PRODUCTION ENGINEERING ARCHIVES 2026, 32(2), 262-277

PRODUCTION ENGINEERING ARCHIVES

ISSN 2353-5156 (print)
ISSN 2353-7779 (online)

Exist since 4th quarter 2013
Available online at https://pea-journal.eu

A Digital Sustainability Maturity Framework for Assessing Industry 4.0 and ESG Integration

Manuela Ingaldi[1*], Robert Ulewicz[1]

[1] Czestochowa University of Technology, ul. Dabrowskiego 69, 42-201 Czestochowa, Poland; manuela.ingaldi@pcz.pl (MI); robert.ulewicz@pcz.pl (RU)
*Correspondence: manuela.ingaldi@pcz.pl

Article history
Received 17.02.2026
Accepted 10.04.2026
Available online 11.05.2026

Keywords
Industry 4.0,
sustainability,
ESG,
organization maturity.

Abstract

The growing convergence of digital transformation and sustainability requirements necessitates the development of integrated analytical frameworks that enable the simultaneous assessment of an organization's technological maturity and its ESG maturity. Existing Industry 4.0 maturity models predominantly focus on technological aspects, while ESG frameworks emphasize reporting and regulatory compliance, often overlooking the organizational and technological conditions required to achieve higher levels of maturity. Although prior research provides growing evidence on the relationships between digital transformation and sustainability, it still lacks integrated frameworks that systematically combine technological maturity, organizational capabilities, ESG maturity, and sustainability performance outcomes within a single analytical structure. The aim of this article is to address this gap by proposing the Digital Sustainability Maturity Framework (DSMF), an integrated maturity model that combines Industry 4.0 maturity, digital enablement factors, ESG maturity, and sustainability performance outcomes within a coherent cause-and-effect structure. The model is based on hypothesized relationships that digital maturity influences the development of ESG maturity both directly and indirectly through organizational capabilities related to data management, digital competencies, and process integration. This article is conceptual and methodological in nature and proposes a theoretically grounded framework for future empirical validation. It develops a theoretical framework and proposes a structured measurement instrument intended for future empirical validation. Based on a literature review, the structure of the model and a set of research hypotheses describing the relationships between its key dimensions were developed. The DSMF model was subsequently operationalized in the form of a survey instrument designed to assess an organization's maturity level across four model dimensions. Conceptual validation and instrument development of the model was conducted, and a procedure for its empirical verification using Partial Least Squares Structural Equation Modeling (PLS-SEM) was outlined. The proposed model contributes to the literature by integrating the perspectives of digital transformation and sustainability within a single maturity framework, treating ESG maturity as a data-driven organizational capability supported by Industry 4.0 technologies. From a practical perspective, the DSMF is proposed as a potential diagnostic tool that may support managers in assessing the alignment between digitalization and ESG performance and in identifying areas requiring further development, subject to future empirical validation.

DOI: 10.30657/pea.2026.32.21

1. Introduction

Digital transformation and sustainability have become two of the most important paradigms shaping contemporary industrial development. Industry 4.0 technologies, such as the Internet of Things (IoT), cyber-physical systems, advanced data analytics, artificial intelligence, and collaborative robotics (cobots), enable organizations to achieve an unprecedented level of data integration, process automation, and real-time operational optimization (Marszałek-Kotzur, 2025; Awotunde et al., 2025; Agrawal & Nargund, 2024). In practice, these technologies not only enhance production efficiency, process flexibility, and responsiveness to adverse process changes, but also support the implementation of innovative business models and the design of products and services tailored to a dynamically changing market environment. Consequently, they constitute a key factor in enhancing the competitiveness and adaptability of enterprises under conditions of increasing environmental complexity.

At the same time, the importance of sustainability in organizational management is steadily increasing. Growing regulatory pressure, particularly reporting obligations arising from the Corporate Sustainability Reporting Directive (CSRD) and the European Sustainability Reporting Standards (ESRS), as well as stakeholder expectations and global environmental and social challenges, compel organizations to achieve higher levels of maturity in environmental, social, and governance (ESG) areas (Directive (EU) 2022/2464 of the European Parliament and of the Council) and ESRS standards (European Sustainability Reporting Standards). Companies are required not only to minimize the negative environmental impact of their operations, but also to implement socially responsible practices and ensure transparent and accountable corporate governance (Li, et al. 2021); Yoo & Managi, 2022). These challenges apply to both large corporations and small and medium-sized enterprises (SMEs), for which the integration of digital and ESG requirements is often particularly complex due to limited organizational and competency resources.

