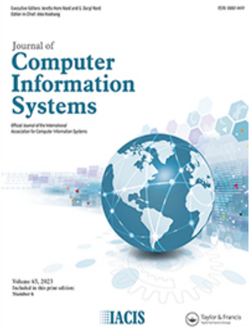

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Driving Industrial Digital Transformation

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ABSTRACT

The fourth industrial revolution has increased focus on industrial digital transformation (IDT) for its industrial value creation potential. However, practical implementation continues to require improved support from tools and frameworks. This research develops an empirically based conceptual framework for IDT. The study utilizes semi-structured interviews with technology experts, building on and extending the dynamic capabilities theory as its theoretical foundation to identify how IDT uses technologies to create organizational value via smartness capability. The results identify four groups of technological features that support enterprise smartness (1. intelligence, 2. simulation, visualization, and remote interaction, 3. data and information management, and 4. stimuli responsiveness) and the organizational features that characterize IDT, including digitization, integration, persistent customer engagement, production ecosystems, data capability, information transparency, and smartness. The framework identifies that transformation results in organizational value creation. The study's implication for professionals is to re-focus IDT strategy on developing value-creating capability in the enterprise.

KEYWORDS

Digital transformation; smartness; Industry 4.0; capability development

Introduction

Production organizations are pressed to optimize, in response to increasing requirements for sustainable business,[1] changing needs of consumers,[2] and variability in the production environments, including through socio-economic crises.[3,4] Industry 4.0 promises to address production optimization challenges through smartness, introducing autonomy and flexibility in production systems.[5,6] Applications include repurposing infrastructure for crisis response, mass customization of products (as production systems can handle a batch size of one), and autonomous response to disruptions in the production value chain. A convergence of technological developments enabled commercially viable cyber-physical systems and created an entirely new production phenomenon. The developments include innovations in sensors that miniaturized and reduced their power consumption, advancements in artificial intelligence, extended reality, cloud computing, and collaborative robotics.

Industrial digital transformation (IDT), Industry 4.0, the Industrial Internet, and the Industrial Internet of Things (IIoT) are often used synonymously.[7–9] They are associated with the fourth industrial revolution (4IR), where industrial processes are digitally transformed by technologies that implement cyber-physical systems, integrating the production value chain and indicating smartness in the production enterprise.[10,11] While the 4IR is about digital transformation, industrial revolutions are not generally about digital transformation. Industrial revolutions involve the emergence of new production paradigms based on technological developments. The first revolution was achieved using steam power to drive mechanical production functionalities (the factory). It moved production from being bespoke artisan-driven into a predominantly uniform operation that could be accomplished faster by comparatively less-skilled workers.[12] The second revolution enabled mass production using electrical power and electronic functionalities. The third revolution utilized information systems based on computer technologies to drive information-led production capabilities. The fourth uses cyber-physical systems (CPS) to enable smart production capabilities.[13,14] With each revolution, there is progressively less reliance on labor for the skill and intelligence required to perform tasks. Machines and devices have taken over more production functions. Also, with the advent of Industry 4.0 and the associated smart systems, capabilities for flexibility at scale in product design and production are now realizable. This flexibility at this scale was impossible in previous iterations, and producers can increasingly accommodate product customization requirements[15] and even personalization.[16] Product customization is in stark

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contrast to Henry Ford's comment that customer could have their car in "any color so long as it is black."[17] Although there is some dispute as to if Ford's comment was in jest, it does encapsulate the reduced flexibility and increased uniformity indicative of previous industrial revolutions. This study focuses on IDT as a generalized concept.

The 4IR employs IDT to optimize the production value chain,[18,19] and Industry 4.0 has been used synonymously with both 4IR and IDT.[14,20] This study presents the IDT perspective, focusing on its organizational capability developing capacity.[21] IDT, as a capability development mechanism, represents a business value opportunity for organizations,[22,23] which is the study's focus. The study aims to explore the value creation process of IDT, determining the impact on organizations, including how they develop relevant capabilities. Furthermore, the lack of tools and formal models for coordinating the transformation process has been identified as playing a role in the challenges of developing IDT capabilities for organizations.[24] The study further aims to develop a conceptual framework to aid the IDT process in organizations. The effectiveness of many IDT models in practice is impacted by a poor reflection of reality.[25] Models should sufficiently represent reality because "the major epistemic virtue of successful models is their capacity to adequately represent specific phenomena or target systems."[26] Conversely, models should not be excessively abstract or complex to be overly cumbersome to implement correctly. This study contributes a model of IDT, with an empirical basis, derived from canvassing experts with a holistic view of optimizing the industrial value chain. This study's model aims for simplicity of application while retaining sufficient fidelity to be impactful practically. It considers the essence of IDT and answers the *what* question by characterizing the enabling technologies and the functional attributes of the transformed production enterprise.

Defining the IDT conceptual framework would benefit from identifying its technologies based on high-level functional attributes rather than individual listings. The specific set of technologies required is, however, not clearly defined or as obvious as in the earlier revolutions, i.e., first (steam power), second (electrical power), or third (computing) industrial revolutions.[27] Furthermore, it is reasonable to expect the applicable technologies to evolve, given the pace of technological development and further development in industrial revolutions to Industry 5.0 and beyond.[28,29]

Therefore, this study aims to develop an IDT conceptual framework that answers the following questions:

(1) How does digital transformation create organizational value? - What are the feature developments within the organization in the process of IDT-related value creation?
(2) What are the key technology groupings relevant for IDT that facilitate avoidance of exhaustive listing of applicable technologies?

