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Leveraging I4.0 Readiness Assessment to Drive Digital Pilots and Productivity Enhancement: The Case of a Large Manufacturing Firm

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Abstract: This research examines how an Industry 4.0 (I4.0) readiness assessment can inform the development of a digital transformation roadmap for smart manufacturing, while accounting for firm-level challenges, drivers and readiness conditions. The single case study approach involved I4.0 readiness assessment and analysis of inputs from cross-functional teams and experts. The firm's digital transformation roadmap is based on the prioritisation of key areas for the I4.0 adoption, supported through an I4.0 readiness assessment and inputs from intra-firm/external experts. The analysis revealed that prioritised key interventions are required across Information and Communication Technology (ICT). Furthermore, mapping process-related areas and influencing factors enabled the identification of targeted pilot projects and innovation opportunities that align with the organisation's digitalisation journey from computerisation to adaptability. This research advances theoretical understanding of digital transformation by integrating perspectives on phased transformation, demonstrating how process and technology-oriented evaluation co-constitute one another across sequential stages of transformation. The key limitation is that the study is based on a single 'revelatory' case study, which limits the generalisability of findings. This study provides guidance for manufacturing firms in emerging economies to develop a digital transformation roadmap using I4.0 readiness assessment outcomes, combined with expert inputs.

Keywords: digital transformation; Industry 4.0; Industry 4.0 readiness assessment; prioritisation; pilot projects

1. Introduction

The fourth industrial revolution, referred to as Industry 4.0, represents significant opportunities for the manufacturing sector in the value chain. The impact of Industry 4.0 adoption on the overall value chain at local and global levels is increasingly evident from several studies in recent times [1]. Industry 4.0 brings together manufacturing and advanced technologies such as cyber-physical systems, artificial intelligence, virtual and augmented reality, and 3D/additive printing technology to facilitate the digital transformation and enhance the productivity of the industrial value chain [2]. This convergence can therefore form the basis for the smart factory of the future, characterised by vertical integration of production systems at the firm level, horizontal integration of value chain systems and through engineering across the value chain [3], thereby leading to productivity improvement, enhanced business value, improved performance, and greater competitive advantage [4].

The integration of I4.0 concepts and advanced technologies drives digital transformation, enabling adaptive and intelligent manufacturing environments that fundamentally reshape industrial production. In this context, digital transformation can provide manufacturing with enhanced productivity and a competitive advantage through reduced cost of manufacturing, differentiation using improved product quality, and improved responsiveness through product innovation [5]. It can also promote the creation of sustainable manufacturing industries by effectively managing and monitoring over-production, energy consumption, and wastage [6]. Furthermore, it can enable access to accurate and real-time information that helps overcome uncertainty across all supply chain processes and reduce the risk of human errors through automation [7].

However, the adoption and implementation of advanced technologies associated with I4.0 face several challenges and barriers [8]. Challenges of digital transformation in the context of I4.0 adoption have been investigated from different perspectives. These include barriers to digital manufacturing [9], challenges specific to SMEs [10], different industry contexts [11,12], organisational and technological complexities [13], challenges specific to emerging economies [9], and issues in the context of global supply chains [14]. Several studies have elaborated on lessons and strategies to overcome such challenges and indicated enablers for digitalisation [14,15].

The complex process of I4.0 adoption requires careful planning involving not only existing and advanced technology integration but also prioritised and targeted organisational level changes to enable a phased implementation approach [6]. It may thus be said that a fundamental and critical prerequisite in the planning of I4.0 adoption at the firm level is assessing a company's I4.0 readiness. I4.0 readiness is dependent on many factors including technology infrastructure, organisational factors (e.g., strategy and leadership support, culture, geographical location, human skills), external factors (e.g., economic and political stability) and product and service factors [16,17]. Several studies have reported on I4.0 readiness at the firm level, from a simple targeted approach to a holistic approach of combining several organisational, technological, and process aspects [16,18].

While several studies have reported useful findings from the perspective of individual and isolated contexts through respective case studies using readiness assessment frameworks or maturity models, the main research gap on the broader topic of digitalisation is a lack of research on combining digital transformation and readiness assessment towards I4.0 adoption, taking into consideration challenges and drivers for digital transformation as well as levels of readiness at the firm level. In addition, a secondary research gap is the lack of a digitalisation roadmap with prioritised key interventions from a process perspective, considering current practices and challenges in each level of transformation.

To address these research gaps, this research is set out with the following research question (RQ): How can a digital transformation roadmap based on I4.0 readiness assessment be developed to effectively address the challenges of I4.0 adoption at the firm level? Thus, the broader aim of this research is to investigate the role of I4.0 readiness assessment in planning digital transformation for I4.0 adoption. To achieve this through empirical validation, an in-depth case study was carried out in a manufacturing firm located in an emerging economy setting, which had carried out an I4.0 readiness assessment using a self-assessment framework, and used the findings to develop a digital transformation roadmap to facilitate the adoption of I4.0 technologies. It is envisaged that the findings from this case study can extend the existing body of knowledge on digital transformation associated with I4.0 adoption, using I4.0 readiness assessment frameworks and prioritisation of key areas, and also provide a basis for developing an implementation roadmap for similar organisations to transition from traditional manufacturing to smart and intelligent manufacturing.

The paper is structured as follows. The next section outlines the research context and background, followed by an overview of the research methodology. Section 4 presents the case study, with a concise description of the case organisation, findings of the I4.0 readiness assessment, and a subsequent digital transformation roadmap adopted by the case organisation. Section 5 discusses the research findings and managerial implications. Finally, conclusions and theoretical implications are presented.

2. Research Context/Background

2.1. Challenges and Barriers to an I4.0 Transition from a Digitalisation Perspective

Embarking upon a digitalisation program in the production and value creation process is radical and can pose many challenges to a company [19]. Many studies focus on investigating challenges and barriers, such as technical challenges including lack of infrastructure and internet-based networks [20]; lack of standardisation and cybersecurity risk [21]; and poor existing data quality and lack of integration of technology platforms [16]. Moreover, strategic level and organisational challenges that companies can face include lack of government support and policy [19], lack of digital culture; lack of financial resources; reluctance to change [22]; low management support and dedication [19]; lack of competency in adopting new business models and poor research and development on I4.0 adoption [16].

On the other hand, barriers are significant obstacles that can prevent or significantly delay the digitalisation, such as high initial investment and lack of human capital/expertise [23]. Thus, examining the potential of a firm to assess its readiness to transition to an I4.0 setting and prioritising critical areas relevant to the digital transformation journey would be of value from strategic and operational level planning perspectives.

