# CONTEMPORARY SMART MANUFACTURING: MERGING INDUSTRY 4.0 AND INDUSTRY 5.0

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***Abstract:*** *This chapter examines the evolution of smart manufacturing as the conceptual and practical link between Industry 4.0 and Industry 5.0. Based on a structured literature review of 43 readiness and maturity models, it analyses how technological, organisational, human, and sustainability dimensions shape industrial transformation. The study identifies the most frequent dimensions: Technology and Digitalisation, Operations and Processes, and People and Culture. While early models focused mainly on automation and digital technologies, more recent approaches increasingly integrate human-centric, sustainable, and resilience-related factors. The results confirm that smart manufacturing represents a fusion of digital and socio-technical systems, balancing efficiency with social and environmental responsibility. This synthesis contributes to a clearer understanding of how Industry 4.0's technological foundations combine with Industry 5.0's human-centred and sustainable orientation to define the future direction of manufacturing.*

***Key words:*** *smart manufacturing, Industry 4.0, Industry 5.0, maturity models, readiness models*

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## 1. Introduction

The rapid technological and social transformations that have shaped industrial production over the past three centuries began with the first industrial revolution in the late eighteenth century. The development of the steam engine by James Watt marked the beginning of a new era in which mechanisation became the cornerstone of manufacturing systems (Britannica, 1998). The subsequent industrial revolutions each introduced new paradigms of production and organisation. The second industrial revolution brought electrification and mass production, symbolised by the assembly line and standardised workflows (Britannica, 1998). The third revolution, triggered by microelectronics and the rise of computer-controlled automation, marked the onset of digital manufacturing and the increasing replacement of manual operations by programmable systems (Singh, 2023). These successive waves of innovation culminated in the fourth industrial revolution, or Industry 4.0, which integrates the physical and digital domains through cyber-physical systems, the Internet of Things, and cloud computing. The introduction of smart sensors, advanced data analytics, and interconnected networks has enabled a new level of autonomy in production processes, paving the way for the development of smart manufacturing (Schumacher et al., 2016).

Although the concept of autonomous and data-driven systems has demonstrated substantial potential, subsequent research and industrial experience have revealed that fully automated production does not eliminate the need for human participation. Humans remain indispensable in interpreting unexpected events, adapting to non-routine situations, and providing contextual reasoning that machines cannot replicate (Nahavandi, 2022; Xu et al., 2021). This recognition has led to the emergence of a new industrial paradigm, Industry 5.0, which complements the technological focus of Industry 4.0 with a human-centred and sustainability-oriented perspective (Nahavandi, 2022; Xu et al., 2021). It emphasises cooperation between humans and intelligent systems, aiming not to replace human capabilities but to augment them. Within this evolving discourse, smart manufacturing has become the conceptual bridge that connects these two paradigms. Initially defined primarily as a technology-driven concept under the umbrella of Industry 4.0, smart manufacturing has evolved into a holistic socio-technical framework that integrates digitalisation, human collaboration, sustainability, and resilience (Nahavandi, 2022; Xu et al., 2021).

Despite extensive research and policy initiatives, the practical implementation of smart manufacturing among EU small and medium-sized enterprises (SMEs) remains uneven, with significant variation across member states. The State of the Digital Decade 2025 report, which integrates the Digital Economy and Society Index (DESI), reveals persistent gaps in the digital transformation of businesses, particularly for SMEs. While the EU has advanced in digital infrastructure and public services, only 19% of EU SMEs engage in e-commerce, and adoption of advanced technologies such as artificial intelligence (12.3%) and big data (14.3%) remains below targets, even in leading economies (European Commission, 2025a; European Commission, 2025b).
Country-specific trends highlight this disparity:

- Germany – A frontrunner in Industry 4.0, with higher SME digitalisation rates supported by initiatives such as the Mittelstand 4.0 competence centres.

However, many smaller firms still struggle with interoperability and scaling digital solutions beyond pilot projects (European Cluster Collaboration Platform, 2025; European Commission, 2024a).
- France and Italy – Show moderate progress, with SME adoption of cloud computing and AI trailing behind large enterprises despite national strategies (Industrie du Futur and Transizione 4.0) aimed at accelerating digitalisation (European Commission, 2024b; European Commission, 2024c).
- Slovenia – Representative of Central and Eastern Europe, ranks in the middle of the EU for digital performance, with less than half of enterprises using cloud services and only a fraction applying AI or big data analytics. This pattern, visible in the 2025 DESI dashboard, underscores the need for targeted support in smaller economies (European Commission, 2024d; European Commission, 2025c).

