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# Self-Assessment Model for Digital Retrofitting of Legacy Manufacturing Systems in the Context of Industry 4.0

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## ABSTRACT

In the current competitive landscape, digital retrofitting of legacy manufacturing systems is crucial for maintaining a competitive edge. Digital retrofitting involves adapting existing systems to modern technologies to enhance efficiency and capabilities. To select the most appropriate retrofitting approach, an assessment model is required due to the diversity of legacy systems and the varying readiness levels of organizations. In this study, a comprehensive assessment model is designed for Small and Medium Manufacturing Enterprises (SMMEs) to facilitate digital retrofitting strategies. The model starts with a questionnaire to evaluate existing systems, followed by a classification of maturity levels, and then provides tailored recommendations, aiming to guide SMMEs in successfully integrating Industry 4.0 technologies. The methodology includes a literature review and surveys, which were used to develop, test, and refine the model. The model assesses 21 items across four dimensions, Strategy and Organization, Development of the Workforce, Smart Factory, and Smart Process, using a five-point scale. Furthermore, the model introduces a four-level maturity classification for digital transformation in manufacturing and offers customized recommendations. The validation through the surveys involves content validity testing with 18 industry practitioners and a pilot study with a sample of 32 SMMEs.

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## 1. Introduction

In the dynamic landscape of modern manufacturing, adopting new technologies is a crucial step towards advancement and staying competitive [1]. Manufacturing enterprises face a critical juncture as the global market becomes more competitive [2], [3]. The journey towards technological integration is challenging for Small and Medium Manufacturing Enterprises (SMMEs) due to their inherent heterogeneity [4], [5]. These enterprises often grapple with adopting cutting-edge technologies, primarily due to constraints related to limited resources, smaller scales of operation, and diverse operational needs. The challenge is further compounded by the considerable variation in the technological capabilities, advanced functionalities, and adaptability to updates of legacy manufacturing systems [6].

Digital retrofitting has emerged as a promising solution in this context. It offers a cost-effective and practical approach for SMMEs to stay competitive [7]. Digital retrofitting entails incorporating new digital technologies, such as Internet of Things (IoT)

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components, including sensors, gateways, and actuators, into existing systems [8]. This integration facilitates connectivity and real-time data analytics [9], [10]. However, digital retrofitting presents its own obstacles, particularly in securing knowledge, understanding specific requirements, and ensuring the availability of resources, especially for SMMEs [11]. In response to these constraints, the development and application of maturity and assessment models have become pivotal. These models aid the adoption of Industry 4.0 technologies, such as Cyber-Physical Systems (CPS), and provide a framework to effectively gauge operational capabilities and strategies [12]. These models diagnose current development stages and illuminate pathways for enhancing operational and technological maturity [13].

Academic research has extensively examined readiness and maturity models related to Industry 4.0. These models are commonly classified by technology, people, and strategy, with a primary focus on the technological aspect [14]-[16]. Despite these theoretical contributions, practical implementations in terms of infrastructure assessment and managing organisational change remain somewhat limited [17]. Industry models, such as Lichtblau, et al. [18] model, Price water house Coopers' assessment model [19], and the maturity model by Rockwell Automation [20], provide valuable instruments for gauging organisational readiness. However, these models frequently fail to address the specific digital retrofitting exigencies of SMMEs. This oversight is significant since small and medium enterprises (SMEs) are a fundamental component of the economy in any country, making significant contributions to both employment and the Gross Domestic Product (GDP). For instance, in the UK, Small and Medium-Sized Enterprises (SMEs) contribute over 67% of private-sector employment and generate more than 50% of the nation's GDP [21].

To bridge these gaps, it is necessary to understand existing generic models, identify their strengths and weaknesses and propose an initial focused mode for digital retrofitting. Then, validate this model to ensure its reliability and relevance. This process will refine key components and design principles, ultimately creating a comprehensive assessment model tailored to SMMEs. This paper explores the development of a comprehensive assessment model for evaluating the readiness of manufacturing companies, particularly SMMEs, for digital transformation. It examines existing assessment models and investigates methods to validate the proposed model from both academic and industry perspectives.

## 1.1 Assessment Models in Manufacturing

Several studies have been conducted to assess manufacturing companies from various perspectives. For instance, Schumacher [22] delineates an assessment model that categorises manufacturing companies based on technological, organisational, and cultural dimensions to highlight areas for improvement. Lichtblau [18] introduced the IMPULS Industrie 4.0 Readiness model, which assesses six dimensions using 24 questions to gauge maturity. The Warwick Manufacturing Group [23] developed a tool covering six dimensions, with 37 questions to provide a detailed readiness analysis, stressing the importance of legal and business model considerations. Anderl and Fleischer's Guideline Industrie 4.0 [24] offers a simpler, production-focused model with two dimensions and five maturity levels. Despite its bifocal viewpoint, with five maturity levels and 12 questions, the model offers a focused assessment mainly in the functional aspect. The Smart Industry Readiness Index (SIRI) by the Singapore Development Board [25] uses a three-part framework (process, technology, organization) with six maturity levels to support strategic planning. The COMMA4.0 model by Nazarbayev University [26] emphasises workforce development along with technology, covering five dimensions with 33 questions.

Despite the extensive work on these assessment models, a significant gap remains: the specific digital retrofitting needs of SMMEs are often overlooked. This gap is critical as SMMEs play a fundamental role in the economy, contributing significantly to employment and GDP. Addressing this gap with tailored assessment models can enhance the digital transformation journey of SMMEs, making it more efficient and effective.

## 1.2 Digital Retrofitting as a Solution

Digital retrofitting in the manufacturing sector is vital for transitioning towards Industry 4.0. It involves upgrading legacy equipment to intelligent, connected systems, enabling the adoption of advanced technologies characteristic of Industry 4.0 [27]. This transformation is particularly valuable for SMMEs, offering multiple benefits and emerging as a strategic necessity. One of the primary advantages of digital retrofitting is sustainability [10], [28]. Updating existing machinery minimises the need for purchasing new equipment, resulting in less waste and a longer asset life [29]. This aligns with the United Nations Sustainable Development Goals (SDGs) [30], partic-

ularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production), by promoting sustainable practices and reducing environmental impact. Digital retrofitting is a cost-effective alternative to replacing machinery, avoiding the high costs and disruptions of equipment replacement [28], [31]. It extends machinery life through condition monitoring and predictive maintenance, reducing breakdowns [32], [33], and improves operational efficiency by providing real-time data for process optimization [10], [34]. Another noteworthy approach employed in the context of legacy systems is Robotic Process Automation (RPA), which facilitates the automation of routine, rule-based tasks and enables integration with contemporary digital workflows [31]. Through mimicking human interactions with outdated interfaces, RPA allows legacy equipment to function within modern operational environments without necessitating substantial hardware or software modifications [32]. Nonetheless, the present study focuses specifically on digital retrofitting as the primary enabler for modernising legacy manufacturing systems. For SMMEs, retrofitting is key to integrating Industry 4.0 technologies, enabling them to remain competitive [35]. Thus, developing an assessment model to facilitate retrofitting adoption is essential.

The remaining of the paper is structured as follow. The methodology used in this paper is described in Section 2, encompassing a literature review and surveys, which include content validity and a pilot study. In Section 3, the findings of the literature review are analysed and discussed in detail. The development of assessment model is presented in Section 4. In Section 5, the results of the surveys, including content validity and the pilot study, are presented. The discussion and integration of the findings are presented in Section 6. Finally, Section 7 summarises the key insights, discusses the research limitations, and outlines potential avenues for future research.

## 2. Research Methodology

This section outlines the methodology, structured around a literature review and surveys for validation. The literature review synthesises key findings from academic and industry sources, focusing on Industry 4.0 readiness levels to inform the initial model design. The surveys are then conducted for validation, using content validity via expert judgment and a pilot study with real SMMEs to test and refine the efficacy and applicability of the model (see Figure 1 and Figure 2).