Literature review

Digital transformation

Digital transformation (DX) is a process for increasing productivity, value creation, and social welfare by adopting disruptive technologies. It alters organizations by digitalizing business processes using information systems.[30,31] Digitalization and digitization are used as synonyms in this study. They both refer to the conversion of analog entities to digital. While digitization applies to raw data, digitalization applies to more complex structures like business processes. Digitalization also refers to adopting digital technologies for socio-economic purposes.[32,33] Digital transformation alters the organizational structure to create more agile and responsive structures.[34] The resultant organization is less hierarchical and siloed; it aims to enable a service brokerage orientation in multiple directions, enabling the flow of information and services across the enterprise. DX creates or promotes new influential roles[35] that encourage innovation and change. It changes the culture, incorporating higher risk-taking, collaboration, experimentation, and change acceptance.[36] It changes its value creation processes (business model), replacing or augmenting products with services (servitization)[37] which is a source of longer-term competitive advantage[38] and exploiting organizational data assets for commercial value.[39] An important feature is transforming the mode of customer interactions with the organization's services through digital channels.[40–42] DX also has negative organizational impacts. It has increased employees' anxiety about being replaced by machines,[43] trust issues in virtual teams,[44] and employee change fatigue[45,46] with mental health implications. The challenges create the latitude for improvement and the need for more research in the DX space.

Impacts of digital transformation on industries include improved productivity in manufacturing,[47,48] higher quality patient care and business efficiency in healthcare,[49] improved access and new learning functionalities in education,[50] better product quality, higher productivity, improved working conditions and safer decisions in industrial production,[51] and stimulation of economic growth through smart cities.[52]

IDT is a unique form of DX, extending transformation across production value chains, end-to-end, using cyber-physical systems (CPS).[53] CPS bridges the information exchange gap between physical and virtual elements of production networks. It removes the constraint on information transparency and improves the organization in aspects such as productivity,[54] the ability to handle uncertainty,[55] and meet environmental and social responsibilities.[56]

Dynamic capabilities

Embedding digital technologies in industrial production processes enables new organizational capabilities; these capabilities are the basis for IDT's value proposition.[21] Organizational capabilities are a collection of repeatable routines that enable it to execute specific functions, giving it the capacity to deliver value and transform its inputs into outputs.[57–59] Capabilities also represent intermediate outcomes for organizations as they transform inputs into outputs.[60]

The theory of dynamic capabilities has links to the theory on the Resource Based View (RBV) for the firm.[61] Under RBV, an organization should identify and make use of resources that are valuable, rare, difficult to copy, and non-substitutable to gain competitive advantages and generate abnormal profits.[62,63] Dynamic capabilities further build on and extend RBV in versatile environments. Ordinary capabilities are not guaranteed to sustain an organization's competitive advantage.[64] They are susceptible to factors external to the firm, including technological developments and strategic challenges from competing firms. Firms can sustain such advantages through dynamic capabilities that enable them to sense and seize emerging opportunities by transforming their resources.[61] Furthermore, Teece [61] argue that dynamic capabilities satisfy the requirements of valuable, rare, imperfectly imitable, and non-substitutable (VRIN) resources for competitive advantage, as defined by Barney.[62]

Smartness is such a capability. It is created in industrial production by digital transformation through integrating the production value chain and enabling information transparency. The enterprise can sense and seize opportunities and transform its processes and resources through intelligence-backed stimuli responsiveness functionalities.[5,65]

This study proposes that IDT creates value for industrial organizations by generating enterprise smartness as a set of dynamic capabilities that enhance performance, including productivity, customer experience, product, and business model innovation, supply chain performance, sustainability, and occupational health and safety.[51,66–68]

Industrial digital transformation (IDT) conceptual framework

Conceptual frameworks are useful in scientific studies. They present and narrate important factors, variables, and relationships that define a concept.[69] They are mechanisms for presenting complex entities. They provide lenses for addressing challenges related to that entity.[70] The approach to capability development is a key IDT challenge to industrial organizations,[71,72] as such conceptual frameworks could serve an important purpose. Industry 4.0 maturity models are a rich source of IDT conceptualizations. Conceptualizations of IDT underlying maturity models are mostly linear.[73–75] They present IDT as developments on a single plane. They determine parameters that define IDT and whose graduation on a linear scale reflected the development of associated organizational capabilities. These models have been built around quantitative measures of management and technical competencies or sequentially graduated capabilities deemed to be dimensions of Industry 4.0.[11,19,73–76] These ideas illustrate simple, intuitive, and process-focused approaches. However, they are often not reflective of the realities of practical business scenarios.[25]

An approach to developing an IDT conceptual framework is integrating existing technologies with IDT design considerations. Salkin, Oner, Ustundag and Cevikcan [53] proposed a framework based on design principles identified by.[77] Design or architecture principles are critical to defining system architecture; they describe the essential aspects of the system design and provide the necessary guide for its management.[78] Principles relate the system's high-level strategies to its practical design, ensuring its design and evolution track its objectives. They are critical for presenting the essence of system design.[79] The Salkin, Oner, Ustundag and Cevikcan [53] model adopted the design principles of Li, Xu and Zhao,[77] including real-time data management, interoperability, virtualization, decentralization, agility, service orientation, and integrated business processes.

Similarly, Zheng, Ardolino, Bacchetti and Perona[80] integrated identified technologies with manufacturing company processes. This approach seeks to identify how technology creates practical value in advanced manufacturing and could present a pragmatic framework for industrial development. However, the lists of technologies, principles, and processes employed in such models are not exhaustive. Consequently, a research process for deriving generalizable insights on IDT strategy and value proposition based on them is challenging. While the technologies are widely referenced in digital transformation literature, they acknowledged that the list is not exhaustive. Furthermore, the design principles are not universally agreed upon.[81,82]

This study is critical in addressing the gap in IDT conceptual frameworks in the digital transformation literature. The development of IDT-related organizational capabilities is challenging in practice, practitioners have difficulty determining the starting point and charting the course to value delivery, and the requirement for improved tools, methods, and frameworks remains.[72] Furthermore, the low level of industry adoption of the maturity and development models based on existing conceptualizations suggests that further improvements that reflect the practical realities of Industry 4.0 scenarios are useful.[83] Therefore, there is a need to take another look at the conceptualization of IDT with a sufficient representation of practical scenarios for business usefulness. The conceptualization should have empirical validity to support research activities and address the gap between digital technologies integration in production processes and industrial value creation.