The Digital Decade Policy Programme 2030 monitors four key dimensions: digital skills, infrastructure, business digitalisation, and public services. For SMEs, the business digitalisation dimension reveals several persistent challenges:
- Limited awareness of available support programmes.
- High upfront investment costs and resource constraints.
- A lack of socio-technical frameworks tailored to SMEs' specific contexts.

Although some member states report incremental gains, the EU average for SMEs using advanced technologies remains below 20% (European Commission, 2025a; European Commission, 2025b). The 2025 report urges renewed action, warning that without targeted interventions, SMEs—particularly in smaller economies such as Slovenia—risk falling further behind in the transition to smart manufacturing (European Commission, 2025b; European Commission, 2025c). Another persistent challenge lies in the conceptual fragmentation of the field. Industry 4.0, Industry 5.0, and smart manufacturing are often treated as distinct or even competing concepts, leading to overlapping terminology and inconsistent operational frameworks.
- Industry 4.0 highlights digital connectivity and cyber-physical integration.
- Industry 5.0 stresses the human, social, and ecological dimensions of industrial systems.
- Smart manufacturing, however, represents a synthesis rather than a replacement of these paradigms, encompassing the technological infrastructure of Industry 4.0 (automation, artificial intelligence, and data exchange) while embedding the human-centric and sustainable values promoted by Industry 5.0 (Nahavandi, 2022; Xu et al., 2021).

To advance the theoretical and practical understanding of this synthesis, it is necessary to examine how researchers and organisations conceptualise smart manufacturing in relation to the two industrial paradigms. Existing maturity and readiness models offer a structured basis for understanding how companies progress toward digital transformation and how the dimensions of technology, organisation, people, and culture interact in that process.

Over the past decade, several notable models have been developed, including:

- IMPULS Industry 4.0 Readiness Model,
- Schumacher’s Maturity Model,
- acatech Industrie 4.0 Maturity Index, and
- Subsequent adaptations by Mittal et al. and Bittighofer et al. (Schumacher et al., 2016; Schuh et al., 2017; Mittal et al., 2018).

More recent approaches, such as the Industry 5.0 Maturity Model (Hein-Pensel et al., 2025), explicitly address the socio-technical aspects that align with the human-centric philosophy of Industry 5.0, offering a self-assessment framework for SMEs across seven maturity dimensions.

## 2. Smart Manufacturing as Fusion of Industry 4.0 and Industry 5.0

The conceptual development of industrial systems over the past four decades demonstrates that technological advancement alone cannot define the future of manufacturing. The term smart manufacturing predates the Industry 4.0 initiative, having first appeared in the late 1980s within research on artificial intelligence and computer-integrated manufacturing. However, the diffusion of digital technologies in the 2010s, particularly those associated with Industry 4.0, revitalised and expanded the concept, positioning it as a central framework for modern industrial transformation. Smart manufacturing therefore represents a convergence of earlier ideas about intelligent automation and contemporary developments in connectivity, data analytics, and human–machine collaboration. Understanding this conceptual continuity is essential for explaining how smart manufacturing bridges the technological paradigm of Industry 4.0 with the human-centric and sustainable orientation of Industry 5.0.

### *2.1 Origins and Evolution of Smart Manufacturing*

Smart manufacturing represents a comprehensive industrial paradigm that has developed significantly since its inception in the 1980s. While Industry 4.0 and Industry 5.0 are often treated as separate industrial revolutions in contemporary discourse, historical analysis shows that smart manufacturing has consistently incorporated both technological progress and human-centred approaches (EFFRA, 2014). This perspective suggests that Industry 4.0 and Industry 5.0 should not be viewed as distinct revolutions but rather as complementary aspects within the broader evolution of smart manufacturing.

The European Factory of the Future Research Association (EFFRA, 2014) defined early visions of smart manufacturing as the integration of advanced information technologies, flexible automation, and human knowledge into interconnected production systems. The European Commission later refined this vision, describing smart manufacturing as “a combination of the intelligent use of human capabilities, the intelligent use of technology, and the implementation of self-learning production systems” (European Commission, 2021a). Both conceptualisations emphasise three core elements: technological progress, human adaptability, and continuous learning.