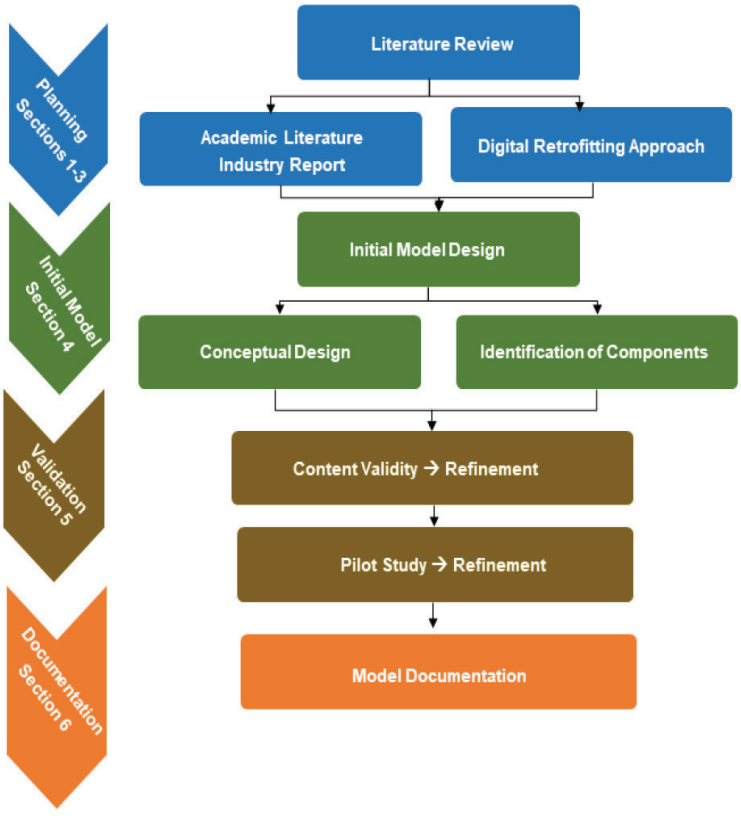


**Figure 1.** Methodology workflow for assessment model development

## 2.1 Literature Review Methodology

The literature review, guided by the PRISMA guidelines, systematically examined Industry 4.0 research in the manufacturing sector, particularly readiness and assessment models for SMEs. The review included English-language studies published between 2015 and 2024, using databases like Scopus, ScienceDirect, and Google Scholar. This search yielded 31 relevant articles. Details such as authors, publication year, country, sectors, dimensions, maturity levels, and scales were extracted and catalogued, providing a comprehensive overview of Industry 4.0 readiness and assessment models in manufacturing sector (see Table 1).

## 2.2 Survey Methodology

Following the literature review, the methodology of the surveys included content validation through expert judgment and a pilot study with real SMMEs. To ensure the relevance and quality of responses, specific inclusion criteria were applied. Participants were required to have a minimum of five years' experience and either work directly in the manufacturing sector or possess professional experience in digital transformation initiatives aligned with Industry 4.0. These criteria ensured that insights were drawn from individuals with substantial practical and contextual knowledge.

### 2.2.1 Content Validity

To ensure content validity, the Content Validity Ratio (CVR) method, originally developed by Lawshe [36] and later refined by Lynn [37], is applied. CVR is widely used in industrial research to assess the accuracy of an instrument in representing its intended construct. For example, Ishanuddin [38] used CVR to validate a tool measuring customer perceptions of Automatic Emergency Braking (AEB) systems. In this study, a panel of 18 practitioners assessed the relevance of each item in the evaluation model for digital retrofitting. The detailed methodology of the CVR approach is explained in previous work [8].

### 2.2.2 Pilot Study

A total of 32 participants were selected for the study representing SMMEs. Participants are recruited from the Fame database [39], which provides detailed company profiles, and suitable companies are invited through direct contact. The pilot study focused on the practical application of the model and participant understanding [40]. Feedback and statistical analysis from this phase are crucial for enhancing the validity and reliability of the model. Figure 2 illustrates methodology structured approach, detailing the key phases from the literature review to model refinement.

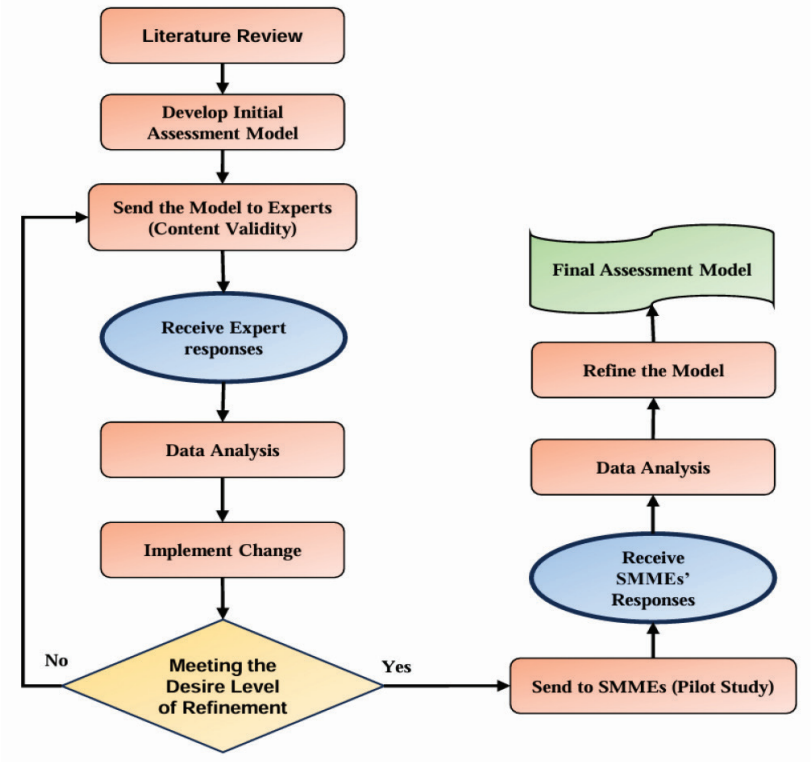


**Figure 2.** Structured approach for model design and validation

## 3. Literature Review Results

The literature review results are outlined, beginning with the search process outcomes. The narrative details the screening and eligibility criteria that are instrumental in selecting the most pertinent studies. A subsequent analysis of the sources includes a descriptive analysis, a thematic analysis, a dimension analysis, and finally a maturity level and scale analysis.

### 3.1 Descriptive Analysis

The selected 31 studies focus on assessment models in the manufacturing sector (see Table 1). A frequency analysis of these publications by year revealed an interesting temporal trend.

A distinct geographical distribution characterises research efforts in this field, with Europe emerging as a dominant force with approximately 61% of the studies. Germany leads with nearly 29% of all pub-