Research method

The methodology for the study comprises semi-structured expert interviews. Semi-structured interviews are effective where the respondents have significant objective knowledge of the subject matter.[84] The study follows the approach of existential phenomenology, exploring the experiences of members of a group to gain their perspectives to facilitate theory development.[85] Interviews are particularly appropriate in this scenario. Appendix A contains the interview questions framework. Sixteen highly experienced digital transformation professionals from seven organizations with expertise in IDT were interviewed. The group comprises senior members of top global firms' digital transformation and technology advisory functions by revenue,[86] they all have responsibility for delivering their client's critical digital transformation objectives. The study employed snowballing sampling.[87] Respondents were encouraged to facilitate the participation of their colleagues in the study. The top global technology service providers involved in providing technology for digital transformation were approached, from where a snowballing technique was deployed. Senior management personnel of global businesses is an elusive target group, and snowballing facilitated multiple respondents from organizations which helped triangulation for research quality.[88]

According to their financial reports, the smallest of the firms by annual revenue had over USD 30B in revenue in 2021. The respondents had a minimum of twenty-one years of technology and management experience and were based in Australia, the USA, the UK, France, and Singapore during their interviews. The profile of respondents, particularly the length of their industry experience, improves the chances of expansive views acquired from different organizations they have worked. Their overall career experience spanned many more countries, including India, Nigeria, Germany, Brazil, China, The Netherlands, and South Africa. The profiles of respondents are presented in Table 1. The interview questions guide was shared with participants before the interviews to allow them to prepare adequately for the interviews. The questions involved digital transformation, smartness, and technology-related organizational capabilities. They were also asked about perceived benefits, hindrances, and enablers of these capabilities.

Responses to questions and further elaborations were recorded, coded, and analyzed for theory development

Table 1. Participant's profiles.

Respondent	Location	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

on Industry 4.0, what it is, how it is achieved, and why it is done. Coding and analysis followed the Gioia methodology.[89] It has been used effectively for contextual analysis in qualitative research,[90] which is at the core of this study. Furthermore, it identifies the aggregate dimensions of the subject in very short iterations, which lends itself to applications in conceptual framework development. The Gioia methodology establishes the underlying structure of the research concept through a uniform process that allows consistent treatment of participants who may not have been interviewed at the same time, enabling the recognition of convergence at a point where new emergent concepts are no longer observed. According to Gioia, Corley and Hamilton,[89] researchers must constantly cycle through concepts and emergent themes to determine if new concepts are discovered. For this study, convergence was achieved after 16 interviews.

The Gioia methodology consists of three stages, the first-order analysis, the second-order analysis, and the aggregate dimensions.[89] The first-order analysis consists of *open coding*.[91] The researcher captures the participant's thoughts as originally as possible, identifying concepts that emerge directly from the participant's words. The first-order concepts feed the second-order analysis with a relatively large number of concepts from which the researcher identifies emerging orders, groupings, and associations, names them, and arrives at a reduced number of concepts as the second-order concepts. The researcher then embarks on another iterative process, applying the lenses of applicable theory to the second-order concepts. In this study, the foundational theory is dynamic capabilities. We posit that technology represents inputs into the IDT process that generate organizational value as outcomes via organizational capabilities. We apply this lens to reviewing the second-order concepts and observe emerging concepts representing the inputs, outcomes, and intermediate changes to the organization as aggregate dimensions. Appendix B: Gioia methodology data structure maps the concepts across the analysis iterations, presenting the final dimensions defining the digital transformation process.

The study considered critical issues in research quality.[92,93] They ensure that research instruments measure the concepts they purport to measure and do so accurately. Research quality was addressed in multiple ways. Firstly, there was expert validation by research colleagues.[94] The experts consisted of research colleagues with extensive experience in digital transformation and qualitative research who provided inputs for refining the question framework. Secondly, triangulation is a viable method for addressing validity.[88] This study deployed triangulation by having multiple respondents across industry segment expertise and within firms and applying the interpretative rigor of three researchers for reviewing the emergent data structure from the coding and analysis of responses.[88]

Results

We derived first-order concepts, second-order concepts, and aggregate dimensions by applying the methodology to the data collected from the respondents. The aggregate dimensions are the technology and organizational features.

Appendix B maps the first-order concepts to second-order and second-order concepts to the aggregate dimensions.

Technological features

Analysis of the research data revealed four classes of technological features. These groups broadly address key requirements of smart production systems. They are intelligence, simulation, visualization, and remote interaction, data and information management, and stimuli responsiveness.

Intelligence

Seven of the 16 respondents (4, 5, 7, 11, 13, 14, and 16) identified machine Intelligence as an essential feature of IDT as it is critical for smart systems. Respondents 7 and 13 further noted that artificial intelligence is a part of a collection of technologies that collectively create unique emergent characteristics of IDT. According to Respondent 7, *"Industry 4.0 capabilities are facilitated by advanced technologies that enable stimuli responsiveness, artificial intelligence, data processing, visualization, and robotic actuation."*

Technologies noted by respondents in this category include machine learning, natural language processing, machine vision, and predictive analytics.