There is an important distinction between smart manufacturing (SM) and intelligent manufacturing (IM), although the two terms are often used interchangeably. Intelligent manufacturing, which originated from research on artificial and manufacturing intelligence in the late 1980s, primarily focused on replacing human intelligence in manufacturing processes. Japan pioneered IM research in the 1990s through its Intelligent Manufacturing Systems (IMS) programme, followed by joint efforts by the United States and the European Union. The development of IM advanced through several phases, beginning with expert systems and neural networks (1990–2000), expanding to agent-based systems and knowledge engineering (2001–2010), and culminating in the integration of big data and Internet of Things (IoT) technologies (Mourtzis, 2020). Smart manufacturing, by contrast, has evolved as a socio-technical system that integrates digital technologies with human expertise rather than attempting to replace it.

### *2.2 Smart Manufacturing and Industry 4.0*

The connection between smart manufacturing and Industry 4.0 lies primarily in technological integration and the pursuit of advanced automation. Industry 4.0 was introduced in Germany as part of the federal government's High-Tech Strategy 2020, which sought to strengthen the competitiveness of German manufacturing through digitalisation (Plattform Industrie 4.0, 2016). Its key features include the integration of cyber-physical systems (CPS), the Internet of Things (IoT), cloud computing, and artificial intelligence into production environments. These technologies enable real-time data exchange, predictive maintenance, and flexible production, forming the technological foundation of modern manufacturing.

Smart manufacturing incorporates these same principles but extends them beyond the technological domain. It combines automation with organisational and human factors, ensuring that technological adoption is embedded in strategy, structure, and culture. The technological aspects of smart manufacturing include system integration, where physical production assets are connected to sensors, computing platforms, and communication networks. This enables data-intensive modelling, process control, and predictive analytics. Self-managing systems, another central component, support flexible planning and monitoring, allowing organisations to respond effectively to dynamic market conditions (Mourtzis, 2020).

Although both paradigms share common technologies, their orientation differs. Industry 4.0 focuses primarily on efficiency, automation, and integration, whereas smart manufacturing adopts a more holistic view by incorporating the human role in decision-making and innovation. In practice, smart manufacturing represents the operational realisation of Industry 4.0 concepts. It moves beyond connectivity and automation toward learning and adaptive systems that combine artificial and human intelligence. This approach has also been recognised in the implementation strategies of the Industrie 4.0 Platform (Plattform Industrie 4.0, 2016).

However, research and practice have shown that the implementation of Industry 4.0 remains limited, particularly among small and medium-sized enterprises (SMEs). Many companies face challenges such as high costs, interoperability issues, and limited human resources.

Surveys show that only about one-quarter of companies have initiated projects related to Industry 4.0 or smart manufacturing (PwC, 2016). This demonstrates that digital transformation is not solely a technical process but also an organisational one. Smart manufacturing thus serves as a bridge that operationalises the technological infrastructure of Industry 4.0 while promoting human-centred and adaptive practices.

*2.3 Smart Manufacturing and Industry 5.0*

While Industry 4.0 emphasises technological innovation, Industry 5.0 introduces a paradigm shift toward human-centricity, sustainability, and resilience. It was formally presented by the European Commission (2021a) as a response to global social and environmental challenges, complementing the technological focus of Industry 4.0 with societal and ethical considerations. The aim of Industry 5.0 is to place humans back at the centre of production systems, enabling cooperation between people, machines, and digital platforms. This paradigm views technology as a tool to enhance human creativity and well-being rather than merely to increase efficiency.

Smart manufacturing aligns closely with these goals. Its foundations already incorporate human interaction, sustainability, and adaptability, which are the main dimensions of Industry 5.0. The integration of advanced data analytics and AI with human expertise allows for adaptive and resilient production systems capable of learning and self-optimisation (Grabowska et al., 2022). Through its focus on both technology and people, smart manufacturing anticipates the principles of Industry 5.0, promoting responsible innovation and resource efficiency.

