart operations	Resource and Process Optimization	Productivity Sustainability
Smart processes	Resource and Process Optimization	Productivity Sustainability
Smart product	Product lifecycle transformation	Customer experience Productivity
	Smart product	Capability
Smart production and supply chain processes	Resource and Process Optimization	Productivity Sustainability
Smart production systems	Resource and Process Optimization	Productivity Sustainability
Smart solutions	Resource and Process Optimization	Productivity Sustainability
	Technology features	Safety
Smart supply chain	Smart supply chain	Capability

(*continued*)

Table A1.

First-order concepts	Second-order concepts	Aggregate dimensions
Smartness	Resource and Process Optimization	Productivity Sustainability
Sovereign Manufacturing Capability	Economic transformation	Productivity Sustainability
Stimuli responsiveness	Resource and Process Optimization	Productivity Sustainability
	Technology features	Safety
Superior value realization	Economic transformation	Productivity Sustainability
Value of data	Economic transformation	Productivity Sustainability
Vertical integration	Supply chain optimization/ Interoperability	Productivity
Visibility	Resource and Process Optimization	Productivity

Source(s): Authors work

Table A1.

Appendix 3

Respondent	Location	Experience (Years)	Education	Principal industry expertise
1	Australia	29	BA	Government, Natural Resource
2	Australia	30	BA	Government, Natural Resource
3	Australia	28	M.Sc	Aerospace
4	Australia	33	B.Sc	Industrial, Utilities
5	France	34	B.Eng	Industrial
6	USA	31	MBA	Automotive
7	USA	35	MBA	Utility, Natural Resources
8	Australia	20	M.Sc	Exploration
9	USA	23	B.Eng	Automotive
10	USA	27	PhD	Industrial, Supply Chain
11	USA	25	MA	Industrial, Supply Chain
12	USA	21	MBA	Industrials, Automotive, Pharmaceuticals
13	USA	25	BA	Industrial
14	Australia	25	B.Eng	Industrial
15	Singapore	36	B.Com	Government, Healthcare
16	USA	29	B.Sc	Technology, Media, Telecommunications

Table A2. Participant profiles

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