Simulation, visualization, and remote interaction

Respondents 3, 4, 13, and 16 recognized the importance of technologies that facilitate simulation, visualization, and remote interaction for IDT. According to Respondent 3, Extended reality (XR) enables remote interactions between users and production elements (systems and processes) by removing boundary constraints. They note that removing boundary constraints is a defining characteristic of post-Industry 4.0 industrial operating environments. They stated, *"Development in cybersecurity and extended reality suggests that removal of environmental boundary constraints is key to Industry 4.0 and might define its evolution into Industry 4.1 or* *even 5.0"*. Respondent 4 identified the role of Virtual Reality (VR) in Operating Technology (OT) digitization, IT-OT integration, and the importance of simulation and visualization capabilities of digital twins in Industry 4.0-related advanced product development capabilities. XR is identified as one of the technologies that create the integrative property of CPS (Respondents 13 and 16), enabling the integration of virtual and physical production components. Technologies in this category referenced by respondents include augmented reality, virtual reality, live virtual construct/mixed reality, and digital twins.

Data and information management

Respondents 1, 5, 7, 13, 14, and 16 identified digital infrastructure (DI) for data and information management is key for IDT. According to Respondent 7, data processing is an underlying requirement of IDT, hence the requirement for acquiring, storing, processing, securing, communicating, and transporting data. Respondents 5 and 14 identified computing infrastructure as key for Industry 4.0. These are not new to organizations, being the hallmark of the third industrial revolution, predating Industry 4.0. According to Respondent 3, *"the previous revolutions had pockets of gains in automation and computing."* Industry 4.0, however, builds on developments in DI, like cloud computing, combined with advancements in other technology areas to create smart solutions (Respondents 1, 5, and 13). Respondent 14 further recognized infrastructure democratization as a social value created by Industry 4.0 and enabled by cloud technology. According to Respondents 1 and 16, Industry 4.0 capabilities require next-generation data communication functionalities featuring hyperconnectivity and high throughput, low latency communication. Overall, technological capacities for acquiring, processing, securing, transporting and storing data and information including enterprise information systems, cloud computing, edge computing, 5 G networks, cyber security, and data analytics were identified as key for IDT.

Stimuli responsiveness

Sensing and actuation are considered in tandem because they combine to give systems stimuli responsiveness functionalities, enabling systems to interact with their environments. Four respondents (4, 7, 13, and 14) identified the role of sensing and actuation. Respondent 7 stated, *"Industry 4.0 capabilities are facilitated by advanced technologies that enable stimuli responsiveness"*. Respondent 4 identified sensors and the ability to measure physical processes within the environment as one of the key underlying technologies without which Industry 4.0 would not be possible. Sensors accomplished this by enabling the digital transformation of OT (operating technologies). Respondent 14 singled out changes in the working of machines due to advancements in sensor technologies as an important enabler of Industry 4.0.

Production systems respond to their environments using actuation technologies. According to respondents 4, 7, 9, and 14, advanced robotics is an important actuation mechanism in Industry 4.0. Respondents recognized the importance of cobots, industrial robots, and Automated guided vehicles (AGVs).

Organizational features

The results identified the following defining organizational features enabled by Industry 4.0.

Digitization

Eleven of the respondents (1, 4, 5, 6, 7, 8, 9, 10, 11, 12, and 14) identified the role of digitization as the base concept of Industry 4.0. Respondent 8 viewed digitization as definitive of Industry 4.0; according to them, *"Industry 4.0 is the digitization and integration of the entire production enterprise to deliver an end-to-end digital value chain."* The unique importance of digitizing OT or machines to Industry 4.0 is a running narrative across the respondents on digitization. Respondents 4 and 10 noted that OT digitization is a niche functionality of Industry 4.0. They proposed that OT digitization extends prior digitization of the front office with Information Technology (IT). Respondent 10 stated Industry 4.0 included the *"Fusion of IT and OT, or the digital and physical components of production (with IoT) to create new socio-economic values."* The digitization of OT is distinctive and significant as it enables IT-OT integration to facilitate the 360-degree flow of data between the cyber and physical components, thus enabling the Cyber-Physical System (Respondent 4).

Integration

Integrating the production enterprise as an objective of Industry 4.0 was highlighted by the majority of respondents (3, 4, 5, 6, 7, 8, 11, 12, 15, and 16). Along with digitization, Respondent 8 considered integration as definitive of Industry 4.0. According to the respondents, the context for integration in Industry 4.0 covers all production entities to achieve end-to-end integration. Cyber-physical integration is, however, the characteristic feature of Industry 4.0, according to Respondents 9, 10, 12, and 13, as it enables the networking of physical and virtual elements, enabling a physical-virtual information loop. On the enterprise level, CPS achieves IT-

OT integration, which according to Respondent 10, enables the delivery of socio-economic values.

Industry 4.0 builds on CPS to create a non-linear value chain through horizontal, vertical, and end-to-end engineering integrations. According to Respondent 16, integrated value chains create capabilities not seen in linear value chains. Relating the value proposition of Industry 4.0 directly to CPS, Respondent 3 claimed, *"Industry 4.0 is revolutionary, resulting in efficiency and effectiveness gains through CPS."* Similarly, according to Respondent 9, the enhanced production capabilities of Industry 4.0 are associated with cyber-physical integration. The advanced capabilities emerge through the enablement of seamless man-machine interaction, process digitization, and data transparency. Respondent 13 notes the attribute of the transformation induced by CPS to include speed, transparency, visibility, autonomy, and flexibility.