2.2. Readiness Assessment for Transitioning to an I4.0 Setting: An Emerging Economy Perspective

Several studies have elaborated the I4.0 maturity and readiness framework for assessing I4.0 readiness at the firm level [18,24,25]. Maturity models are tools used to measure, compare, and describe an organisation's current state, identify the desired future state, and determine the potential path for evolution [26,27]. Readiness models/assessments are evaluation tools to assess and determine the level of preparedness, attitude, and resources at all levels of a system [10].

Acceleration of I4.0 for sustainable manufacturing in the COVID-19 era is also seen as a way of encouraging the adoption of digital technologies to improve resilience after the shock [28]. However, transitioning to I4.0 presents many difficulties to firms. Ref. [24] stated that the inability to determine the status of development with regard to I4.0 and the incapability to link specific domains and business strategies are the main issues organisations are facing in digital transformation. Thus, they argued that to overcome uncertainty in manufacturing firms in adopting I4.0, it is important to provide the methods and tools with the needed guidance to plan a smooth digital transition and align with business strategies.

2.3. Digital Transformation of Manufacturing

Digital transformation through digitalisation and the adoption of I4.0 technologies is a complex process. In this context, I4.0 readiness assessment can be considered as a critical part of the process [1]. On the other hand, the selection of advanced technologies, aligned with the level of readiness, as well as developing a roadmap for transformation, depends on several factors, including current practices, challenges/barriers, and enablers. Recent studies on I4.0 adoption have revealed that challenges, barriers, and enablers are extensive, while some are very specific to industry, geography, and scope context [29,30]. From the perspective of different industries, geographical context, and level of maturity/capability, which is directly related to the size of the organisation, significant differences in adoption challenges are identified [31]. For example, small and medium-sized enterprises (SMEs) recognise the impact of I4.0 and integrate digital technologies into their processes, increasing productivity (profits or market positions) or supporting supply chains to meet the needs of I4.0 development [32].

In examining advanced technology adoption within digital transformation, particularly in terms of aligning current readiness levels with organisational strategies and functional areas, several studies highlight the importance of developing a digital transformation program [33,34]. In addition, some studies have reported on digital transformation from various perspectives, including the need for alignment of technology with levels of maturity at the organisational level [35] and levels of transformation from computerisation to smart factory [36]. To make digital transformation a success, a program of pilot projects is essential not only for prioritising key areas of technology adoption but also for managing the transformation in stages [37].

It is evident from the research background outlined above that many organisations in emerging economies are facing challenges and barriers in transitioning to an I4.0 setting. Ref. [6] applied the I4.0 Readiness Assessment Framework (I4.0RAF) and demonstrated its practical applicability as an eight-determinant, self-diagnostic tool (shown in Table 1 in Section 4.2) for assessing a firm's readiness to transition toward an I4.0 setting. The determinants (D1–D8), drawn from [17]'s I4.0RAF, provide a comprehensive framework encompassing organisational, process, and technology measures, directly linked to assessing firm-level I4.0 readiness. In addition, I4.0 readiness self-assessment can be used to validate and guide existing I4.0 adoption modalities such as digital transformation initiatives. Thus, this study uses this self-diagnostic tool as a basis to assess I4.0 readiness and guide an existing digital transformation initiative through a case study in an emerging economy setting. It is envisaged that the findings of the I4.0 readiness assessment could illustrate the value of using the information for developing a digital transformation program for an organisation to embark upon an I4.0 transition project.

Table 1. Summary of self-assessment of I4.0 readiness at TBPL.

Determinant	Criteria						Overall Score	Average Score
	C1	C2	C3	C4	C5	C6		
D1. Strategy and Organisation	2	3	3	1	1	4	14	2.33
D2. Plant and equipment	2	2	3	2			9	2.25
D3. Information technology systems and data management	3	2	2	2	2	2	13	2.17
D4. Human resources	3	0	2	2			7	1.75

Table 1. *Cont.*

Determinant	Criteria						Overall Score	Average Score
	C1	C2	C3	C4	C5	C6		
D5. Product definition	0	0	3				3	1.00
D6. Managing operations–energy consumption management	2	1	1				4	1.33
D7. Managing operations–quality management	1	2					3	1.50
D8. Managing operations–supply chain management	2	2	2	2	1		9	1.80
Overall Score							62	1.88

Source: Compiled by authors.

3. Materials and Methods

In accordance with the overall objective of this study, the empirical part of this study is aimed at investigating the role of I4.0 readiness self-assessment in planning digital transformation and elaborating how the findings can be used to develop a digital transformation roadmap to facilitate the adoption of I4.0 technologies. This study adopts an interpretivist perspective using a qualitative single-case study design. Data was collected from multiple sources, including expert interviews and internal documents. Participants were purposively selected based on their domain expertise and involvement in digital initiatives. The data were analysed through a structured approach to inform the development of the readiness assessment, digital transformation model, and digital pilot program. It was thus decided to conduct an in-depth single-case study of a digital transformation exercise currently being carried out in the subsidiary, located in an emerging economy, of a multinational firm. The single-case design [38] was considered most appropriate due to the following reasons. First, the single-case study design can be used as a "revelatory case" [38] where, as emphasised by [39], "the phenomenon can be studied in its natural setting and meaningful, relevant theory generated from the understanding gained through observing actual practice". Secondly, the organisation was willing to share information on current operational and strategic thinking at the company. As emphasised by [38], this met a critical requirement of reducing the chances of misrepresentation while enhancing access needed to collect desired case study evidence. Due to resource and time constraints, it was not feasible to conduct multiple case studies involving subsidiaries of the parent company, located in other emerging economy settings.

To identify companies that were willing to participate in the research study, the authors conducted an online webinar, for the manufacturing sector titled, "Are you ready for Industry 4.0 Transformation". This webinar was organised in partnership with a leading university in the case study country and consisted of two presentations: (i) An Integrated Approach for Assessing Industry 4.0 Readiness of a Firm in the Manufacturing Sector; and (ii) Industry 4.0 Readiness Assessment: A Case Study. To ensure a better understanding of the readiness assessment tool and the materials presented in the workshop, these were translated into the local language by the partnering university. More than 40 managers from several manufacturing firms joined the webinar. This was followed by a second webinar to provide clarifications on issues raised by designated contact persons of each organisation interested in completing the I4.0 self-assessment. Self-assessment was based on the I4.0RAF mentioned above in Section 2.2 and was administered through the Qualtrics platform. Results of the self-assessment were presented using an easy to interpret dashboard. Verbal informed consent was obtained from all participants prior to their involvement in each stage of data collection, including those contributing data from the case study organization.