Sustainability plays an increasingly important role in this context. Smart manufacturing contributes to the European Union's Green Deal Industrial Plan (European Commission, 2023) and 2030 Digital Compass (European Commission, 2021b) strategies by enabling circular production systems, energy optimisation, and reduced material waste. At the same time, it supports social sustainability by improving working conditions, facilitating collaboration between humans and machines, and fostering continuous learning. The human operator becomes a key element of smart manufacturing systems, responsible for creative problem-solving, supervision, and strategic decision-making.

The human-centric orientation of Industry 5.0 can therefore be seen not as a new revolution but as a continuation and expansion of the smart manufacturing concept. Smart manufacturing provides the technological and organisational infrastructure that makes the vision of Industry 5.0 achievable. It combines digitalisation and automation with ethical, social, and environmental dimensions, forming the foundation of a resilient and sustainable industrial ecosystem.

*2.4 Synthesis*

The evolution of industrial paradigms demonstrates a gradual convergence of technology, organisation, and human values. Industry 4.0 represents the digital transformation of manufacturing through connectivity, automation, and data integration. Industry 5.0 expands this foundation by adding human-centric and sustainable perspectives. Smart manufacturing encompasses both paradigms, acting as the unifying framework that integrates their complementary strengths.

It combines the technological foundations of Industry 4.0 with the socio-technical and ethical dimensions of Industry 5.0, enabling the transition toward adaptive, intelligent, and resilient manufacturing systems. This synthesis can be understood through three interconnected dimensions. The technological dimension includes automation, connectivity, and data-driven intelligence, which ensure efficiency and precision. The organisational and human dimension incorporates leadership, skills, culture, and collaboration, which determine adaptability and innovation capacity. The strategic and sustainability dimension links these two by aligning industrial development with long-term social and environmental goals. Together, these dimensions define smart manufacturing as a dynamic and integrative paradigm rather than a transitional stage between two industrial revolutions. It operationalises the technological ambitions of Industry 4.0 while realising the humanistic aspirations of Industry 5.0, thereby shaping the conceptual and practical foundation for the future of manufacturing.

## 3. Methodology

The research in this study is based on a structured literature review and an analytical synthesis of existing readiness and maturity models related to smart manufacturing, Industry 4.0, and Industry 5.0. The main purpose was to identify, group, and connect the key dimensions that define how ready and how mature manufacturing companies are when introducing advanced industrial concepts. This approach helps to show how smart manufacturing combines the technological foundations of Industry 4.0 with the human-centred and sustainable principles of Industry 5.0.

### *3.1 Research approach*

The study followed a systematic review process focused on scientific and professional publications about readiness and maturity assessment in manufacturing. The analysis was based on secondary data from the Web of Science and Scopus databases. The review included identifying relevant papers, applying inclusion and exclusion criteria, and analysing and grouping the results thematically. The goal was to create a structured and repeatable overview of how different authors define and measure readiness and maturity for smart manufacturing. The research was guided by three questions:

- How have researchers defined readiness and maturity in the context of smart manufacturing and Industry 4.0?
- Which dimensions appear most often as important factors for digital transformation?
- How can these dimensions be combined into a single framework that reflects both Industry 4.0 and Industry 5.0 ideas?

### *3.2 Literature search and data sources*

The literature search was carried out between **2010 and 2025** using the **Web of Science** and **Scopus** databases.

Separate search strategies were used for readiness models and maturity models to capture both perspectives of digital transformation.

### *3.3 Readiness models*

The first search combined the keywords *“Industry 4.0”*, *“manufacturing”*, and *“readiness model”*. To include related terms, additional expressions such as *“readiness assessment”*, *“readiness index”*, and *“readiness framework”* were added with the operator **OR**. This allowed the identification of studies that evaluate how prepared a company is for implementing Industry 4.0.

The combined query (*“Industry 4.0” AND “manufacturing” AND (“readiness model” OR “readiness assessment” OR “readiness index” OR “readiness framework”*) returned **17 results in Web of Science** and **60 results in Scopus**. Including “manufacturing” in the search was important because it excluded results from unrelated sectors, such as chemical, oil, or energy industries.

### *3.4 Maturity models*

The second search focused on models that assess how developed or advanced companies are in implementing Industry 4.0.The keywords used were *“Industry 4.0”*, *“manufacturing”*, *“maturity model”*, *“maturity index”*, *“maturity level”*, *“maturity framework”*, and *“maturity assessment”*.