**Table 1.** Overview of the models examined

| No | Author | Model name | Sector | Country |
|---|---|---|---|---|
| 1 | Lichtblau, et al. [18] | IMPULS—Industrie 4.0 Readiness (V) | Manufacturing company | Germany |
| 2 | Warwick Manufacturing Group [23] | Industry 4.0 readiness assessment tool: i4 Ready | Businesses & manufacturing | UK |
| 3 | Anderl & Fleischer [24] | Toolbox Industrie 4.0 | Manufacturing company & SMEs | Germany |
| 4 | Board [25] | The Singapore Smart Industry Readiness Index | SMEs & manufacturing | Singapore |
| 5 | Nazarbayev University [26] | A comprehensive model for I4.0 maturity assessment COMMA4.0 | Manufacturing | Kazakhstan |
| 6 | Rockwell [20] | The Connected Enterprise Maturity Model | Manufacturing | US |
| 7 | Reinhard, et al. [41] | Digital operations self-assessment | Manufacturing | UK |
| 8 | Kayikci, et al. [42] | SCSC readiness and maturity model | SMEs | Turkey |
| 9 | Dikhanbayeva, et al. [43] | Maturity model (MM) | SMEs | Kazakhstan |
| 10 | Schroderus, et al. [44] | Pay-Per-X maturity model | Manufacturing company | Finland |
| 11 | Simetinger and Basl [12] | 14MMSME | Manufacturing company & SMEs | Czech Republic |
| 12 | Schumacher, et al. [22] | Industry 4.0 maturity and readiness model | Manufacturing SMEs | Australia |
| 13 | Stefan, et al. [45] | Maturity-based Industry 4.0 migration model | Industry & SMEs | Germany |
| 14 | Spaltini, et al. [46] | 6Ps maturity model for manufacturing SMEs | Manufacturing SMEs | Italy |
| 15 | Colli, et al. [47] | 360 digital maturity assessment model | Manufacturing sector | UK |
| 16 | Nick, et al. [48] | Industry 4.0 readiness model | Car company | Hungary |
| 17 | Rafael, et al. [49] | Maturity model (MM) | Manufacturing companies | Spain |
| 18 | Schumacher, et al. [50] | Industry 4.0 digitalisation maturity model | Manufacturing enterprises | Australia |
| 19 | Kolla, et al. [51] | Lean and Industry 4.0 assessment model | Manufacturing SMEs | Luxembourg |
| 20 | Lukhmanov, et al. [52] | Industry 4.0 readiness and maturity model | Manufacturing companies | Kazakhstan |
| 21 | Nick, et al. [53] | Industry 4.0 readiness and maturity model | Manufacturing companies | Hungary |
| 22 | Jayashree, et al. [54] | Maturity model (MM) | SMEs | Malaysia |
| 23 | Ariffin and Ahmad [55] | Industry 4.0 readiness and maturity model | Digital forensic | Malaysia |
| 24 | Bibby and Dehe [56] | Maturity model (MM) | Manufacturing companies | UK |
| 25 | Horváth and Szabó [57] | Industry 4.0 readiness and maturity model | Manufacturing companies | Germany |
| 26 | Valentin [58] | Assessment model | Manufacturing company | Austria |
| 27 | Gerlitz [59] | Industry 4.0 readiness and maturity model | SMEs | Germany |
| 28 | Basl and Doucek [60] | Met model | SMEs | Czech Republic |
| 29 | Bretz, et al. [61] | ECO maturity model | Manufacturing companies | Germany |
| 30 | Colangelo, et al. [62] | Maturity model (MM) | Smart production companies | Germany |
| 31 | Brozzi, et al. [63] | Digital assessment model | Manufacturing SMEs | Italy |

lications, followed by significant contributions from the UK and Italy, each at about 10% (see Figure 3).

The analysis of the 31 studies revealed a focus on maturity, readiness, and assessment models for Industry 4.0, covering various approaches for manufacturing and SMEs. Several studies proposed models specifically for SMEs [24], [42], [43], [45], [51], while others developed frameworks to evaluate manufacturing capabilities and stages of Industry 4.0 adoption [18], [20], [26], [41]. Some studies addressed specific industries, like transportation and architecture, while others provided general models applicable to the manufacturing sector. Overall, the studies identified key factors and dimensions essential for assessing digitalization in manufacturing. However, a common limitation was that many models lacked comprehensive coverage of digitalization dimensions or clear response scales, limiting their effectiveness. There remains a need for a complete assessment model that includes a detailed questionnaire, defined maturity levels, and practical implementation solutions.

## 3.2 Dimensions Analysis

The dimensions analysis identified 127 items across Industry 4.0 readiness models for manufacturing firms. These align with Hajoary's [64] identification of 56 dimensions and Hizam [14] listing of 158 maturity factors, which are essential for assessing organizational capabilities and guiding strategic decisions. Most models include 2–9 dimensions, with five being the most common, indicating a balanced approach. For clarity, similar dimensions have been consolidated.

The most frequently cited dimension is strategy and organization, mentioned 25 times, emphasizing its role in planning and coordination. Smart operations and process and technology appear 19 times each, highlighting the focus on operational efficiency and tech integration. Data and IT, cited 14 times, reflects its importance in the digital landscape, while smart products and human resources, each mentioned nine times, emphasise innovation and workforce development. The cited frequency for the remaining dimensions is illustrated in Figure 4.

## 3.3 Maturity Level and Scale Analysis

Maturity model dimensions offer different perspectives for assessing the current position, capabilities, and growth potential of a manufacturing company. In the reviewed models, the number of questions ranged from 12 to 99, with scale options from two to nine per question, and maturity levels from three to six (see Appendix B). These variations reflect differences in assessment depth based on each model's design. While more questions can provide a detailed evaluation, a concise approach can ensure a focused and impactful analysis.

Understanding dimensions, maturity levels, and scales is essential for determining the appropriate balance of depth and practicality in an assessment model tailored for SMMEs. This comprehensive literature review illuminates the current landscape of Industry 4.0 readiness assessment models. Synthesising key findings and identifying gaps, provides a foundation for developing a tailored assessment model for manufacturing companies, particularly SMMEs, to evaluate their readiness for digital transformation.