Two companies that had completed the I4.0 self-assessment agreed to participate in the case study development. One of the requirements before commencing the case study was that the firm should be engaged in developing a digital transformation strategy for I4.0 adoption. Only one of the two firms met this requirement and was thus selected for the case study development. The broader aim of the case study is to illustrate how managers of the case organisation can utilise the readiness assessment findings to support the development of their digital transformation model through intra-firm interactions, experts' inputs, and prioritisation of key areas for the adoption of I4.0 technologies. An overview of the research methodology is shown in Figure 1. The details of self-assessment and the digital transformation model developed by the case organisation, within a broader roadmap of digital transformation of manufacturing, are presented next.

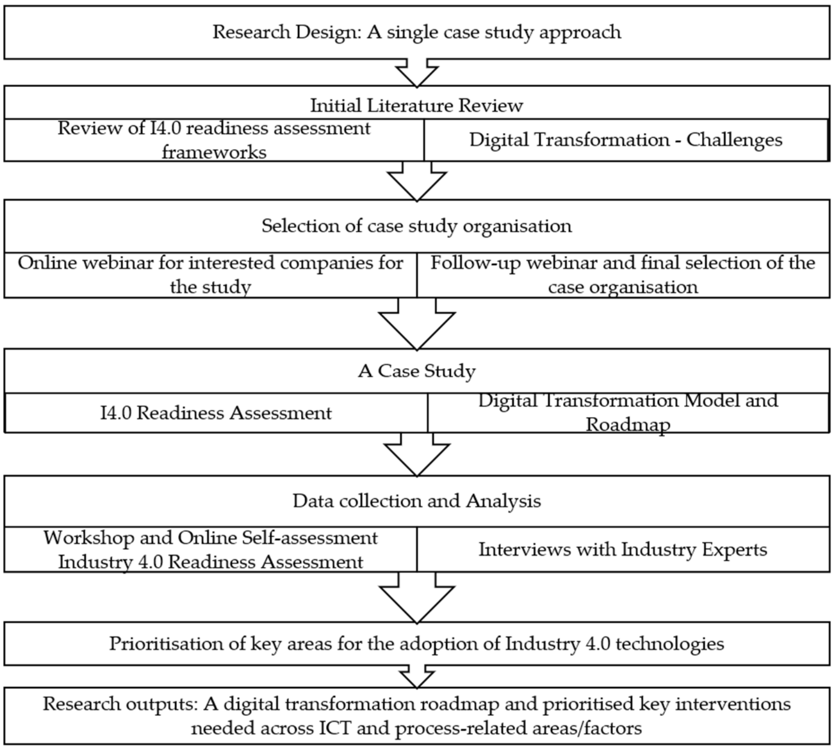

Figure 1. Overview of research methodology.

Ethics Approval Statement

The authors confirm that this research project was conducted in compliance with the conditions stipulated in the approved ethics application at the coordinating institution. The study was approved under the ethics application titled "Investigating Industry 4.0 Maturity in the Manufacturing Sector in Vietnam: Evaluation through a Status Assessment Framework" (Approval No. H14577).

4. Case Study—I4.0 Readiness Assessment and Digital Transformation Model

The company that participated in the case study development is identified by a pseudonym: Top Beverage Pty Ltd. (TBPL). The first stage of the case study involved conducting a workshop for a team of participating managers from TBPL on I4.0 adoption and the importance of readiness assessment for digital transformation. The team of managers then conducted a self-assessment of I4.0 readiness using the I4.0RAF. Then, interviews were conducted with the team, senior management, and experts to gather inputs and feedback on drivers of digital transformation, the role of readiness assessment in developing a digital transformation model and roadmap, and the challenges faced.

4.1. Background of Case Organisation TBPL

TBPL is a subsidiary, of a large multinational beverage company World Leading Beverages (pseudo name) (WLB), that has been operating in the emerging economy for more than 30 years. TBPL employs more than 1800 employees and produces several popular brands. TBPL has three bottling plants and eighteen production lines in several regions of the country and has a large distribution network of third-party logistics (3PL) service providers, suppliers, and customers (mainly retailers). The distribution network provides a full range of products to customers across the country. The company has a mission of maintaining responsible practices and giving back to the community it serves. To ensure customer satisfaction and loyalty, TBPL provides a wide range of quality beverages, including low-sugar and sugar-free product lines. Since the resumption of full production after the COVID-19 pandemic, TBPL has been licensed to invest in new manufacturing plants. Cognisant of the disruptions during the pandemic, TBPL regards smart manufacturing as an important first step to make its supply chain more resilient and agile.

At TBPL, the digitalisation strategy is based on guidelines provided by WLB and is standardised across all countries where WLB subsidiaries operate. However, WLB customises the digitalisation roadmap for each country, considering that a one-size fits all approach cannot be used, given the differences in the operating environment of each country and the varying technological and operational levels of the subsidiaries in each location. WLB has already mapped out approximately 40 countries for the roadmap and is actively engaging with them. TBPL has been guided by WLB to tailor their technological and production strategies to match those adopted by WBL subsidiaries in China, Hong Kong, and Taiwan which are recognised as being high-productivity subsidiaries. This internal benchmarking approach appears to have made the digital transformation roadmap program development less arduous for TBPL. According to [40], multinationals that possess many plants prefer to transfer the best practices applied and tested at some processes from one unit to another, or from one department to another to create uniformity of internal best practices across all their units. This may well be the thinking behind WLB transferring know-how to TBPL on best practices of manufacturing, logistics and supply chain practices adopted in their US and Brazilian plants.

4.2. Self-Assessment of I4.0 Readiness at TBPL

TBPL, with the guidance of the research collaborators, one of whom was based in the country where the subsidiary is located, carried out the self-assessment using the I4.0RAF online tool accessed through the Qualtrics platform. Profiles of managers from the TBPL cross-functional team that carried out the self-assessment are given in Table 2. The three managers chosen were part of the senior management team at TBPL. They all had professional qualifications and extensive shop floor experience, which gave them a holistic view of operations at TBPL. Furthermore, they were key members of the team tasked with planning and implementing digital transformation at TBPL. They also had experienced technical and operational staff reporting to them who could be used for brainstorming prior to carrying out the readiness assessment exercise. They also assumed responsibility for assuring that the technical and operational staff involved in the production, logistics, and digital transformation programs were widely consulted and that their views had been fully incorporated when arriving at the readiness assessment scores.

It was ensured that the three experts and their teams were present at a face-to-face Zoom session where the research team explained the I4.0 readiness assessment framework and how it could be deployed using the Qualtrics platform. The research collaborator present in the country was able to provide a translation in the local language when needed. Over the next few weeks, after the Zoom meeting, additional clarifications needed by the teams were provided by the authors through emails. Based on these clarifications, the I4.0 readiness assessment was revised by the functional teams with respect to two determinants, namely, plant and equipment and quality management. A follow-up Zoom meeting was organised with the three experts and the research team to gain a fuller understanding of how the readiness assessment values were reached, to ensure validity. All questions related to demographic data (both high-level and firm-level) were answered and completed. The criteria of all determinants (33 in total) were completed. The final summary of the self-assessment is shown in Table 2 and as a web diagram (Figure 2).