The combined query (*“Industry 4.0” AND “manufacturing” AND (“maturity model” OR “maturity index” OR “maturity level” OR “maturity framework” OR “maturity assessment”*) returned **66 results in Web of Science** and **192 results in Scopus**.

### *3.5 Selection process*

After removing duplicates and screening abstracts, more than **90 publications and reports** were selected for closer review. This included peer-reviewed journal papers, conference proceedings, and professional frameworks developed by **research institutes or consultancy organisations** that proposed structured models for digital transformation in manufacturing.

From these, **43 readiness and maturity models** met the inclusion criteria:

- they directly addressed manufacturing readiness or maturity,
- they presented a clear methodological procedure, and
- they were published between 2010 and 2025 in recognised academic or institutional sources. Conceptual papers without methodological content and studies outside the manufacturing sector were excluded.

### *3.6 Analytical framework*

Each model was analysed to identify its structure, dimensions, and indicators. A structured extraction template was used to ensure consistency and allow comparison across studies. The template focused on several key elements that describe how each model was designed and applied:

**methodology** *(how the study was conducted and data collected)*, **model development and conceptual design** *(theoretical basis and structure of the model)*, **model validation** *(evidence of testing or practical application)*, **dimensions and sub-dimensions** *(main areas, factors, or indicators used in the model)*, **assessment method** *(how readiness or maturity was measured, for example through questionnaires or scoring systems)*, and **defined readiness or maturity levels** *(the number, names, and descriptions of levels used to classify companies)*. These fields captured both the conceptual structure and the practical application of each model, making it possible to identify common patterns and methodological differences. This systematic approach provided a comparable dataset for all reviewed publications, including those developed by research institutions and consultancy organisations. It ensured that the synthesis of results in Section 4 was based on consistent and verifiable information about how readiness and maturity were defined, measured, and validated in the literature. The analytical process was carried out in four main steps:

1. **Extraction of model characteristics**: identifying the dimensions, indicators, and validation methods presented in each model.
2. **Classification and grouping**: organising similar elements into thematic categories according to their conceptual focus.
3. **Aggregation of dimensions**: combining related categories into broader areas that describe the main transformation aspects.
4. **Interpretive synthesis**: comparing Industry 4.0-focused models with newer Industry 5.0-oriented models to identify overlaps and differences.

This structured analysis helped to identify recurring factors that appear in many models and to highlight less represented topics such as culture, resilience, and environmental sustainability. The results confirm that smart manufacturing includes not only technology but also people, organisation, and sustainability.

*3.7 Overview of selected models*

Among the most recognised and influential frameworks are the IMPULS Industry 4.0 Readiness Model (Lichtblau et al., 2015), Schumacher et al. (2016) Maturity Model, and the acatech Industrie 4.0 Maturity Index (Schuh et al., 2017). These models created the foundation for later approaches that integrate both technological and organisational aspects.Other notable examples include the DREAMY Model (de Carolis et al., 2017), the Digitalisation Maturity Model (Canetta et al., 2018), and the SM3E Model for SMEs (Mittal et al., 2018). Recent work, such as Hein-Pensel et al. (2025), expands maturity-model thinking toward *Industry 5.0* by including human-centric and sustainability-oriented dimensions. These models are discussed because they are methodologically clear, empirically tested, and widely recognised in the literature. While only several examples are mentioned here for illustration, the comparative analysis and aggregated framework presented in Section 4 are based on all **43 validated models**.

*3.8 Synthesis procedure*

The synthesis used dimensional mapping and cross-model comparison. Three levels of analysis were applied:

1. **Aggregate dimension**: broad thematic areas such as *Technology and Digitalisation*, *People and Culture*, *Governance and Organisation*, and *Sustainability and Resilience*.
2. **Dimension**: specific sub-areas within each aggregate dimension (for example, *Connectivity*, *Leadership*, *Process Management*).
3. **Reference source**: identification of the model or publication where each element was found.

Each dimension's occurrence across the models was recorded and compared to determine which factors appear most often. These recurring elements were interpreted as the main enablers of smart manufacturing. The aggregation also showed that cultural and environmental aspects were less represented in earlier models but are gaining importance in newer, Industry 5.0-oriented frameworks. The results of this synthesis are presented in the results section, which introduces the integrated dimensional structure of contemporary smart manufacturing.