Data capability

Seven respondents (4, 5, 7, 11, 12, 13, and 14) highlighted the importance of data to Industry 4.0. According to Respondent 11, *"data is the lifeblood of Industry 4.0"*. The respondents addressed the data capability of production organizations in acquiring data, processing data, and using assets data for business intelligence and digital enablement. Respondents 4 and 14 discussed the role of sensors in deepening the data acquisition capacity of production systems as important for Industry 4.0. Respondents 7 and 11 elaborated on the role of digital infrastructure for data processing, storage, and transport, and respondents 5, 11, and 13 pinpointed digital infrastructure's role in analytics and business intelligence. According to Respondent 12, Industry 4.0 business models exploit data commercially.

Production ecosystems

Respondents 1, 11, and 15 described the emergence of production ecosystems from the integrated value chain. According to Respondent 1, interoperability facilitates ecosystem formation. The respondent predicted shifting production value chains away from tight integrations toward more agile, ecosystem-friendly approaches. According to Respondent 15, the integrated ecosystem approach delivers superior production value than the unintegrated enterprise. They stated: *"Industry 4.0 uses the connectedness of systems and processes across the entire production value chain to create an intelligent, flexible production ecosystem, delivering superior value compared to the unintegrated enterprise."* To highlight the value proposition of ecosystems, Respondent 11 associates the smart characteristics of Industry 4.0 production enterprises with the flexibility of the ecosystem approach.

Information transparency

Seven respondents (3, 7, 9, 10, 11, 13, and 16) identified information transparency as key to Industry 4.0. According to Respondent 10, the value of Industry 4.0 relates to its role in completing the information loop started in Industry 3.0. They stated: *"The fourth revolution completes the digital-physical loop by feeding back analyzed information into the physical space from the digital."* According to Respondent 16, it enables the flexibility required for the responsiveness of Industry 4.0 production systems. Respondent 11 associates data access and real-time information availability with smartness. Respondent 3 identified removing boundary constraints to facilitate ubiquitous access to information as a defining feature of Industry 4.0 and beyond. Remote interactions are possible because of the exposure of information beyond the physical barriers of Industry 4.0 systems. Respondent 9 posited that the visibility of data and processes in Industry 4.0 was universal. The respondents connect the relationship between data capability, information transparency, and smartness in the Industry 4.0 context.

Persistent customer engagement

According to Respondents 2 and 8, the increasing need to customize products is one of the key drivers for Industry 4.0. Respondents 8 and 16 identified persistent customer engagement as a characteristic of Industry 4.0 aimed at facilitating mass product customization. Respondent 8 claimed that an early engagement of the customer in the production process and continual engagement throughout the product lifecycle is necessary for mass customization. Respondent 16 claimed that producers must have constant visibility of customer behaviors and preferences as an input into the production cycle to fulfill the objectives of Industry 4.0. They state that Industry 4.0 creates a fully integrated enterprise through which *"producers have both visibility of and dynamic insights on their own operations end to end, covering supply chain, customers and production systems, and processes."*

Smartness

All respondents except three (Respondents 3, 4, and 10) related Industry 4.0 to smartness. According to Respondent 11, digitization and integration are foundational to Industry 4.0, creating the platform for smartness. Respondent 12 claimed that industry 4.0 technologies are associated with smartness, and transforming the production enterprise into a smart one is a characteristic of Industry 4.0. Similarly, Respondents 2, 6, 7, and 13 identified connections between Industry 4.0 technologies and smartness. Respondents 6, 7, and 13 linked smart system characteristics to digital technologies, and Respondent 2 claimed that the problem-solving capacity of Industry 4.0 is attributable to the smartness of solutions created out of digital technologies and addresses the socio-economic challenges.

The respondents presented smartness as a characteristic feature of Industry 4.0. Respondent 5 identified smartness as the emergent capability of Industry 4.0 through which it creates value. They stated: *"the implementation of these technologies enable the integration of the value chain and the factory elements resulting in three capabilities, smart products, smart factory, and smart supply chain."* The respondents collectively argued that digital technologies combine to induce smartness in the production processes and the organization's business functions. Furthermore, they posit that smartness is a means to an end. It provides functionalities that enable the delivery of Industry 4.0's value propositions.

Value creation

All the respondents identified socio-economic values created by Industry 4.0, demonstrating it is a core outcome or focus for the process. Respondent 1 noted organizational productivity and national economic gains, other value creation identified by respondents included: productivity (respondent 15), cost efficiency (respondent 3), product innovation (respondent 12), customer experience (respondent 6), employee well-being (respondent 15), environmental sustainability (respondent 2), sovereign manufacturing capability (respondent 1), social equity (respondent 14), and economic growth (respondent 1). According to Respondent 2, Industry 4.0 emerged to address challenges in three aspects of production – product customization, environmental impact, and increased variability in the production environment. Respondents 2, 8, and 16 claimed that it addresses those challenges. Respondents 7 and 10 indicated that Industry 4.0 is a set of capabilities that deliver optimal socio-economic outcomes in industrial production. Respondent 15 compared the value creation of Industry 4.0 with the unintegrated production paradigm that existed before it and claimed that Industry 4.0 delivers superior value by organizing its integrated production chain into an intelligent and flexible ecosystem.

Conceptual framework

In addition to validating the importance of factors (as discussed in Sections 4.1 - 4.3), Figure 1 illustrates these relationships in the conceptual framework developed in this study which will be discussed further in this section.