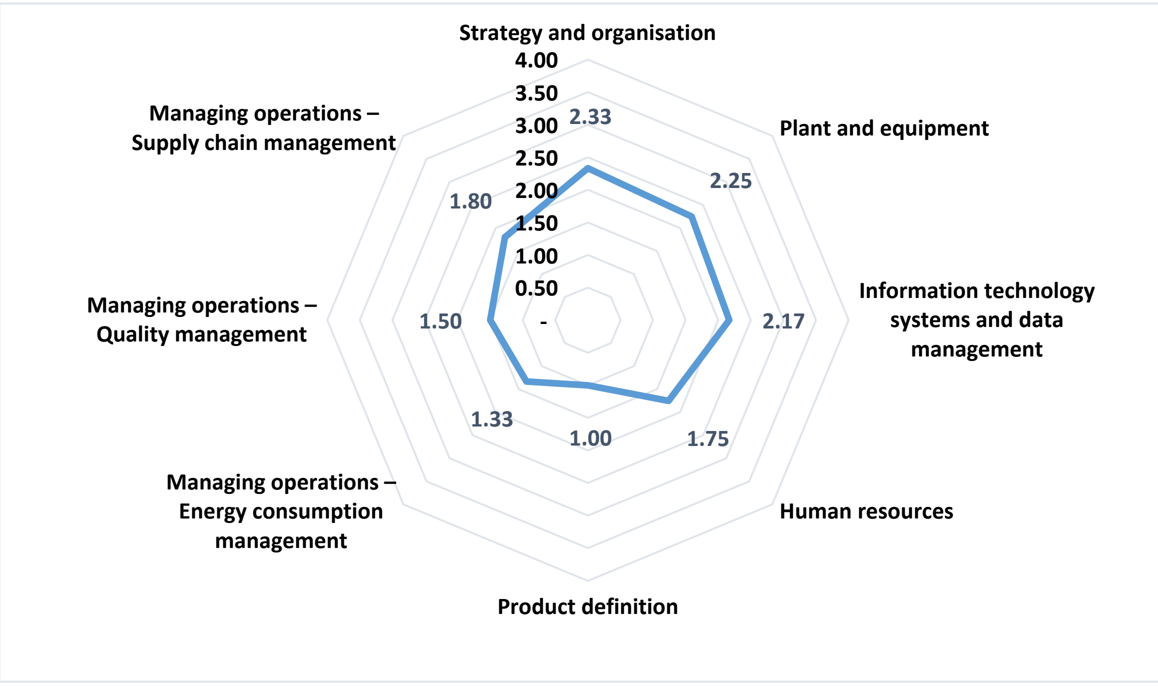

Figure 2. Web diagram of the I4.0 readiness self-assessment findings at TBPL.

Table 2. Participant profiles.

Job Profile	Years of Experience	Areas of Expertise
Expert 1–National Project Manager	>33 Years	Quality and Safety
Expert 2–Operations Excellence Director	>23 Years	Technology/Customer Service
Expert 3-Engineering execution and system management	>30 Years	Production/Maintenance

Source: Compiled by authors, based on Project Team's inputs.

4.2.1. Findings from I4.0 Readiness Self-Assessment at TBPL and Implications for Digital Transformation Strategy

The overall scores show that the highest score (2.33) is that of the 'Strategy and Organisation (SO)' determinant, suggesting that senior management recognises I4.0 as important but that implementation of an I4.0 adoption strategy is at an early stage. The next highest value of 2.25 is that of the 'Plant and Equipment (PE)' determinant, suggesting that existing plant and equipment can be upgraded for I4.0 with minimal disruption and some machines can be digitally controlled with machine-to-machine (M2M) capability. It appears that good preventive maintenance procedures are in place, which is not surprising since TBPL has to ensure high-capacity utilisation at the plant.

The 'Information Technology Systems and Data Management (ITS&DM)' has the third highest score of 2.17, indicating good digital data collection and in-company information sharing through Enterprise Resource Planning (ERP) systems. The value of 1.75 for the 'Human Resources (HR)' determinant, shows that basic skills related to ITS&DM and PE are present but need to be strengthened further. This has important implications from a digital transformation perspective. The value 1.00 of 'Product Definition (PD)' is low. However, this is not surprising since the 'make to stock (MTS)' beverages produced by the firm are standardised for the end-consumer. As a subsidiary of a multinational, TBPL follows product definition decisions made by global headquarters.

From an operational perspective, the values of 'Managing Operations–Supply Chain Management (MO-SCM),' 'Managing Operations–Quality Management (MO-QM)' and 'Managing Operations–Energy Consumption Management (MO-ECM) have relatively low values of 1.80, 1.50, and 1.33, respectively. This suggests that in MO-SCM, even with a high level of vertical integration and intra-firm information, inter-firm horizontal integration, visibility, and effective inventory management across the supply chain are still low. This has important digital transformation implications since digitalisation of the supply chain can strengthen inter-firm horizontal integration, visibility, agility, resilience, and better inventory management.

Also, in MO-QM, the value of 1.33 suggests that, while TBPL may have a robust quality management system, approaches such as the deployment of advanced control systems (e.g., artificial vision), machine learning (ML) systems, and automatic adjustment of machine parameters are not yet in place. Implementing a digitalisation strategy that will enable these I4.0 technologies to be adopted can enhance MO-QM and reduce costs, increase productivity, and can enhance reputation.

The lowest value of 1.00 is for MO-ECM, indicating the lack of a proactive approach in managing energy consumption. TBPL uses conventional power management and relies on its external energy provider for energy needs and energy consumption information. A digitalisation strategy can facilitate automated monitoring of energy consumption, adoption of IT-based 'Green Technology' systems, and energy self-generation thereby enabling TBPL to conserve energy and reduce dependence on external energy providers.

The above discussion suggests that, based on the findings of the I4.0 readiness assessment at TBPL, the company has the necessary capital and human infrastructure, top management support, and strategic and operational imperatives for adopting I4.0 technologies. However, to ensure effective I4.0 technologies adoption, the firm should undergo a digital transformation to leverage existing capabilities with respect to ITS&DM and strengthen operations, quality, and energy management. The next section elaborates how, based on this realisation, TBPL developed a set of pilot programs for a corporate digital transformation to accelerate the adoption of I4.0 technologies.

4.3. Digital Transformation Based on Manufacturing and Logistics Needs

Studies have explored diverse facets of digital transformation, encompassing enabling factors [41], strategies, challenges [42], and drivers across a range of industry sectors, geographical locations and organisational contexts [43]. However, organisations moving towards digital transformation encounter various barriers, such as the absence of standardised implementation protocols, and readiness assessments that are aligned with business needs [44]. Manufacturing organisations must have a better understanding of challenges and address them when implementing digitalisation in manufacturing [45].