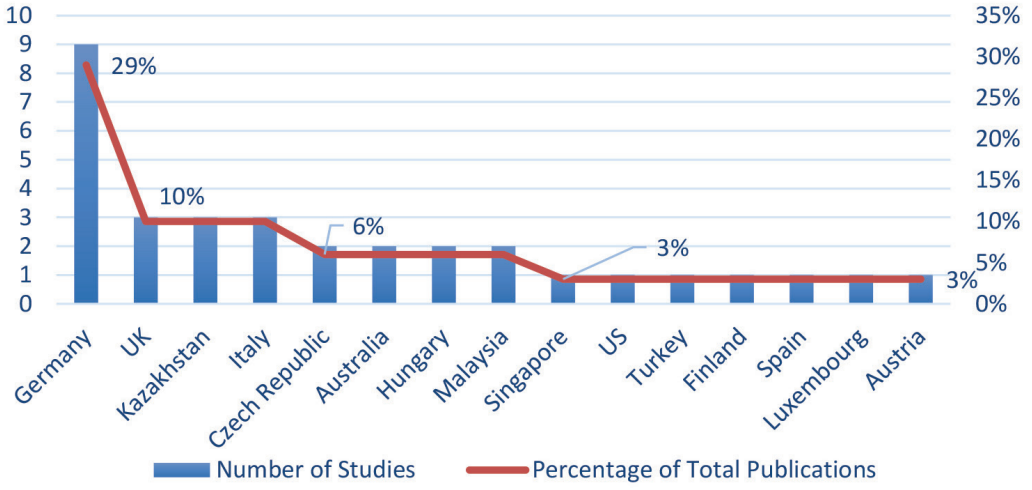


**Figure 3.** Geographical distribution of the selected studies

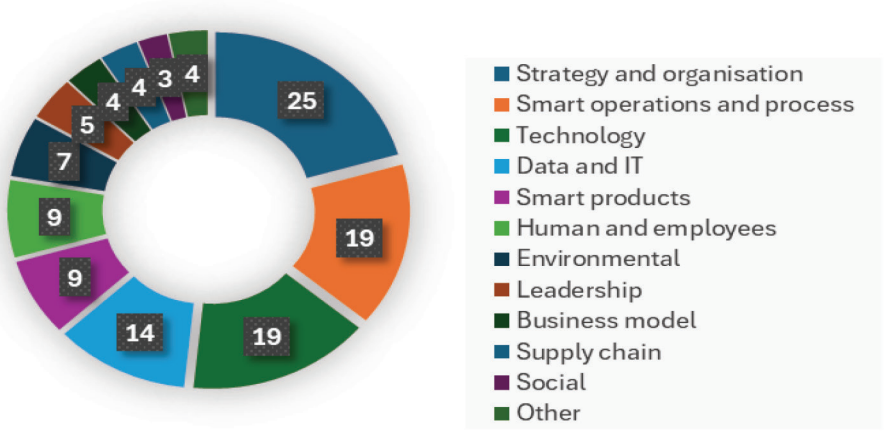


**Figure 4.** Dimensions frequency

## 4. Developing the Assessment Model

This section outlines the initial phase of developing a distinct assessment model for digital retrofitting in manufacturing companies. The literature review provided an in-depth understanding of relevant dimensions, maturity levels, and the scope and depth of questions used in existing models. Integrating these insights and tailoring them to the specific requirements of digital retrofitting, a comprehensive and contextually appropriate foundation for the assessment model was established. The proposed model includes four dimensions considered most relevant and impactful for SMMEs undergoing digital retrofitting: Strategy and Organisation, Development of the Workforce, Smart Factory, and Smart Processes. These dimensions were the most frequently cited in the literature and verified through expert judgment (Content Validity) to ensure their practical applicability. Although dimensions such as supply chain integration, customer satisfaction, and financial risk are recognised as important within broader digital transformation frameworks, they were intentionally excluded from this study to maintain conceptual clarity and ensure practical applicability for SMMEs. The selected dimensions represent the most direct internal enablers of successful digital retrofitting, offering a balance between theoretical grounding and operational relevance.

**Strategy and Organisation:**

- The literature review revealed that Strategy and Organisation was the most frequently mentioned dimension, appearing in 25 sources [18], [43]. This highlights its critical role in organisational planning and coordination.
- This dimension in the assessment model assesses how effectively an organization's culture, leadership, and management align with its digital retrofitting efforts. This alignment is crucial for the successful implementation of digital transformation strategies.

**Development of the Workforce:**

- The readiness and skill development of the workforce were emphasised in multiple studies [12], [60] indicating the need for a culturally ready and skilled workforce.
- In the proposed model, this dimension assesses the level of cultural readiness and skill development within the workforce to effectively embrace and implement digital retrofitting. This is essential for ensuring that employees can support and sustaining digital initiatives.

**Smart Factory:**

- The integration of advanced technologies and infrastructure was a recurrent theme, identified 19 times in the literature [22], [25]. This dimension is key to enabling efficient and intelligent retrofitting processes.
- This dimension assesses the degree to which advanced technologies and infrastructure are incorporated into the manufacturing environment, enabling efficient and intelligent digital retrofitting processes.

**Smart Processes:**

- The data and IT dimension, along with the focus on smart processes, was cited 14 times [49], [62]. The importance of technology and data

processing for optimising digitalisation processes was highlighted.
- This dimension measures the use of technology and data processing to enhance and streamline retrofitting processes, supporting a smooth transition to digital practices. Effective use of technology and data is critical for enhancing process efficiency and achieving digital transformation goals.

The assessment model for digital retrofitting is specifically designed for SMMEs, addressing their distinct challenges such as limited resources and smaller operational scale. The model consists of four dimensions and includes 21 questions, developed from an extensive literature review to streamline the assessment process (see Table 4). Each question uses a five-point scale to ensure data clarity and quality, enabling an effective evaluation of critical factors for digital retrofitting readiness. A structured maturity framework with four levels: Initial, Developing, Intermediate, and Advanced, is proposed in this study. This maturity framework aligns with established models by Schumacher et al. [50], Horváth and Szabó [57] and is detailed in Section 6.3. Targeted recommendations are provided in Section 6.4 based on the assessed maturity levels.

## 5. Survey results

In this section, the results of content validity and the pilot study are discussed. The content validity process ensured that the questionnaire accurately reflected the objectives of the study and covered all relevant aspects. The pilot study evaluated the feasibility of the proposed model, refining it based on real-world feedback from participants to enhance its clarity, practicality, reliability, and validity.

### 5.1 Content Validity Results

The Content Validity Ratio (CVR) (Equation 1) is employed to validate the identified factors. The CVR for each item revealed that most factors are highly relevant, with CVR percentages ranging from 78% to 100% as presented [8].

### 5.2 Pilot Study Results

A pilot study was conducted with 32 respondents from SMMEs to evaluate the current state of Industry 4.0 implementation and to assess the reliability of the research instrument. Data were analysed using the Statistical Package for the Social Sciences (SPSS) [65]. The sample comprised participants from a diverse range of industrial sectors, representing a variety of manufacturing enterprises. As summarised in Table 2, the largest proportions of respondents were from the Metals and Parts Industry (28.1%) and the Plastic and Non-Metal Industry (28.1%). These were followed by the Chemicals and Medicine Industry (18.8%), the Food and Drink Industry (12.5%), and Research and Development or academic roles (9.4%). A small proportion (3.1%) came from other sectors.

Professional roles are outlined in Table 3, with a significant majority (87.5%) holding decision-making positions. Middle management accounted for 46.9% of respondents, while senior management represented 40.6%. The remaining participants included shop-floor supervisors (9.4%) and engineering or technical staff (3.1%). This distribution supports the validity of the data, given the strategic and operational responsibilities of the respondents.

A reliability test was performed to evaluate internal consistency, providing evidence for the robustness of the instrument and its suitability for further application [66]. As shown in Figure 5, 94% of partic-

**Table 2.** Participant distribution across manufacturing sectors

| Industry | Percentage (%) |
|---|---|
| Metals and parts industry | 28.1% |
| Plastic and non-metal industry | 28.1% |
| Chemicals and medicine industry | 18.8% |
| Food and drink industry | 12.5% |
| Research and development, solutions provider, academic | 9.4% |
| Other | 3.1% |

**Table 3.** Participants' roles within the organisations

| Role | Percentage (%) |
|---|---|
| Middle-level management | 46.9% |
| Top-level management / executives | 40.6% |
| Shop floor management / supervision | 9.4% |
| Engineering and technical staff | 3.1% |

ipants were employed directly within the manufacturing sector. While 75% indicated plans to undertake digital retrofitting initiatives, only 37.5% reported prior experience with digital transformation within their manufacturing operations.

### 5.2.1 Descriptive Analysis

The readiness of SMMEs for Industry 4.0 is assessed across four key dimensions as mentioned previously. Each dimension provided insights into both operational and strategic factors, including the adoption of digital strategies and the integration of advanced technologies. The dimensions and individual items, along with their respective mean (M) and standard deviation (SD), are summarised in Table 4.

With a mean of 3.06, *Strategy and Organisation* dimension indicates moderate to high prioritization of strategic elements like digitalisation objectives. However, inconsistencies in change management (M = 3.00, SD = 1.30) suggest a need for more structured and comprehensive plans to support digitalisation goals, ensuring smoother transitions and better alignment across the organisation. *Development of the Workforce* dimension has a mean of 2.74, highlighting challenges in employee readiness for digital transformation. Notably, employee skill acquisition scored low (M = 2.41), indicating a clear need for increased investment in training and development programs. Prioritizing skill acquisition and continuous learning will help bridge the skills gap and prepare employees to effectively handle new digital tools and processes. With a mean of 2.73, *Smart Factory* dimension reflects the ongoing use of legacy machinery in SMMEs. High scores in machine connectivity (M = 3.34) show progress, but there is a need to further upgrade infrastructure. Enhancing connectivity and integrating advanced technologies will improve efficiency and enable intelligent manufacturing processes. *Smart Process* dimension has the lowest mean (2.34), with low scores in digital integration and significant variability in cloud adoption. These results indicate a need for improvement in data management and technology integration. Focusing on digital tools, especially in cloud solutions and data sharing, will enhance process efficiency and facilitate a smoother transition to digital practices.

### 5.2.2 Reliability Test

The internal consistency of the assessment model is measured using Cronbach's alpha, chosen for its efficiency over test-retest methods [66], [67]. The overall Cronbach's alpha was 0.967, indicating excellent reliability. Individual dimensions also showed strong reliability: Strategy and Organisation ($\alpha = 0.974$), Development of the Workforce ($\alpha = 0.904$), Smart Factory ($\alpha = 0.806$), and Smart Processes ($\alpha = 0.959$).