The respondents discussed the impact of technology in creating value through a range of organizational features. Respondent 7 attributed the value to multiple functionalities from different technologies, and according to Respondent 13, *"Industry 4.0 happens when several developments in technology are considered collectively rather than individually."*

The basic value of technology is the enablement of digitization and integration (Sections 4.2.1 and 4.2.2). Respondents 8, 11, and 12 simplify many relationships between factors. They established links between integration and customer engagement, ecosystems, data capability, and information transparency. Respondent 11 provided a link between digitization and integration,

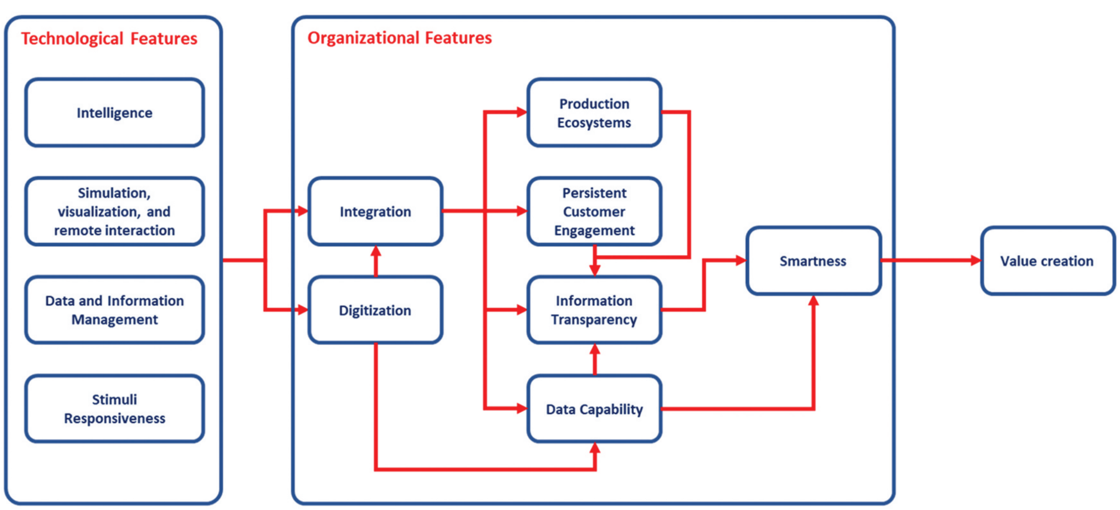

Figure 1. Industry 4.0 conceptual framework.

stating: "*the digitization provides the platform for the integration.*" They identified production ecosystems and customer integration as key integration contexts. Listing key attributes of Industry 4.0, Respondent 11 described Industry 4.0 as: *"the horizontal integration of the production ecosystem,"* and Respondent 8 stated: *"Industry 4.0 integrates the entire value chain and enables the engagement of the customer early in the process and throughout the process."* Respondent 11 links digitization and integration to data capability. They stated: *"digitization and integration are crucial for data capability."* The integration connects production ecosystems and facilitates customer engagement, facilitating information transparency and data capability, leading to smartness in the enterprise.

Respondent 12 stated that the integration *"seamlessly funnels data and analyzed information back and forth between the digital and the physical elements,"* establishing the link between all integrated entities and information transparency. They also attributed the smartness of the enterprise to data capability and information transparency, stating:

> Industry 4.0 ultimately transforms the enterprise into a smart one … The organization exhibits autonomous functionalities and seamlessly funnels data and analyzed information back and forth between the digital and the physical elements to enable further intelligent actions in the physical world. (Respondent 12)

Respondent 2 attributed Industry 4.0 value creation to smartness. Respondent 2 stated: *"Through smartness, Industry 4.0 addresses the challenges that necessitated it.*

The research thus synthesized the relationships across the factors into the conceptual framework for Industry 4.0:

- Digital technologies collaborate to enable digitization and integration.
- The integration connects customers and creates a connected production ecosystem.
- The integrated ecosystem and customer enable data capability and information transparency, which lead to smartness.
- The enterprise uses smartness to generate socio-economic value.

Discussion

While there is an industrial revolution perspective of Industry 4.0 with broader implications for society, this study explored Industry 4.0 from an organizational perspective that creates value through digital transformation. The study produced a conceptual framework to drive the IDT process within organizations. The framework provides a pragmatic approach to managing the many technologies, tools, and methods of Industry 4.0 for value creation. Validating the technologies, tools, and methods of Industry 4.0 is important for implementing the concept, and the digital transformation literature dedicates considerable focus to it.[95] The framework presents technology as inputs into the transformation process and organizational value creation as the outcomes. It focuses on the inputs on the organization between the technology inputs and the value outcomes, initiating organizational features that culminate in smartness and result in organizational value creation.

Technology

According to Respondent 3, some technological features that predate Industry 4.0 play critical roles in IDT. The pace of technological developments also implies that new technologies with IDT relevance will continually emerge. This study, therefore, avoids attempting to identify IDT or Industry 4.0 technologies. Determining Industry 4.0 technologies is also complicated because many "technologies" usually referenced in the Industry 4.0 literature are systems comprising multiple technologies, e.g., additive manufacturing consists of sensors, actuators, AI, and DI. However, the study finds that developing key organizational features and focusing on value creation provides the necessary context for IDT value proposition. IDT technologies conceptually are, therefore, those with unique or significant contributions to smart production and its underlying features, including digitalization, integration, data capability, and information transparency. Given the role of technology in IDT, its framework must reflect technology. This study identifies four groups of technological features that drive the technology application in IDT. Building the model on functional features rather than specific technologies enables a framework with a degree of technology agnosticism.

Smart systems are stimuli-responsive (sensing and actuation),[96] intelligent,[97] and have enhanced data capabilities,[98–102] including digital infrastructure for data handling.[103] The IDT context for smartness also has unique requirements for extended reality [104–106] to facilitate simulation and visualization.