Since TBPL manufactures standard consumer products based on a make-to-stock (MTS) strategy, good logistics operations, and timely information flow within the company and its supply chain, are needed for efficient production, logistics, and distribution of quality output. Thus, TBPL concluded that manufacturing transformation through digitally connected manufacturing processes and systems should be the priority to achieve operational excellence, cost optimisation, high asset utilisation, and productivity enhancement.

Based on managers' inputs and experts' feedback, TBPL developed a digital transformation model to support manufacturing transformation by taking into consideration challenges and drivers, and also benefits, and actions needed for initiating the process. Challenges identified by the managers included: high production downtime; lack of visibility and analytics; lack of predictability; people skills/productivity; siloed value chain; manual processes; and quality improvement. These challenges span across technology, processes, and people, including some interdependencies of these challenges, and lack of integration between processes (Figure 3). The delineation of these challenges find support from [46], which identified three levels of challenges namely, technological, architectural and strategic. Also, strategic, organisational and technological challenges are identified as common challenges to digital transformation [47].

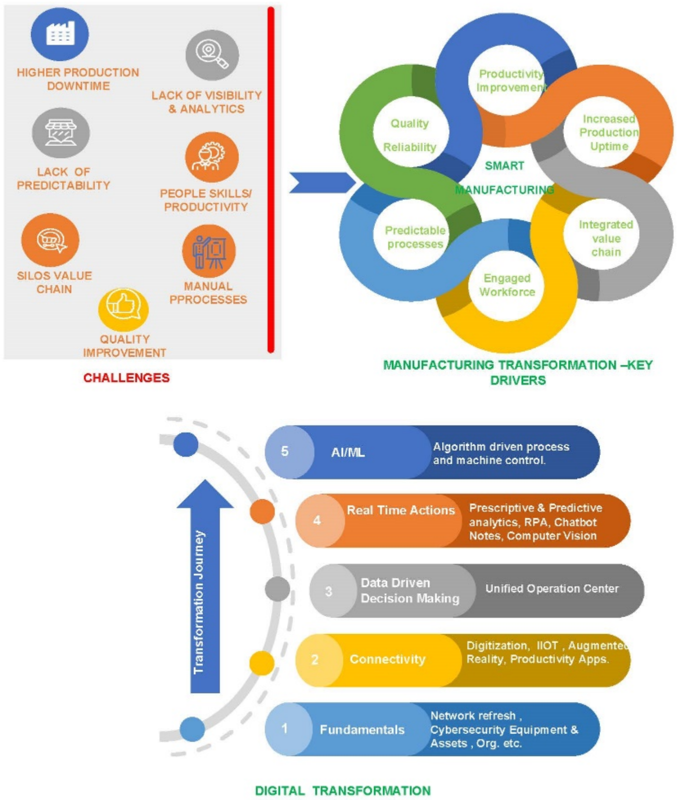

Figure 3. Digital transformation model for TBPL depicting associated challenges and drivers. (Source: TBPL Project Team).

Key drivers of manufacturing transformation within the broader digital transformation initiatives, (Figure 3) included: productivity improvement; increased production uptime; integrated value chain; engaged workforce; predictable processes; and quality reliability. These drivers are aligned with the challenges and could be considered as opportunities for TBPL in its manufacturing transformation journey. Several studies have investigated drivers of digital manufacturing, from a range of perspectives including categorisation of several drivers into internal and external factors [48], digital technologies adoption in SMEs [43], institutional levels at subsidiaries [49] and influence on business model innovation [50]. These studies emphasise that identifying which drivers push the adoption of digital transformation is vital for a better understanding of the process changes needed in manufacturing transformation. Furthermore, productivity, process and workplace improvements, as well as process integration, at organisational level are identified as key drivers of digital transformation [48].

Figure 3 also shows the digital transformation model of manufacturing transformation. The consensus reached by the functional teams at TBPL was that digital transformation should lead to the following benefits: increased production uptime; lower maintenance cost; improved cross-functional collaboration; improved quality;

continuous improvement (e.g., logistics, supply chain performance); improved manufacturing visibility; production visibility; productive workforce; and process compliance. Collectively, these benefits lead to productivity enhancement. These are aligned with the concept that companies that have implemented one or more I4.0 technologies pursue competitive priorities (quality, delivery, flexibility), with quality being the highest priority [51].

In Figure 3, the key drivers of manufacturing transformation are directly related to challenges identified by TBPL and are centred around smart manufacturing. For example, the integrated value chain is a key driver for addressing the challenge of the siloed value chain. Furthermore, the benefits outlined above are closely connected with the key drivers of digital transformation. TBPL subsequently followed key steps that were aligned with the process suggested by the research team based on the I4.0 readiness assessment. These were:

(i) Verification of the status of I4.0 readiness based on further detailed discussions within individual functional teams at TBPL and making revisions if needed.
(ii) Identification of priorities by each functional team, in their respective areas, using the current level of I4.0 readiness in each criterion within the determinant(s) relevant to them.
(iii) Selection of priority determinants and criteria through a brainstorming session, chaired by a senior TBPL manager, with the management team of all the functional areas.
(iv) Developing a roadmap for manufacturing transformation using the digital transformation model (Figure 3), that would take into consideration the current level of adoption with challenges, drivers, and key elements of digital transformation.

Findings from Empirical Validation of Digital Transformation Model Using Stakeholder Inputs

Based on the consideration of challenges, key drivers and expected benefits outlined above, TBPL then developed a roadmap for manufacturing transformation using connected technologies and identified target states with respect to each dimension. Support was obtained from experts across various functions at TBPL. In addition, inputs were sought from external consultants and Original Equipment Manufacturer (OEM) companies like KHS GmbH (Beverage Technology, Bad Kreuznach, Germany), KRONES (Greenfield Brewery Company, Neutraubling, Germany), and SIDEL (A subsidiary of the Heineken Group, Le Havre, France). WLB also offered support by providing internal benchmarking study findings of successful practices observed in their plants globally, particularly in the US and Brazil, to facilitate learning and replication of effective strategies.