## 4. Results: Comparative Model Analysis and Dimensional Synthesis

The analysis of 43 readiness and maturity models yielded a comprehensive overview of the dimensions most frequently used to evaluate the implementation of advanced manufacturing concepts. By aggregating and comparing these models, recurring themes were identified that collectively define the structure of contemporary smart manufacturing. Each model was decomposed into its constituent dimensions and indicators, which were subsequently grouped into higher-level aggregate dimensions. The number of appearances of each element across the reviewed models was recorded to determine its relative importance. This approach provides a quantitative foundation for understanding how the academic and industrial communities conceptualise the transformation toward smart manufacturing.

The analysed models span the period from 2010 to 2025, covering the evolution from early Industry 4.0 readiness frameworks to more comprehensive socio-technical maturity models. While the earliest studies were primarily technological in orientation, later publications increasingly introduced human, organisational, and sustainability elements. This chronological spread provides insight into how the notion of smart manufacturing has evolved from a narrow, technology-centred concept toward a balanced framework integrating digital, organisational, and human factors. The methodology adopted here enables a cross-model comparison that highlights both convergence—where dimensions appear consistently across the majority of models—and diversification, where new categories emerge to capture Industry 5.0 priorities such as resilience and sustainability.

Across the analysed literature, technological and digitalisation-related factors were the most common (32 of 43 models), followed by human and cultural (30) and operational and process-related aspects (29). Together, these form the core of smart-manufacturing assessment, highlighting the central role of the socio-technical interaction between people, processes, and technology.

Strategic and governance factors (23 and 22) appear less frequently but show their growing importance as enablers of transformation. In contrast, product and service dimensions (16), logistics and supply-chain aspects (10), financial and business models (9), environmental and data-related factors (8 each), and infrastructure and resilience (5) remain underrepresented. Overall, the distribution indicates a gradual shift from a narrow technological focus toward a more integrated, socio-technical, and sustainability-oriented perspective.

Another important trend observed is the shift in granularity and conceptual linkage between dimensions. Earlier frameworks, such as the IMPULS (VDMA) (Lichtblau et al., 2015) model and Schumacher et al.'s maturity framework (Schumacher et al., 2016), treated technology, operations, and organisation as separate evaluation areas. Newer models, including those by Canetta et al. (2018) and Colli et al. (2018), integrate these areas through hybrid dimensions that combine digital infrastructure with governance, leadership, or cultural readiness. This suggests that modern frameworks no longer consider digital transformation as a discrete technological event, but as an ongoing organisational capability requiring alignment across multiple domains.

Table 1 summarises the aggregated results. Each aggregate dimension represents a thematic category synthesised from multiple related dimensions. The second column indicates the number of occurrences across the 43 models, while the third column lists representative dimensions identified in the literature.

| **Aggregate Dimension** | **Frequency** | **Key Examples and Focus Areas** |
|---|---|---|
| Technology and Digitalisation | 32 | ICT infrastructure, connectivity, automation, data analytics, smart products, IoT integration, digital backbone, asset management, application management, Industry 4.0 awareness, smart manufacturing technology, digital transformation, cybersecurity, smart factory, cognitive functionality |
| Operations and Processes | 29 | Production management, quality management, maintenance, lean, process optimization, process transformation, product development, manufacturing operations, process organization, steering and control, design and engineering |

| | | |
|---|---|---|
| People and Culture | 30 | Human resources, skills and competence, training, culture of innovation, communication, intellectual capital, workforce management, employee engagement, people capability, social and institutional capability, maturity of HRM |
| Governance and Organisation | 22 | Organisational structure, change management, management systems, cross-functional coordination, governance, organisational alignment, leadership, organisational enablers, management and leadership strategies |
| Strategy and Leadership | 23 | Strategy formulation, leadership commitment, strategic governance, planning, vision alignment, business and organisation strategy, goals, strategy and organisation, strategy and culture, technology innovation decision making, managerial aspects |
| Products and Services | 16 | Product development, customer integration, smart services, data-driven value creation, product feedback, smart products, data governance, customer-centric product development, service innovation |
| Data and Information | 8 | Data management, big data, information flow, data transformation, intelligence, smartness, virtual world |
| Logistics and Supply Chain | 10 | Supply chain integration, material flow, logistics management, smart supply chain strategies, digital twins for logistics |

| | | |
|---|---|---|
| Finance and Business Model | 9 | Investment management, “cost-benefit” analysis, business model innovation, value capture, company resources, economic/financial situation, business processes |
| Infrastructure and Resilience | 5 | Infrastructure readiness, organisational resilience, operational continuity, structural operability |
| Environment | 8 | circular economy practices, CSR activities, stakeholder engagement, regulation, green subdimensions, knowledge, skills & attitude, government intervention, institutional collaboration |

Tab. 1. Aggregated dimensions of smart manufacturing and their frequency of occurrence.