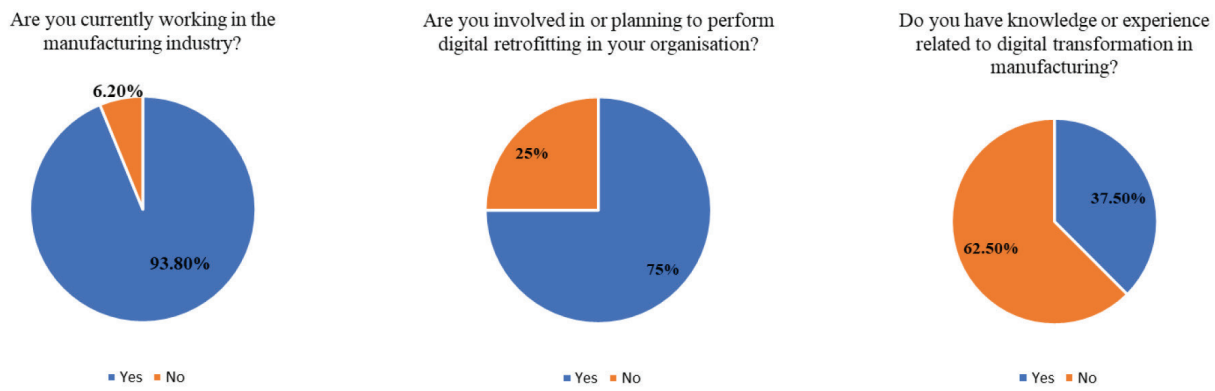


**Figure 5.** Participants background

**Table 4.** Descriptive analysis results

| Dimension | Item | Mean (M) | SD |
|---|---|---|---|
| 1st dimension M 3.06 | Industry 4.0 strategy | 3.41 | 1.21 |
| | Collaboration with external partners | 2.59 | 1.04 |
| | Budget for Industry 4.0 | 2.72 | 0.99 |
| | Leadership support for Industry 4.0 | 3.31 | 1.06 |
| | Digitalisation objectives | 3.81 | 1.12 |
| | Change management plan | 3.00 | 1.30 |
| | Risk management plan | 2.56 | 1.24 |
| | State of ICT function | 2.59 | 1.13 |
| 2nd dimension M 2.74 | Employee acceptance of change | 2.72 | 0.77 |
| | Employees' digital competency | 3.03 | 1.06 |
| | Budget for employee development | 2.81 | 0.97 |
| | Employees' skill acquisition | 2.41 | 0.88 |
| 3rd dimension M 2.73 | Machine connectivity | 3.34 | 1.23 |
| | Machine-to-machine communication | 2.28 | 1.11 |
| | Human–machine interface systems | 2.13 | 0.79 |
| | Machine control systems | 3.31 | 1.00 |
| | Data privacy and IT security | 2.28 | 0.85 |
| 4th dimension M 2.34 | Cloud adoption | 2.53 | 1.22 |
| | Digital technology integration | 2.12 | 0.94 |
| | Data-driven decision-making | 2.16 | 0.99 |
| | Data sharing | 2.62 | 1.01 |

## 6. Integration and Discussion

This section relates to the final stage of the methodology, 'Refinement and Model Documentation,' which results in the presentation of the final assessment model. It combines insights from the literature review and the survey to develop a comprehensive digital retrofitting assessment model. In this process, three parts are involved: the creation of a questionnaire, the determination of maturity levels, and the formulation of tailored solutions in accordance with these maturity levels. This section addresses the key components and design principles necessary for developing an assessment model to evaluate and guide SMMEs in implementing digital retrofitting practices.

### 6.1 Interpretation of Findings

The results from the pilot study reveal distinct readiness patterns among SMMEs. The relatively higher mean in the Strategy and Organisation dimension (M = 3.06) suggests that many firms are strategically aware of digital retrofitting needs but face challenges in operational execution. Notably, Change Management and Risk Management scored lower (M = 3.00 and M = 2.56, respectively), indicating strategic planning often lacks supporting mechanisms. This gap reinforces the need for practical models that go beyond awareness and support structured implementation.

The Development of the Workforce dimension (M = 2.74) shows significant internal variability, particularly in Skill Acquisition (M = 2.41). This highlights a misalignment between strategic intentions and workforce capabilities, a critical barrier to effective digital transformation in SMMEs. Interestingly, Smart Factory and Smart Processes dimensions had the lowest means (2.73 and 2.34), particularly in Machine-to-Machine Communication and Digital Integration. While the development of digital strategies appears to be underway, the lower scores in infrastructure and technology adoption reflect ongoing challenges in translating strategic intent into operational capability. The assessment model thus validates that readiness is unevenly distributed and that retrofitting efforts must be customised according to maturity profiles.

Compared to existing Industry 4.0 readiness models, the proposed framework introduces a distinctive and practical focus on digital retrofitting tailored specifically for SMMEs. While models such

as Schumacher et al. [22], and Schumacher et al. [50] present comprehensive frameworks covering up to 9 dimensions and over 60 indicators, they are often too complex for smaller enterprises. Others, like Nick et al. [48], include nearly 99 questions, and Hizam et al. [14] identify over 158 indicators, which may overwhelm resource-constrained organisations. Conversely, more compact models such as Anderl & Fleischer [24] or Stefan et al. [45], though easier to implement, often lack the analytical depth required for meaningful digital transformation planning.

This proposed model balances depth and usability by providing 21 carefully curated core questions across four critical dimensions: Strategy and Organisation, Development of the Workforce, Smart Factory, and Smart Processes. Uniquely, it introduces Solution Zero, recommending that organisations at low maturity levels delay digitalisation efforts until foundational elements like strategic alignment and employee readiness are in place, an approach not present in the most models. Furthermore, this model incorporates legacy system capability assessments, enabling a more accurate evaluation of technological compatibility, another gap in most existing assessments. Thus, this model contributes a streamlined yet targeted tool that supports informed decision-making in retrofitting scenarios, making it particularly relevant for SMMEs navigating Industry 4.0 transformations.

## 6.2 Develop Questionnaire

Through a comprehensive literature review, content validity assessments, and a pilot study, 21 key questions are developed to evaluate digital retrofitting readiness. Derived from both academic and industry insights, these questions assess organisational readiness across strategy, technology, employees, and processes. The development process ensured alignment with the objectives of the study, covering all relevant aspects of digital retrofitting. The finalised questionnaire, presented in Appendix A, serves as the foundation of the assessment model, enabling a focused evaluation of digital transformation maturity among SMMEs.

## 6.3 Maturity Level

A structured maturity framework with four levels is developed to evaluate an organisation's digital maturity and growth potential, as depicted in Figure 6. This classification aligns with established studies such as Warwick Manufacturing Group [23], Horváth and Szabó [57], and Schumacher et al. [16]. As the decision to initiate digitalisation or to plan its roadmap often relies on maturity assessments, adopting a simplified model is considered more practical and effective. The average mean score, derived from the assessment results, is classified as follows.

- Initial level (mean: 1–1.99). Organisations have a basic awareness of digital retrofitting and the potential of Industry 4.0 but lack strategic approaches and resources. Workforce digital skills are minimal.
- Developing level (mean: 2–2.99). Organisations have begun establishing strategies aligned with Industry 4.0, marking the start of their digital transformation journey.
- Intermediate level (mean: 3–3.99). Organisations have a structured digital strategy with leadership support and engage in external collaborations.