Organizational features

Respondent 11 states that data is the lifeblood of Industry 4.0. Data is a lens through which the Industry 4.0 framework can be understood. Digitization and integration enable Instrumentation, interconnection, and intelligence, which are properties of effective smart systems.[107] They facilitate data acquisition, transportation, and utilization, the foundational infrastructure for data management capabilities, and transform the production enterprise into a network of production information systems that facilitates information transparency.[108] Information transparency is the basis for smartness by enabling real-time information on production parameters for optimal decision-making and autonomous functionalities.[109,110]

Data is a new source of business value through business model change, enabled by persistent engagement of the customer for customer-driven innovations.[111] Respondent 12 notes that business model transformation in Industry 4.0 exploits the value of data. It thus transcends enabling the value creation process; it is value itself. IDT promotes the adoption of new organizational business models and embedding new business practices that intend to evolve the organizational efficiency level and simultaneously address social and environmental challenges. Aiming to simultaneously deliver performance and ensure transformation, creating enduring value for its key stakeholders and achieving remarkable results as the EFQM 2020 model advanced. These novel Business Models can add a strategic and technologically unbiased perspective to a technology-centered Industry 4 approach[51]

Conclusion

Developing IDT capabilities in production organizations is complex[21,112] and often chaotic.[72] This work offers valuable contributions. It has made a theoretical contribution of an evidence-based conceptual model for driving Industry 4.0 maturity and value creation. This model can serve as a guide for practitioners.

IDT employs digital technologies to enable smartness for outcome optimization. Following the input-output system model of Dutta, Narasimhan and Rajiv,[60] smartness is the value-creating intermediate capability of IDT. The smart enterprise capability is built on information transparency functionality, resulting from digitalizing and integrating the production value chain. Integrating the value chain results in a production ecosystem of multiple partnering firms and the end-to-end embedding of the customer in the product lifecycle, enabling real-time, contextual information on production elements, including people, materials, products, devices, systems, and organizations. Digitization, integration, enhanced data capability, efficient production ecosystem, customer integration, and information transparency are organizational features that signpost the digital transformation process. They are parameters from this study that can help embed an IDT strategy in practical reality, defining a conceptual framework to guide execution and value delivery quality.

Managerial implications

While Industry 4.0 has been conceptualized widely as the digital transformation of the production organization,[11,19] the outcomes of this study provide further insights into the nature of this transformation for information systems managers and operations managers tasked with introducing industry 4.0 technologies in their workplaces. Previous studies established that Industry 4.0 considerations must expressly cater to business and management elements of transformation beyond technology.[11,30,113] This study highlights features within an organization that should be targeted for development. Implemented technologies should impact the organization's capacity to digitalize processes and functions, all integrating physical and virtual entities. It should improve the data capability of the organization, including acquisition, management, and utilization. Persistent integration of the customer into the product life cycle and enablement of production ecosystems through interoperability is critical in successful Industry 4.0 implementation.

Technology creates the capability for digital transformation in the production enterprise. It combines functional attributes of sensing and actuation technologies, artificial intelligence, extended reality, and digital infrastructure to create smart solutions that support digitization and integration. The technology implementation must have traceability to smart functionalities in production processes and business functions. Managers must realize that implementing these technologies does not actualize Industry 4.0, and many of these technologies would already exist in the organization as they predate Industry 4.0. The Industry 4.0 strategy must target capabilities by integrating the enterprise end-to-end through digitizing OT and implementing CPS using existing and newly implemented technologies.

Table 2 summarizes the managerial implications of factors identified in the research.

Limitations and future directions

The study is designed to produce generalizable results across industrial production; it, therefore, does not explore industry sector-specific insights. Further studies designed to elicit sector-specific insights for industrial digital transformation will be valuable. While the study utilized 16 interviews of respondents from seven organizations based in four countries, a broader scope of organizations and countries and a larger pool of respondents

Table 2. Research factors.

Factor	Implication
Stimuli Responsiveness	The technology strategy must identify opportunities to sensorize machines and expand IoT. It must identify manual activities and repetitive processes that represent good opportunities for automation.
Data and Information Management	The Industry 4.0 strategy must consider the digital infrastructure's adequacy, flexibility, and optimality. It is foundational to data capability and will perverse the technology landscape. It could drive costs.
Intelligence	Business intelligence and automation requirements should drive Artificial intelligence technologies adoption. Its value should be measured by decision-making accuracy and autonomous functionalities.
Simulation, Visualization, and Remote Interaction	Extended reality technologies should be part of the digitization strategy. Extended reality integration into processes should be driven by requirements from the value end of the strategy, particularly product innovation.
Digitization	Managers should ensure that business requirements drive digitization. The focus of digitization should be on sensorizing machines and automating manual processes. Digitalized business processes and functions should characterize the target state.
Integration	The target state should be characterized by eliminating silos and stand-alone elements in the production process.
Production Ecosystems	The transformation should eliminate all isolated business functions in the production process. Visibility of all entities at all points throughout the value chain must be a goal.
Persistent customer engagement	The transformation must embed the customer's perspective in all phases of the product lifecycle. It must enable customer-driven product innovation.
Information Transparency	Information transformation should be a key driver of strategy. At each point in the strategy, an important question should be, "do we have all the necessary information on all production elements in real-time?"
Data Capability	The ability of the production enterprise to acquire, manage and utilize data. This capability should be driven by a maturity model mapped to the business objectives.
Smartness	All activities in the strategy should have traceability to this capability. Technologies must contribute to stimuli responsiveness, intelligence, decision-making, information transparency, or autonomous functionalities.
Value Creation	Industry 4.0 implementations must be targeted toward specific value creation objectives for the organization. The research identified several social and economic value creation potentials of Industry 4.0, including productivity, sustainability, cost efficiency, social equity, and economic growth.

could improve the validity and reliability of the study and hence its generalizability. Furthermore, a quantitative study to validate the outcomes of this study is useful.