The quantitative synthesis demonstrates that most frameworks continue to prioritise technological and operational enablers, confirming that digitalisation remains the backbone of industrial transformation. Nevertheless, a marked increase in the inclusion of human-centred, organisational, and sustainability-related dimensions signals the emergence of a broader understanding of what constitutes maturity in contemporary smart manufacturing. For example, dimensions such as *People and Culture* or *Governance and Organisation* were often absent in pre-2016 models but appear consistently after 2019, paralleling the conceptual rise of Industry 5.0 and the EU’s emphasis on human-centric innovation. Similarly, categories linked to *Environment and Sustainability* or *Infrastructure and Resilience* began to surface more frequently in post-2020 frameworks, particularly in models addressing supply-chain vulnerability and circular-economy strategies.

Several models illustrate this evolution in scope. The acatech Industrie 4.0 Maturity Index introduced cultural and organisational factors as prerequisites for technological advancement, while Sheen and Yang’s SME model integrated strategy and innovation culture as readiness indicators. More recent frameworks, such as the Digital Transformation Capability Maturity Model (DTCMM), further extend these ideas by coupling digital competence with environmental performance and workforce empowerment. This progression across models underscores a conceptual convergence toward balanced socio-technical systems in which technology, people, and organisational processes are interdependent rather than sequential.

The aggregated data also reveal that financial, environmental, and institutional factors remain under-represented, despite their recognised importance in achieving long-term industrial resilience.

This underlines a potential research and policy gap: while companies are investing in technology and process optimisation, corresponding mechanisms for sustainable financing, regulatory alignment, and external collaboration are less mature. Such gaps are particularly critical for small and medium-sized enterprises, which often lack the resources to develop comprehensive digital-sustainability strategies.

The comparative synthesis of 43 models confirms that technological excellence and operational performance continue to form the foundation of smart manufacturing maturity assessments. Yet, the increasing representation of human, organisational, and environmental dimensions reflects a paradigmatic transition toward a more holistic framework that integrates social responsibility and adaptive capacity alongside digitalisation. These results demonstrate that contemporary smart manufacturing is no longer defined solely by its technological sophistication but by its capacity to coordinate people, processes, and technology within sustainable and resilient organisational systems.

## 5. Discussion and Conclusions

The synthesis of forty-three readiness and maturity models reveals that contemporary smart manufacturing represents an evolutionary integration of technological innovation, human-centric design, sustainability, and resilience. The results confirm that the dominant focus of early Industry 4.0 frameworks—digitalisation, automation, and cyber-physical connectivity—has gradually expanded into a multidimensional paradigm that aligns with the emerging principles of Industry 5.0. This development reflects the shift from efficiency-driven digital transformation toward a holistic socio-technical system designed to achieve both competitive and societal value.

From a theoretical perspective, the findings substantiate the view that smart manufacturing acts as the connecting framework between Industry 4.0 and Industry 5.0. The technological foundations established under Industry 4.0—such as interoperability, data analytics, and automation—remain essential, but they no longer define maturity alone. Contemporary models increasingly interpret technological progress as an enabler rather than the ultimate objective of transformation. The integration of people, organisational learning, and environmental responsibility reflects the Industry 5.0 orientation, where competitiveness is balanced with human well-being and long-term sustainability. Smart manufacturing thus emerges not as a separate industrial revolution but as a comprehensive socio-technical ecosystem that absorbs and unifies the defining principles of both paradigms.

The growing inclusion of human and cultural dimensions in the analysed models underscores a renewed understanding of workers as central actors in digital ecosystems. Instead of replacing human decision-making, automation and artificial intelligence now serve to augment human capabilities: enhancing problem-solving, creativity, and adaptability. This transition from automation to augmentation mirrors the broader rehumanisation of production and supports the European Commission's definition of Industry 5.0 as a people-centred, sustainable, and resilient industrial paradigm.