It can be noted from the digital transformation model, that TBPL has prioritised information technology systems and data management (Determinant 3 of I4.0 readiness assessment framework) for its transition to an I4.0 setting. Key members of the TBPL project team acknowledged to the research team that carrying out the I4.0 readiness assessment provided the following insights:

- Firstly, it was useful in verifying and confirming the rationale for embarking upon a digital transformation model.
- It provided a baseline for assessing the actual and progress of I4.0 adoption against the planned activities and milestones.
- It enabled potential gaps and challenges in the implementation to be identified.
- The readiness assessment provided a basis for examining the strengths and weaknesses of the current approach, highlighting areas that require further attention or improvement.
- It also helped to ensure that the digital transformation model remains aligned with the overall objectives of the organisation by identifying weaknesses that need to be eliminated through the development of appropriate strategies and activities.
- Furthermore, by identifying areas of concern, it provided a basis to collect focused feedback from stakeholders, including beneficiaries, experts, consultants, project personnel, and other relevant parties to enable refinement of the digital transformation implementation roadmap, to improve the chances of success.
- Lastly, the I4.0 readiness assessment enabled the company to demonstrate its commitment to accountability, transparency, active monitoring, and progress evaluation thereby fostering trust and credibility.among stakeholders.

Table 3 shows the conceptualisation of the proposed digital transformation program. It can be seen that TBPL has mapped six levels of the roadmap based on findings of the 14.0RA, as seen in the first column of Table 3, and has six levels, starting from Level 1 (computerisation) to Level 6 (adaptability). Input was obtained from both internal and external expertise, as explained above. Each level is outlined by the status of four broader dimensions of I4.0 adoption areas. Each level builds on the preceding level, providing a structure that can guide and monitor the progress of each dimension towards eventually achieving Level 6 of the smart can be illustrated through the plant maintenance and support dimension where, at Level 1, ‘Reactive Maintenance’ is due to a basic level of computerisation, such as the absence of PLC configurations. In contrast, at level 6 of the smart factory, AI and ML technologies enable the shift towards prescriptive maintenance.

Table 3. Conceptual program of envisaged digital pilots using connected digital technologies.

Dimension and Determinant(s)	**Digitalisation**			**Smart Factory**		
	Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**	**Level 6**
	Computerization	**Connectivity**	**Visibility**	**Transparency**	**Predictability**	**Adaptability**
Digital Business Capabilities D1 and D6	• Siloed digital interface (mfg. systems) • No reference architecture • No digital unified operation centre (UOC)	• Connected digital interface (mfg. systems) • Ad-hoc reference architecture • UOC strategy formulation	• Digital Shadow in architecture • Integrating discrete digital shadow • UOC implementation	• Integrated Digital Shadow • Semantic linking and aggregation of data across digital thread	• Simulate business scenarios on digital shadow to improve predictability	• Manufacturing process automation based on cost-benefit ratio
Plant Maintenance and Support D2	• Reactive Maintenance • No or ad-hoc process for spare parts, PLC configuration and incident management	• Reactive, preventive, and remote maintenance support • Defined spare parts, PLC configuration and incident management	• Condition monitoring • Integrated spare parts management	• Predictive and prescriptive maintenance strategy • Managed services plants	• Predictive maintenance implementation	• Prescriptive maintenance implementation using AI and ML
Technology Infrastructure and Solutions D3, D7 and D8	• Lack of an optimum IT network • Siloed IT & OT network • No configuration, content, knowledge, incident and asset management system • No MES/SCADA and quality system • ERP for basic operations	• Optimum IT network • Augmented reality (AR) for remote support and user training • Configuration, content, knowledge, incident and asset management system implementation. • Matured ERP systems, MES/SCADA and quality systems	• IOT, big data, cloud-edge infrastructure strategy and enablement • API technologies for E2E integration. • Mobile apps, RPA, and chatbots to improve productivity • Integrated IT-OT network	• Enhanced big data and IOT • Enhanced Technologies for building mobile apps, RPA, and chatbots	• Use of industrial robots • AI and ML algorithms	• M2M automation and AI-assisted decision making.
Data Governance and Information Security D3	• Lack of optimum info-security • No data governance defined	• Optimum level (MSS) info-security • Data governance definition initiated	• Continuous and forensic monitoring • Data governance strategy formulated	• Threat intelligence system implementation • Data governance strategy implemented		

Source: Authors and Project Team at TBPL.

Also, a TBPL priority, according to the project team, is improving cross-functional collaboration for enhanced production management, maintenance performance, and data governance and security, through improved technology infrastructure through ICT interventions. This prioritisation has been achieved by emphasising Computerisation (Level 1) and Connectivity (Level 2) in the digitalisation roadmap. Computerisation at Level 1 has identified and emphasised existing practices, particularly focusing on process and technology-related concerns. For example, the siloed digital interface of digital business capabilities and the absence of a manufacturing execution system in the technology infrastructure are interconnected. The connectivity aspect at Level 2 of the roadmap has identified crucial targets, including the desired level of connectivity, to be achieved to address the issues identified at Level 1. The dimension D4. Human resources has not been shown explicitly since TBPL considers it important across all digital pilots.

4.4. The Four-Step Approach at TBPL for Developing a Digital Transformation Roadmap

Based on the case study findings, it may be said that TBPL appears to have used a four-step phased approach (focused digital SWOT analysis, digital strategy imagineering, digital upskilling, and top management driven seamless transition) to develop a digital transformation program based on I4.0 readiness assessment. These four steps are presented below.

4.4.1. Step 1—Focused Digital SWOT Analysis

TBPL commenced a focused digital SWOT analysis with the I4.0 readiness self-assessment. The findings (Section 4.2.1) revealed that the company has the necessary capital and human infrastructure, top management support, and strategic and operational imperatives for adopting I4.0 technologies. It was also evident that since TBPL manufactures standard, discrete consumer products on a make-to-stock (MTS) strategy, good information flow within the company and its supply chain is needed to meet customer demand effectively through efficient production and the delivery of quality output. As explained in Section 4.3, this led to the conclusion that manufacturing transformation should be the priority to achieve operational excellence, optimise cost and maximise yield from existing assets by leveraging digitally connected manufacturing processes and systems.

It also became evident that such a manufacturing transformation through digitally connected manufacturing processes would have to necessarily involve both digital transformation and the adoption of advanced I4.0 technologies. Further introspection showed that several challenges related to processes could emerge due to the below average ranking of all three determinants of managing operations (energy consumption, quality, and supply chain). In practical terms, managers broke these down as challenges arising due to (i) high production downtime; (ii) lack of visibility and analytics; (iii) lack of predictability; (iv) inadequate people skills/productivity; (v) silos value chain; (vi) manual processes; and (vii) lack of quality improvement. These findings were then used in the development of a digital transformation strategy. Based on these findings and guidelines provided by top management at WLB, managers at TBPL and experts developed a digital transformation model (Figure 3) as a basis for manufacturing transformation from current practices to digitally connected manufacturing processes and systems.