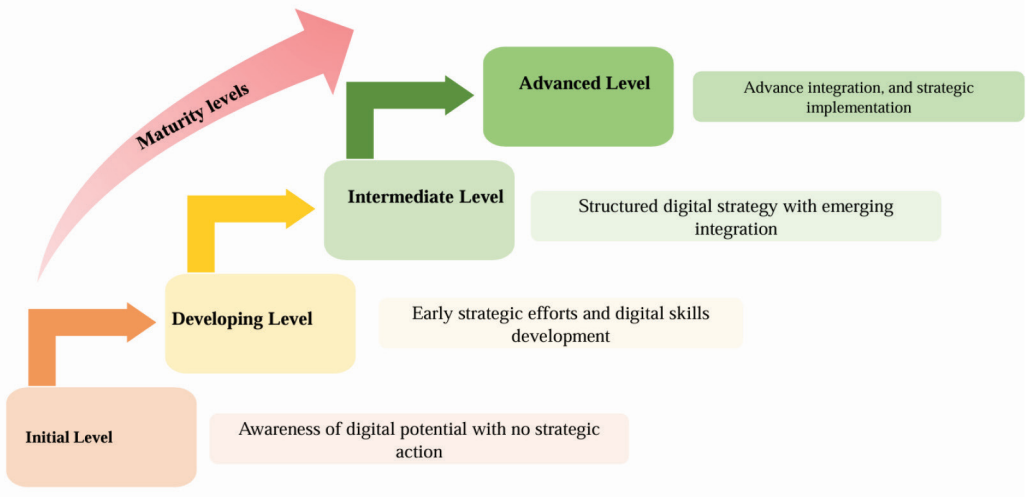


**Figure 6.** The four levels of organisational maturity

- Advanced level (mean: 4–5). Organisations have fully integrated digital retrofitting, with comprehensive Industry 4.0 strategies and advanced digital capabilities.

The mean average score (m) is calculated for each maturity dimension to accurately position the organisation at the correct level. The recommended approach is then customised based on the maturity level to ensure the recommendations are suitable for the organisation based on its current state.

### 6.4 Recommendations Based on Maturity Level

In this section, the digital retrofitting solutions approach proposed by Alqoud et al. [68] is utilised. These solutions were comprehensively detailed and validated through extensive research and analysis of current industry practices [10]. It comprises three key solutions, each designed to address specific aspects of digital retrofitting. Additionally, this study introduces 'solution zero' to minimise the risk of failure in adopting digital retrofitting as detailed below. Each solution is linked to corresponding maturity levels as defined by the assessment model, facilitating a clearer understanding of how each solution aligns with different stages of maturity as illustrated in Table 5.

The expert evaluation, conducted with a select group of five experts according to the criteria outlined in Section 2.2, ensures that these recommendations and solutions are both practical and effective. Furthermore, it verifies that the solutions are appropriately aligned with the corresponding maturity levels.

- Solution Zero: Preparation for digital transformation
  Recommended for organisations at the Initial level. Rather than implementing digitalisation immediately, this solution focuses on foundational steps, refining organisational strategy, establishing a clear vision for digital transformation, and preparing the workforce for future changes.
- Solution One: Starter Kit Solution
  A cost-effective, minimal disruption, retrofitting package designed for organisations moving from the Initial to Developing level. It includes vendor-provided packages with sensors, connectivity software, hardware, and a data analytics platform to monitor machine performance. Data is acquired through mounted sensors rather than directly from machines.
- Solution Two: Embedded Streaming Gateway Solution
  This solution, involves updating machine software to connect to IoT networks, thereby avoiding the need for additional IoT hardware. This solution is advantageous in terms of installation speed and hardware maintenance costs. However, it demands sufficient processing capacity in the machine's Programmable Logic Controller (PLC) and carries the risk of compromising core machine functions if not executed with precision. This solution is suitable for organisations at the Intermediate level, or higher, which typically possess the requisite digital skills to manage PLC updates.
- Solution Three: IoT Hardware-Based Solution
  This augments legacy systems with specialised IoT hardware, enhancing connectivity and data extraction capabilities. This approach facilitates direct data sourcing from legacy machines as well as from additional sensors. While it offers comprehensive data acquisition from diverse sources, it also introduces challenges in achieving interoperability between old and new technologies and increases complexity due to varied protocols. Solution three is most suitable for organisations at the Intermediate level or above, which are typically equipped to manage the complexities associated with technological integration.

The model indicates that organisations at a high level of maturity can apply any of the proposed solutions. Due to the fact that each solution has a different set of capabilities and features. It is essential that these choices are aligned with the organisation's specific goals and readiness to achieve satisfactory results.

## 7. Conclusion

In this paper, a comprehensive assessment model for digital retrofitting in SMMEs is developed and validated. The model is constructed through a methodical process involving a literature review, initial model design, expert validation, and a pilot study. It comprises 21 items across four critical dimensions and is supported by a four-level maturity classification, allowing organisations to assess their current state and plan their digital transformation journey accordingly. In addition to diagnostic capabilities, the model provides tailored digital retrofitting solutions matched to maturity levels, offering a practical

**Table 5.** Recommended solutions for each maturity level in each dimension

| **Strategy and Organisation** | | | |
|---|---|---|---|
| Initial level, 1–1.99 (high risk) | Developing level, 2–2.99 (medium risk) | Intermediate level, 3–3.99 (low risk) | Advanced level, 4–5 (no risk) |
| Solution zero: Emphasise Industry 4.0 strategy formulation, collaboration, budgeting for technologies, leadership support, and change management. This base-level approach reduces risks and fosters strategic maturity in Industry 4.0 implementation. | Starter Kit solution: Initiate foundational Industry 4.0 projects, expand budget allocation, enhance leadership support, and refine change management. This approach lays the groundwork for acquiring insights and progressing towards a more mature implementation stage. | All solutions applicable: With a solid foundation, diversify strategies, expand collaborations, and drive innovation. Ensure alignment with other dimensions for cohesive, robust Industry 4.0 strategies. | All solutions applicable: As an advanced entity, continue integrating diverse, advanced solutions to optimise processes and technologies. Focus on innovation. |
| **Development of the Workforce** | | | |
| Initial level, 1–1.99 (high risk) | Developing level, 2–2.99 (medium risk) | Intermediate level, 3–3.99 (low risk) | Advanced level, 4–5 (no risk) |
| Solution zero: Prioritise employee development, focusing on nurturing a culture of innovation and basic digital skills. Allocate budget for effective training programmes to establish a robust foundation for Industry 4.0 readiness. | Starter Kit solution: Expand workforce digital skills through structured training. Promote adaptability to technological change and allocate budget for ongoing learning and skill development, facilitating steady progress in Industry 4.0 implementation. | All solutions applicable: With a mature workforce development strategy, enhance training programmes, broaden digital competencies, and foster an adaptable working environment. Align these initiatives with broader organisational goals and objectives. | All solutions applicable: Continuously refine workforce strategies to encourage innovation and adaptability. Ensure these strategies are in harmony with insights from other dimensions, promoting cohesive and advanced workforce development in line with Industry 4.0 trends. |
| **Smart Factory and Smart Processes** | | | |
| Initial level, 1–1.99 | Developing level, 2–2.99 | Intermediate level, 3–3.99 | Advanced level, 4–5 |
| The Starter Kit solution is recommended at this early level. | The Starter Kit solution is typically a good starting point. It is possible to consider the IoT Hardware-based solution. | The Starter Kit solution or the IoT Hardware-based solution is typically used. | All solutions are applicable. Consider the solutions' features and organisational preferences. |

roadmap for implementation [69], [70]. This dual academic and practical contribution enhances understanding of Industry 4.0 readiness and supports organisations in taking actionable steps towards transformation. The approach also aligns with the SDGs, particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production), by encouraging sustainable and responsible technological adoption.

However, several limitations should be acknowledged. The literature review focused primarily on digital retrofitting within the manufacturing sector, excluding broader factors such as supply chain integration and customer satisfaction. The paper also does not examine changes in organisational structures, which are an important dimension of digital transformation. Additionally, the small sample size (n=32) used for model testing, while appropriate for pilot purposes, limits the generalisability of the findings.