The results also confirm that organisational culture and leadership play a decisive role in facilitating this integration. Leadership commitment, cross-functional collaboration, and openness to innovation are consistently cited across models as prerequisites for successful transformation, signalling that digital readiness depends as much on managerial orientation as on technological investment.

Equally important is the increasing visibility of sustainability and resilience within recent frameworks. Although these dimensions remain less frequent than technological or organisational factors, their rise after 2020 is consistent with post-pandemic industrial policies and global sustainability agendas. Resilience-related dimensions such as infrastructure robustness, supply-chain adaptability, and risk management now appear in nearly half of the models developed after 2021. This indicates that contemporary smart manufacturing maturity is not limited to process efficiency but extends to systemic agility—the ability to anticipate, absorb, and adapt to disruptions while maintaining operational continuity. Sustainability-oriented dimensions, though fewer in number, introduce environmental accountability and resource efficiency as maturity indicators, signifying that smart manufacturing contributes not only to digital competitiveness but also to the broader sustainability transition.

For small and medium-sized enterprises (SMEs), these insights carry important practical implications. The evidence shows that while SMEs tend to adopt digital technologies incrementally, many maturity models are still designed from the perspective of large corporations. As a result, they often overlook contextual constraints such as limited investment capacity, workforce digital skills, and dependence on external partners. The growing inclusion of cultural, organisational, and collaborative dimensions in newer frameworks provides a more accessible path for SMEs to evaluate readiness and identify achievable transformation priorities. A model that combines technology with people, strategy, and partnerships allows smaller firms to pursue scalable digitalisation rather than one-time technology adoption. This approach aligns with the European Commission’s SME strategy and with the findings from national productivity reports that highlight the need for gradual, structured digital maturity development rather than isolated investments.

Conceptually, the synthesis also contributes to the theoretical refinement of smart manufacturing maturity. The convergence of dimensions across independent models suggests the emergence of a shared ontology of industrial transformation. Dimensions such as technology, operations, organisation, people, and sustainability appear repeatedly across the literature, forming a common vocabulary for assessing digital and organisational capability. This convergence can serve as the foundation for developing integrated decision-making models that connect readiness assessment with strategic investment decisions—an idea further elaborated in the author’s doctoral research. By linking the structural and cultural aspects of transformation, such models can better guide organisations in balancing digital advancement with resilience and social responsibility. At the same time, certain limitations should be recognised. The frequency-based synthesis captures the conceptual emphasis of the literature but does not evaluate the relative performance or interdependencies between dimensions.

Moreover, the predominance of studies from technologically advanced economies means that the distribution of dimensions may not fully represent the challenges faced by developing regions or less digitally mature industries. Future research should therefore extend comparative analyses to cross-country contexts, integrate longitudinal data to track shifts in dimension weightings over time, and explore how maturity translates into measurable performance outcomes. In addition, the growing importance of artificial intelligence, data ethics, and responsible automation highlights the need for new maturity indicators that account for transparency, accountability, and societal impact.

In conclusion, the comparative analysis confirms that contemporary smart manufacturing represents a fusion of technological, organisational, human, and environmental systems. It unites the efficiency-driven logic of Industry 4.0 with the sustainability and human-centric orientation of Industry 5.0, forming an integrated socio-technical framework that defines the next stage of industrial evolution. The findings demonstrate that readiness and maturity are no longer defined solely by technological capability, but by an organisation’s ability to orchestrate people, processes, and technologies in a responsible, adaptive, and sustainable manner. Future research should therefore aim to empirically link these maturity dimensions with measurable outcomes such as productivity, innovation, and sustainability performance, and align them with evolving European initiatives like the Digital Decade and the Green Deal Industrial Plan. Strengthening the connection between theoretical frameworks and industrial practice would enhance both scientific and policy relevance, enabling more evidence-based transformation pathways. Such efforts could also support the creation of common European benchmarks that help companies of different sizes and sectors navigate the digital–sustainability transition. For both researchers and practitioners, this synthesis provides an empirically grounded understanding of how smart manufacturing can serve as a guiding model for resilient, competitive, and human-oriented industry development.

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