4.4.2. Step 2—Digital Strategy Imagineering

The digital transformation model (Figure 3) developed during Step 1, helped the project team to outline both the innovation ambitions and the sustainability of the core business. Several new pilot projects and innovation initiatives were established across Levels 2 through 6 of the digital transformation program, directly targeting key challenges such as low productivity, while systematically enhancing process efficiency, resource utilisation, and overall organisational performance (Table 4). While Level 1 (Table 3) reflects the current state at TBPL, a partial list of new pilot projects and areas to innovate in, commencing from Level 2 of the program, are shown in Table 4.

4.4.3. Step 3—Digital Upskilling

The I4.0 readiness assessment showed that the lower level of digital skills of employees, when compared to the readiness level of ICT&DM, indicated the need for improving digital literacy and skills of employees. There is a strong relationship between successful digital transformation and employee digital literacy [52,53]. Low level of skills can hinder digital transformation in many ways, including resistance to change, limited innovation and difficulty in collaboration [54]. The importance of developing digital culture and skills before investing in digital transformation is emphasized [55]. Top management at TBPL thus prioritised employee digital upskilling programs. While details of the planned training were not made available, it is evident that the quality of these training programs would play a major role in developing the requisite digital skills to effectively implement the innovation pilot projects identified in Step 2. [51,56] point out that: establishment of inter-functional teams; differentiated training plans and on-the-job training (OJT) for personnel involved in implementing and using I4.0 technologies; and commitment to continuous improvement (CI) and active involvement, significantly influence digital upskilling for the effective digital transformation.

At TBPL, there is already a culture of cross-functional cooperation and working in project teams. Thus, the establishment of inter-functional teams will unlikely be a barrier. However, the aspects of differentiated training plans, OJT, and top management commitment to foster a culture of CI will be critical in ensuring that the implementation of the digital transformation program leads to effective outcomes.

Table 4. New pilot projects and innovation opportunities.

Levels	New Pilot Projects and Innovation Opportunities	Related Challenges and/or Key Drivers
2	• Development of remote maintenance support for reactive and preventive maintenance • AR for remote support and user training • Asset management system design and implementation	• Higher production downtime • Low people skills and productivity • Manual processes
3	• Development of asset condition monitoring system using IoT, big data and cloud infrastructure. • Integrated spare parts management system design and implementation • Development of mobile apps, robotic process automation (RPA), and Chatbots for productivity improvement	• Manual processes • Siloed value chain • Low productivity
4	• Development of a predictive and prescriptive maintenance management system • Enhancing technologies used in mobile apps, robotic process automation (RPA), and Chatbots for productivity improvement • Designing and implementing a threat intelligence system for effective data governance and information security	• Lack of visibility and analytics • Low productivity • Lack of visibility and analytics
5	• Developing business scenarios on digital shadow to improve digital business capabilities • Designing and implementing AI and ML algorithms for enhancing production and maintenance performance	• End-to-end integration across suppliers, production, and customers • Improving throughput and operational efficiency
6	• Manufacturing process automation • Implementing AI and ML-based prescriptive maintenance	• Reducing downtime through monitoring and automation

Source: Compiled by authors, based on discussion with TBPL Project Team and Table 3.

4.4.4. Step 4—Top Management Driven Seamless Transition

Veile [57] point out that barriers to I4.0 transition can be reduced if top management driven strategic initiatives related to flattening the hierarchy, decentralising decision-making to promote agility, creating a corporate culture embodying flexibility, openness, CI, entrepreneurial mindset, and promoting intra- and inter-company openness and trust to promote data exchange, are implemented. While these aspects of top management involvement were not explicitly emphasised during the discussions at TBPL, it was evident that top management commitment was adequately explicit to ensure that the program was effectively implemented. It therefore appears that the program implementation approach at TBPL is conducive to facilitating a seamless transition of the current core business to a future core business based on I4.0 technology adoption. Furthermore, accepted standards and government regulations are needed across industries that wish to adopt I4.0 technologies [55]. It may therefore be important for top management to ensure that current standards and government regulations for digital technology adoption, do not become barriers to the effective implementation of the digital transformation program.

4.5. Theoretical and Conceptual Framing of Digital Readiness and Transformation

To strengthen the linkage between Industry 4.0 (I4.0) readiness, digital capability development, and organisational transformation, this study adopts an integrated conceptual framework grounded in three complementary theoretical streams: Dynamic Capabilities View (DCV), digital transformation capability literature, and I4.0 maturity models. Firstly drawing on the dynamic capabilities view [56], the I4.0 readiness assessment (Figure 2) is conceptualised as a measure of the firm's sensing capability, reflecting its ability to identify digital opportunities and diagnose capability gaps across strategy, IT, operations, and human resources. Rather than the standard approach of using I4.0 readiness assessment only to identify the status of key determinants vis-à-vis state-of-the-art, this study uses the assessment findings to identify key domains with limited digital preparedness. Furthermore, based on the readiness scores, it would be possible to determine, with greater clarity, the level at which pilot projects could be launched. This value-added approach with could be regarded as extending I4.0 readiness assessment beyond existing applications in extant literature. Secondly, the digital transformation model (Figure 3) represents capability orchestration, where transformation occurs through iterative cycles of seizing (digital investments) and reconfiguring (process and structural redesign) [58,59]. This highlights a path-dependent evolution shaped by challenges and key drivers. Thirdly, digital pilot programs (Table 3) aligns with I4.0 maturity models [24], progressing from benign computerisation to proactive and intelligent adaptability where early stages build IT/OT integration, intermediate stages enable data visibility and digital shadow, and advanced stages deliver predictive and autonomous capabilities, thereby providing a structured pathway linking digital pilots to maturity progression. Integrating the above perspectives, this study conceptualises digital transformation as an integrated three-layered process:

(1) I4.0 readiness assessment as a sensing diagnostic tool for identifying capability gaps and identifying digital opportunities (Figure 2),
(2) Transformation orchestration as a vehicle for mobilising and aligning resource allocation (seizing and reconfiguring) (Figure 3),
(3) Capability maturation enables staged progression toward higher digital maturity (Table 3).

This integrated framework contributes by explicitly linking diagnostic assessment, capability-building mechanisms, and maturity transitions, thereby providing a theoretically grounded pathway from I4.0 readiness to measurable operational transformation. Figure 3 is a theory-informed conceptual model grounded in the dynamic capabilities view [56] and digital transformation literature [58,59]. It is not intended as a statistically validated model but could be regarded as an integrated model drawing insights from the extant literature with respect to I4.0 readiness assessment that has been enriched with empirical and practical insights derived from the case study to explain the transformation pathway. Consistent with [60], this study articulates its theoretical contribution by clarifying the key constructs (digital readiness, transformation, and capability maturity), explicating their relationships through a dynamic capabilities lens, and integrating established theories to explain how organisations transition from readiness assessment to staged digital transformation. Beyond managerial guidance, the framework contributes to the literature by integrating Industry 4.0 readiness, transformation capabilities, and maturity progression into a coherent theoretical pathway that explains how firms convert digital preparedness into manufacturing transformation outcomes.