This study has produced a model to support managers' Industry 4.0 strategies. It offers aid to information systems managers, digital transformation specialists, and business leaders in charting a pathway from technology implementations to value realization. It focuses its strategy on developing value-creating features in the enterprise, including integrating customers into product lifecycle management end-to-end, enabling an effective production ecosystem, developing the organization's data capability, and developing information transparency and smartness across the value chain. The contribution of this study will help actualize the industry 4.0 vision in practical scenarios.

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Appendices

Appendix A. Semi-structured interview guide

- What is Industry 4.0?
- Which technologies are important for Industry 4.0 and why?
- Which management competencies are important for Industry 4.0 and why?
- Which business factors have driven the adoption of Industry 4.0 capabilities? (productivity, safety, etc.)
- Which business factors have hindered the adoption of Industry 4.0 technologies? (Cost, complexity, etc.)
- What role do environmental factors play in the adoption of these technologies? (Competition, Regulation, etc.)
- What role do organizational factors play in the adoption of these technologies? (Size, complexity)
- What role do technological factors play in the adoption of these technologies? (Exiting technology investments, implementation, integration, management capabilities, etc.)
- How does Industry 4.0 influence organizational performance?
- What is smartness, and how is it related to Industry 4.0?

Appendix B. Gioia methodology data structure

Aggregate Dimension	First-order Concept	Second-Order concepts
Intelligence	Artificial intelligence	Artificial intelligence
	Machine Learning	Machine Learning
Customer engagement	Persistent customer engagement	Customer engagement
Data Capability	Data acquisition	Data Capability
	Data analytics	Data Capability
	Data Capability	Data Capability
	Data processing	Data Capability
	Real-time business intelligence	Data Capability
Data and Information Management	Cloud computing	Cloud computing
	Computing infrastructure	Computing infrastructure
	Edge computing	Edge computing
	Enterprise Information Systems	Supply chain optimization/Interoperability
	Nextgen Communication	Nextgen Communication
Simulation, Visualization, and Remote Interaction	Extended reality	Extended reality
	Live virtual construct	Live virtual construct
Information transparency	Information and data transparency	Information transparency
	Physical virtual information loop	Information transparency
	Visibility	Resource and Process Optimization
Stimuli Responsiveness	Cobots	Cobots
	IoT	IoT
	Robotics	Robotics
	Sensors	Sensors
	Stimuli responsiveness	Resource and Process Optimization
Smartness	Autonomy	Resource and Process Optimization
	Cloud factory	Smart factory
	Flexibility	Resource and Process Optimization
	Flexible production systems	Resource and Process Optimization
	Intelligent actions	Resource and Process Optimization
	Smart capability technologies	Resource and Process Optimization
	Smart enterprise	Resource and Process Optimization
	Smart factory	Smart factory
	Smart operations	Resource and Process Optimization
	Smart processes	Resource and Process Optimization
	Smart product	Smart product
	Smart production and supply chain processes	Resource and Process Optimization
	Smart production systems	Resource and Process Optimization
	Smart solutions	Resource and Process Optimization
	Smart supply chain	Smart supply chain
	Smartness	Resource and Process Optimization

(*Continued*)

(Continued).

Aggregate Dimension	First-order Concept	Second-Order concepts
Value	Autonomy	Resource and Process Optimization
	Cloud factory	Economic transformation
		Social value creation
	Connectivity	Resource and Process Optimization
	Cost effectiveness	Economic transformation
	Enhanced Manufacturing capabilities	Resource and Process Optimization
	Enhanced Operating and production processes	Resource and Process Optimization
		Task transformation
	Improved production capabilities	Resource and Process Optimization
	Integrated systems and processes	Resource and Process Optimization
	Intelligent actions	Resource and Process Optimization
	Man-machine collaboration	Task transformation
	Manufacturing cost optimization	Economic transformation
	Mass Product Customization	Mass Product Customization
		Product lifecycle transformation
	New customer experience capabilities	Product lifecycle transformation
	Optimal socio-economic value	Economic transformation
		Social value creation
	Process digitization	Resource and Process Optimization
	Process Efficiency	Resource and Process Optimization
	Process Flexibility	Resource and Process Optimization
	Product development capability	Product lifecycle transformation
	Product lifecycle integration	Resource and Process Optimization
	Production capability transformation	Resource and Process Optimization
	Rapid delivery of customer requirements	Product lifecycle transformation
	Boundary removal	Resource and Process Optimization
	Smart capability technologies	Technology features
	Smart product	Product lifecycle transformation
	Smart solutions	Technology features
	Sovereign Manufacturing Capability	Economic transformation
	Stimuli responsiveness	Technology features
	Superior value realization	Economic transformation
	Value of data	Economic transformation
Digitization	Digital fabrication	Resource and Process Optimization
	Digitization	Resource and Process Optimization
	Digitization of Shopfloor processes	Resource and Process Optimization
	OT (Operating technologies) Digitization	Resource and Process Optimization
Integration	Connected enterprise	Supply chain optimization/Interoperability
	Digital enterprise	Supply chain optimization/Interoperability
	Holistic Enterprise transformation	Supply chain optimization/Interoperability
	Hyperconnectivity	Resource and Process Optimization
	Integrated production enterprise	Supply chain optimization/Interoperability
	Integrated value chain	Supply chain optimization/Interoperability
	OT-IT Integration	Resource and Process Optimization
	Physical virtual integration	Supply chain optimization/Interoperability
	Production capability transformation	Task transformation
Ecosystems	Emergence (System of Systems)	Supply chain optimization/Interoperability
	Integrated systems and processes	Resource and Process Optimization
	Production ecosystems	Supply chain optimization/Interoperability
	Vertical integration	Supply chain optimization/Interoperability