Future research should aim to expand the development of a structured roadmap that guides organisations in the step-by-step adoption of the proposed solutions, especially as firms transition between maturity levels. Moreover, integrating multi-criteria decision-making techniques could significantly enhance the process of selecting the most suitable digital retrofitting solutions based on organisational priorities, constraints, and technological capabilities. Despite the current limitations the model offers a robust foundation for future research and real-world application. It provides practical guidance to support informed decision-making, enabling SMMEs to enhance their digital readiness and overall competitiveness in an increasingly digital industrial landscape.

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# Appendix

## *Appendix A: Assessment model questionnaire*

| **First dimension: Strategy and Organisation (8 questions)** |
|---|
| 1. Please indicate the level of implementation of the Industry 4.0 strategy in your organisation. |
| There is no strategy available. |
| The strategy is at the development stage. |
| The strategy is formulated but not implemented. |
| The strategy is formulated but implemented partially in some departments only. |
| The strategy is formulated and implemented across the organisation. |
| 2. Please indicate the extent of collaboration with external partners, such as academics and technology providers, for the implementation of Industry 4.0 technologies in your organisation. |
| No collaboration with external partners related to Industry 4.0 technologies. |
| Planned collaboration with external partners specifically focused on the implementation of Industry 4.0 technologies. |
| Some collaboration with local partners for the implementation of Industry 4.0 technologies. |
| Established collaboration with both local and international partners for the implementation of Industry 4.0 technologies. |
| Full integration and collaboration with both local and international partners for the successful implementation of Industry 4.0 technologies. |
| 3. Please indicate the level of budget allocation for investment in Industry 4.0 technologies in your organisation. |
| No investment allocated for Industry 4.0 technologies. |
| Initial investment in Industry 4.0 technologies limited to one area (around 20%). |
| Low level of investment in Industry 4.0 technologies (around 40%). |
| Medium level of investment in Industry 4.0 technologies in a few areas (around 65%). |
| High level of investment in Industry 4.0 technologies across several areas (more than 80%). |
| 4. Please indicate the level of leadership support to implement Industry 4.0 in your organisation. |
| Top management is not aware of Industry 4.0 and its value. |
| Top management is partially aware of Industry 4.0 and has legal obligations for some elements. |
| Top management recognises the benefits of Industry 4.0 and has made initial investments in a few elements. |
| Top management supports Industry 4.0 with investments for implementing selected elements and piloting initiatives in critical departments. |
| Top management fully understands Industry 4.0, actively supports its application, and has made extensive investments while creating networks to leverage opportunities. |
| 5. Please indicate the objective of digitalising and upgrading the factory's equipment in terms of its functionality and capabilities. |
| No specific objective; no clear aim for digitalisation and equipment upgrades. |
| The objective is limited to visualising the manufacturing process. |
| The objective includes visualising processes and enabling decision-making based on the gathered information. |
| The objective encompasses visualising processes, analysing data for informed decision-making, and enhancing overall operational efficiency. |

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| The objective is to automate decision-making through advanced data analytics while visualising processes and enabling remote equipment control for optimised performance. |
| 6. Please indicate the extent of the change management plan to implement Industry 4.0 in your organisation. |
| No change management plan is available to implement Industry 4.0. |
| The change management plan is at the development stage. |
| The change management plan has been formulated but not implemented. |
| The change management plan has been formulated but implemented partially in some departments only. |
| The change management plan has been formulated and implemented across the organisation to adopt Industry 4.0. |
| 7. Please indicate the level of risk management plan to implement Industry 4.0 in your organisation. |
| New risks have not been identified or assessed. |
| The risk management plan has been formulated but not implemented. |
| New risks have been identified and/or assessed, but no mitigations are planned. |
| New risks have been identified and assessed, and limited mitigations have been put in place. |
| A working party has assessed the changing risk profile and established procedures to mitigate these risks. |
| 8. Please indicate the state of the Information and Communication Technology (ICT) function in your organisation. |
| The ICT function is not structured in the organisation. |
| The organisation doesn't have an ICT department but it has IT specialists. |
| The organisation has an ICT department that supports basic information system processes. |
| The organisation has an ICT department that supports information system processes on a moderate level. |
| A strong ICT function exists and is represented at the top level to support all ICT systems and processes, with IT experts in each department. |

| **Second dimension: Development of the Workforce (4 questions)** |
|---|
| 9. Please indicate the level of employee acceptance of new changes in your organisation. |
| Very low, with employees displaying resistance to change. |
| Low, with employees being reluctant to embrace changes. |
| Moderate, with employees becoming more receptive to changes after receiving clarifications. |
| High, with employees showing a positive attitude towards change. |
| Very high, with employees proactively seeking involvement in changes and innovations. |
| 10. Please indicate the average level of employee competency in your organisation. |
| Most employees have no digital skills as these are not required in their work. |
| Low level: basic skills in using common digital devices, such as making phone calls and sending emails. |
| Moderate level: employees are freely able to use most common digital devices and are active users of computers and work-related programs. |
| Extensive level: advanced proficiency in Microsoft programs and expert knowledge of alternative programs. |
| Advanced level: skills in software development, coding, applications, programming, and using computer syntax or statistical analysis packages. |
| 11. Please indicate the type of budget allocated for employee development in your organisation. |
| No special budget is provided to support employee development. |
| Training is provided only based on requirements or legislation, with no dedicated budget. |
| Training is provided in case of urgent need and only for critical personnel, specific positions, or departments. |
| A specific budget is allocated but it does not cover training for employees at all levels. |
| Training is provided to all employees at every level on a predefined schedule with a dedicated budget. |
| 12. Please indicate the level of employee skill acquisition in your organisation. |
| There are no plans to hire new competent employees or train current employees. |
| There are some plans to hire new competent employees or train current employees. |
| Some new competent employees have been hired or current employees have been trained. |
| Multiple new competent employees have been hired or the training of current employees is in progress. |
| Sufficient competent employees have been hired or the training of current employees is ongoing. |

| Third dimension: Smart Factory (4 questions) |
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| 13. Please indicate the level of machine connectivity (requiring digital retrofitting) in your organisation. |
| The machines have no interfaces. |
| The machines send or receive Input/Output (I/O) signals. |
| The machines have field bus interfaces. |
| The machines have industrial Ethernet interfaces. |
| The machines have access to the Internet. |
| 14. Please indicate the level of machine-to-machine (M2M) communication (requiring digital retrofitting) in your organisation. |
| There is no communication between machines. |
| The machines have field bus interfaces for communication. |
| The machines have industrial Ethernet interfaces for communication. |
| The machines have access to the Internet for communication. |
| Machine-to-machine communication is facilitated through software based on Web services. |
| 15. Please indicate the level of human–machine interface systems (requiring digital retrofitting) in your organisation. |
| There is no information exchange between the user and the machines. |
| The machines utilise local user interfaces. |
| Production monitoring or control is centralised or decentralised. |
| The machines incorporate the use of mobile user interfaces. |
| Augmented and assisted reality are employed in human–machine interface systems. |
| 16. Please indicate the level of control system in the machines (requiring digital retrofitting) in your organisation. |
| No Programmable Logic Controller (PLC) or computing system is present in the machines. |
| Legacy PLCs with limited capacity are installed in the machines. |
| PLCs with basic computing systems are utilised in the machines. |
| PLCs with sufficient computing systems and capacity are implemented in the machines. |
| Modern PLCs with advanced computing systems and high capacity are integrated into the machines. |