5. Discussion and Managerial Implications

The research findings show that TBPL adopted I4.0 readiness assessment, firstly for identifying the level of readiness, current practices, and operational issues that need to be addressed. Secondly, the priority areas identified from the I4.0 readiness assessment have helped to prioritise key areas in the digital transformation roadmap (Table 3) for addressing the identified issues across ICT and process-related areas/factors. The phased approach to digital transformation, which prioritises key areas based on issues identified through a readiness assessment, aligns with similar but more limited approaches reported in the literature. The proposed phased approach aligns with a framework of enabling factors, operational capabilities, and resultant value creation within the context of digitalising firm operations [54]; examines the interdependencies of readiness determinants and how readiness aspects interacts with each other [18]; presents an integrated business process management approach to support digital transformation [44]; and highlights the need to improve employees' digital literacy and skills, emphasising that access to the right skills and talent has a major impact on readiness for digital transformation [53].

The imperative of adopting I4.0 technologies in contemporary manufacturing has been well accepted, as mentioned in Sections 1 and 2 above. Yet, its implementation, which requires fundamental digital transformation using a phased approach requires some important preconditions to be met. First, align managerial involvement and project champions with the current stage of transformation and establish consensus on the metrics to evaluate progress. Second, agree on short-term (3–6 month) goals and monitor progress using reliable, high-quality data. Third, avoid relying solely on ROI-based measures to secure executive or financial support; instead, complement them with broader performance indicators such as capability development, delivery speed, and innovation outcomes as the project advances [51]. The four-step approach adopted by TBPL is in conformance with all of the above insights and those provided by [51,57,61] for structuring possible digital transformation approaches. Furthermore, consistent with prior studies on digital readiness and transformation [62], the findings highlight the role of structured capability development and staged maturity progression in enabling effective digital transformation, while also reflecting context-specific implementation challenges. The approach adopted by TBPL thus offers other manufacturing firms a possible approach that they could use as a guide when planning digital transformation.

6. Conclusions

6.1. Theoretical Implications

This research makes a theoretical contribution by extending the existing literature on phased approaches for digital transformation at process and technology levels, using well-established I4.0 readiness assessment frameworks and prioritisation of key areas. Consistent with maturity model theory, which conceptualises organisational transformation as a staged progression of capabilities [63], this study assesses the current I4.0 maturity level for guiding the development of digital pilots needed for a structured, multi-level digital transformation program. It also adds value to the extant literature by demonstrating how I4.0 readiness assessment can be used to identify key domains with limited digital preparedness thereby enabling the determination of needed pilot projects for enhancing digital progression with greater evidence-based support.

Using a case study of a subsidiary of a multinational corporation, operating in an emerging economy, it has been shown how the subsidiary carried out: a self-assessment of I4.0 readiness; incorporated inputs from cross-functional experts; adapted best practices obtained from other subsidiaries of the multinational corporation, through internal benchmarking studies; and synthesised the findings to formulate digital pilots for a multi-level digital transformation program for enabling smart manufacturing. It is shown, through the case study, how the above-mentioned steps could be used in a real-life setting to embark on transformation orchestration for mobilizing and aligning resource allocation. Furthermore, an important theoretical implication, supported by case study evidence demonstrates how capability maturation, through multi-level digital transformation proposed in this research can help identify the current state of adoption and visually show the path toward achieving smart factory status by mapping priority areas over increasing levels of digital technology sophistication.

6.2. Managerial Contributions

The research project investigated a broader problem of manufacturing transformation in a large manufacturing firm, using three stages: I4.0 readiness assessment; conceptualising a digital transformation model; and developing an implementation program consisting of digital pilots for smart manufacturing. The findings demonstrate that the first stage provides a valuable basis for identifying and prioritising key areas essential for conceptualising digital pilots. Such a prioritisation exercise can also help identify inter-dependencies among determinants through a collaborative approach involving functional managers, cross-functional experts in the organisation, and external expertise. The experience of the authors in carrying out I4.0 readiness assessments in manufacturing firms in three countries in the Asia-Pacific region suggests that it is important to have experienced cross-functional managers participate in the assessment exercise. It was also seen that internal benchmarking information can reveal tested and proven best practices that can be adopted, thereby reducing the time taken to decide upon digital pilots needed for multi-level digital transformation.

The prioritisation exercise aligns with the theory of resource-based view of the firm in identifying key internal resources (e.g., functional managers, experts) and external expertise to leverage the transformation. Furthermore, as seen from the case study of TBPL, involving cross-functional teams and utilising internal benchmarking shows how an organisation can leverage its internal resources and capabilities to enhance decision-making and identify best practices.

6.3. Practical Implications

While the managerial contributions discussed above are of practical relevance, there are some additional aspects that could be of value from a practitioner's perspective. It may be said that the four-step approach used by TBPL would be a prudent way to develop digital pilots to implement digital transformation as a foundation for embarking upon I4.0 technology adoption for smart manufacturing. It could help secure top management support since the first step aligns the digital transformation strategy with business strategy while providing insights into company-wide organisational changes needed and required business and technological capabilities. Once top management commitment is secured, discussions on the steps related to digital strategy and digital upskilling can be worked out and resource commitments obtained. The fourth and last step then needs to be linked to the digital transformation program to facilitate a seamless transition of the current core business to a future core business.

6.4. Limitations and Future Research Directions

Despite offering new insights and theoretical contributions, this study has some limitations. First, this study is based on a single case study and, therefore, its findings are not statistically generalizable to the broader industry and restrict insights for wider adoption. Rather, the results provide analytical insights that may be transferable to similar organisational contexts. Secondly, from a conceptual scope perspective, the empirical input primarily focused on a large company in an emerging economy context, which may limit the generalisability. Future research could focus on empirically validating the proposed digital transformation approach through studies involving multiple manufacturing firms within the same industry sector, with particular attention to organisations operating in emerging economies. In addition, industry-specific comparative studies could be undertaken to examine variations in Industry 4.0 readiness levels and to assess how these differences influence the design and effectiveness of digital transformation roadmaps across diverse manufacturing sectors.

Author Contributions

P.S.: conceptualization, formal analysis, data curation, project administration; P.S. and K.R.: methodology, writing—original draft preparation; P.S., K.R., K.N. and S.W.: validation, visualization; K.N.: investigation; P.S., K.R., K.N., S.W., Y.L. and Q.M.: writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study was conducted according to the protocol approved by the Human Research Ethics Committee (HREC) of Western Sydney University, with approved number H14577 dated 22 July 2022.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data supporting this study are not publicly available but are securely stored in the institutional repository of the university where the research was conducted.

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Conflicts of Interest

The authors declare no conflicts of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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