| Fourth dimension: Smart Processes (5 questions) |
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| 17. Please indicate the level of data privacy and IT security measures implemented in your organisation. |
| Minimal data privacy and no IT security measures are in place, with no specific protocols or safeguards. |
| Basic data privacy and IT security measures are implemented but not comprehensive or regularly updated. |
| Moderate data privacy and IT security measures are in place, with regular assessments and updates to mitigate risks. |
| Strong data privacy and IT security measures are implemented and aligned with industry standards and regulations. |
| Robust data privacy and IT security measures are in place, with continuous monitoring, proactive threat detection, and rapid incident response protocols. |
| 18. Please indicate the extent of cloud adoption in your organisation. |
| No cloud solutions are currently in use. |
| Initial plans are in place for adopting cloud-based software, data storage, and data analysis. |
| Initial solutions have been implemented for cloud-based software, data storage, and data analysis. |
| Multiple solutions have been implemented for cloud-based software, data storage, and data analysis. |
| Cloud solutions have been implemented in several areas for cloud-based software, data storage, and data analysis. |
| 19. Please indicate the extent of digital technology integration in manufacturing processes. |
| Limited or no integration of digital technologies in manufacturing processes, which are carried out independently. |
| Some areas of manufacturing processes have been digitised but overall integration is low (around 20%). |
| Moderate integration of digital technologies in selected manufacturing processes (around 40%). |
| Extensive integration of digital technologies in most manufacturing processes (around 65%). |
| Full integration of digital technologies across all manufacturing processes (more than 80%). |
| 20. Please indicate the extent of data-driven decision-making across your organisation's manufacturing processes. |
| Limited or no utilisation of data for decision-making in manufacturing processes. |
| Some data is collected and utilised for production process monitoring and low-level decision-making. |
| Data-driven decision-making is moderately integrated into selected production processes and utilised for tactical decision-making within departments. |

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| Data-driven decision-making is extensively integrated into most production processes and utilised for strategic decision-making within departments. |
| Data-driven decision-making is fully integrated and utilised across all production processes for informed strategic decision-making at the organisational level. |
| 21. Please indicate the level of digitalisation and sharing of enterprise data in your organisation. |
| Enterprise data is collected manually and stored only in paper format without sharing. |
| Enterprise data is primarily stored in spreadsheets or similar programs, with limited sharing capabilities. |
| Digitised enterprise data is stored in isolated ICT systems, with departmental data kept separate and limited sharing between departments. |
| Enterprise data is digitised and stored in a central or networked ICT system, enabling department-specific data to be shared within the organisation. |
| Enterprise data is digitised, stored using a data lake or cloud, and widely shared across the organisation, facilitating seamless data sharing and collaboration. |

## *Appendix B: The research dimensions and assessment metrics*

| Author | Dimensions | | Dimensions | Maturity levels | Questions | Scales |
|---|---|---|---|---|---|---|
| Lichtblau et al. (2015) | -Strategy and organisation<br>-Smart factory<br>-Smart operations | -Smart products<br>-Data-driven services<br>-Employees | 6 | 6 | 24 | Multi |
| Warwick Manufacturing Group (WMG, 2017) | -Products and services<br>-Manufacturing and operations<br>-Strategy and organisation | -Supply chain<br>-Business model<br>-Legal considerations | 6 | 4 | 37 | 4 |
| Anderl & Fleischer (2016) | -Products | -Production | 2 | 5 | 12 | 5 |
| Board (2018) | -Process<br>-Technology | -Organisation | 3 | 6 | 16 | 6 |
| Nazarbayev University (2022) | -Development of the workforce<br>-Smart products and services | -Smart factory<br>-Smart processes<br>-Strategy and organisation | 5 | 5 | 33 | 6 |
| Rockwell (2015) | -Information infrastructure<br>-Controls and devices | -Networks<br>-Security policies | 4 | 5 | - | - |
| Reinhard et al. (2016) | -Digital business models<br>-Product and service digitisation<br>-Value chain integration<br>-IT architecture | -Data and analytics<br>-Compliance and security<br>-Organisational culture | 7 | 4 | 33 | 5 |
| Kayikci et al. (2022) | -Economic<br>-Environmental<br>-Social<br>-Policy | -Process<br>-Product<br>-Strategy<br>-Technology | 8 | 6 | - | - |
| Dikhanbayeva et al. (2020) | -Product and services<br>-Workforce development | -Strategy<br>-Smart factory | 5 | 5 | 40 | 5 |
| Schroderus et al. (2022) | -Organisational governance<br>-Strategy<br>-Risk management<br>-Culture | -Competences<br>-Operations and processes<br>-Technology and data analytics | 7 | 5 | - | - |
| Simetinger & Basl (2022a) | -Strategy<br>-Value chain<br>-Organisation | -Human resources<br>-Technology | 5 | - | 19 | 9 |

| Author | Dimensions | | Dimensions | Maturity levels | Questions | Scales |
|---|---|---|---|---|---|---|
| Schumacher et al. (2016) | -Strategy<br>-Leadership<br>-Customers<br>-Products<br>-Technology | -Operations<br>-Culture<br>-People<br>-Governance | 9 | 4 | 62 | 5 |
| Stefan et al. (2018) | -Organisation<br>-Technology | -Personnel development | 3 | 5–7 | - | - |
| Spaltini et al. (2022) | -Product<br>-Process<br>-Platform | -People<br>-Partnership<br>-Performance | 6 | 6 | - | - |
| Colli et al. (2018) | -Governance<br>-Technology<br>-Connectivity | -Value creation<br>-Competence | 5 | 6 | - | - |
| Nick et al. (2019) | -Strategy and organisation<br>-Smart factory<br>-Intelligent processes | -Smart products<br>-Services based on product data<br>-Employees | 6 | - | 99 | - |
| Rafael et al. (2020) | -Strategy and organisation<br>-Smart factory<br>-Smart operations | -Smart products<br>-Data-driven services<br>-Employees | 6 | 6 | - | - |
| Schumacher et al. (2019) | -Technology<br>-Product<br>-Customers and partners<br>-Value creation | -Data and information<br>-Corporate standard<br>-Employees<br>-Strategy and standard | 8 | 4 | 65 | - |
| Kolla et al. (2019) | -Strategy<br>-Product<br>-Technology<br>-Customer<br>-Operations | -Leadership<br>-Suppliers<br>-Employees<br>-Culture | 9 | - | - | - |
| Lukhmanov et al. (2022) | -Strategy and organisation<br>-Workforce development<br>-Smart products and services | -Smart factory<br>-Smart processes | 5 | - | - | - |
| Nick et al. (2021) | -Physical world<br>-Virtual world<br>-Human<br>-Products and services | -Value chain<br>-Environment<br>-Strategy and culture | 7 | - | - | - |
| Jayashree et al. (2021) | -Top management commitment<br>-Industry 4.0 implementation | -Supply chain<br>-IT infrastructure<br>-Sustainability | 5 | - | - | 5 |
| Ariffin & Ahmad (2021) | -People and capacity organisation<br>-Policy and process | -Technology and technical<br>-Legislation and regulation | 5 | 3 | - | - |
| Bibby & Dehe (2018) | -Strategy<br>-Factory of the future | -People and culture | 3 | - | - | - |
| Horváth & Szabó (2019) | -Technology<br>-Organisation of production and logistics<br>-Management and strategy | -Employees and communication<br>-Interfirm cooperation | 5 | 4 | - | - |
| Valentin (2017) | -Management<br>-Structure and organisation design | -Organisational culture<br>-Processes<br>-Strategy | 5 | - | - | - |
| Gerlitz (2016) | -Environment<br>-Strategy<br>-Finance<br>-Process and operation | -Innovation<br>-Learning and growth<br>-Competitive perspective | 7 | - | - | - |

| Author | Dimensions | | Dimensions | Maturity levels | Questions | Scales |
|---|---|---|---|---|---|---|
| Basl & Doucek (2019) | -Strategy<br>-Leadership<br>-Culture | -Human<br>-Technology | 5 | 7 | - | - |
| Bretz et al. (2022) | -Environment | -Operability<br>-Competence | 3 | 3 | - | - |
| Colangelo et al. (2022) | -Data<br>-Organisation<br>-Human | -Technology<br>-Dynamic capability | 5 | 5 | 18 | |
| Brozzi et al. (2021) | -Strategy<br>-Processes<br>-Information technology | -Industry 4.0<br>-Employees | 5 | 3 | 26 | 5 |