Despite the growing body of research, digitalization and sustainability are still largely treated as separate areas of analysis in the academic literature. Existing Industry 4.0 maturity and readiness models (e.g., the Industry 4.0 Maturity Index) primarily focus on technological and process capabilities, such as the level of automation, IT system integration, data utilization, and employees' digital competencies (Czerwińska, Pacana, 2022; Othen, et al. 2025; Ślusarczyk, 2025). In contrast, ESG frameworks predominantly emphasize the reporting of environmental, social, and governance aspects, often without directly addressing the technological and organizational conditions that enable the achievement of high levels of ESG maturity (Vijaya et al., 2026; Cahan et al., 2025; Blaber & Gougoumanova, 2024; Rosak-Szyrocka, 2025; Mazur & Ingaldi, M., 2025). As a result, organizations face difficulties in assessing whether and to what extent their level of digital maturity supports, constrains, or remains independent of their ESG performance.

In response to this gap, the aim of this article is to develop the Digital Sustainability Maturity Framework (DSMF), a conceptual model designed to assess the alignment between digital maturity in the context of Industry 4.0 and ESG maturity. The model integrates the perspectives of technology, organizational capabilities, and sustainability performance outcomes, enabling a systematic analysis of the relationships between digital transformation and the achievement of sustainability objectives.

The article also proposes a measurement instrument in the form of a survey based on the logic of maturity models, enabling the empirical assessment of the level of advancement of the analyzed enterprises across the DSMF dimensions. The application of a survey-based approach allows for the identification of gaps between technological potential, organizational capabilities, and achieved ESG outcomes, as well as for comparisons between enterprises at different stages of digital–sustainability transformation.

From a practical perspective, the DSMF may serve as a useful tool supporting strategic decision-making. It enables more informed planning of investments in digital technologies that support ESG objectives, optimization of processes towards efficient resource utilization, and the development of sustainable competitive advantage through the integration of technological innovation with responsible management. As a result, the proposed framework can serve both as a research tool and as a practical guide for organizations striving to harmonize digital transformation and sustainability.

It should be emphasized that this study adopts a conceptual and methodological approach. The proposed framework is not empirically validated at this stage; rather, it is designed as a theoretically grounded model and a basis for future empirical testing.

2. Literature review

Contemporary organizations are increasingly faced with the need to simultaneously manage digital transformation and the implementation of sustainability objectives (Rosak-Szyrocka& Knop, 2024). In order to effectively plan, monitor, and evaluate progress in these areas, both researchers and management practitioners employ various maturity models that enable the assessment of an organization's readiness to implement advanced technologies and to meet environmental, social, and governance (ESG) requirements.

Industry 4.0 maturity models primarily focus on technological and infrastructural aspects, such as process automation and robotization, integration of IT/OT systems, the use of data analytics, and the development of intelligent supply chains (da Rocha et al., 2020; Mendonca, et al., 2025; Dwivedy, et al., 2025; Sunder, et al. 2024; Boulitama, et al., 2025). In contrast, ESG and sustainability assessment frameworks mainly emphasize monitoring the impact of organizational activities on the environment, employee safety and well-being, as well as ensuring ethical, transparent, and regulation-compliant corporate governance (Cahan et al., 2025; Blaber & Gougoumanova, 2024; Hąbek, 2025; Bux, et al. 2025; Heldmann, et al., 2025).

Despite the extensive research interest in both digitalization and sustainability, existing models rarely account for the interdependencies between these domains. Digital readiness and maturity models focus on assessing technological potential, without systematically addressing their capacity to support ESG outcomes. Conversely, sustainability and ESG frameworks typically overlook the technological and organizational conditions necessary to achieve high levels of environmental and social performance. As a result, organizations lack a comprehensive tool that would enable the evaluation of synergies between digital maturity, ESG maturity, and sustainability performance outcomes.

A preliminary literature analysis conducted using the Scopus database and the VOSviewer tool confirms the fragmented nature of existing research in this area (Fig. 1). A search of the Scopus database using combinations of keywords such as maturity model, Industry 4.0, ESG, and sustainability (within titles, abstracts, and keywords) does not indicate the existence of a coherent, integrated maturity model combining digital transformation and ESG within a single conceptual framework. This finding confirms both the dispersion of existing studies and the lack of a unified approach integrating these two domains.

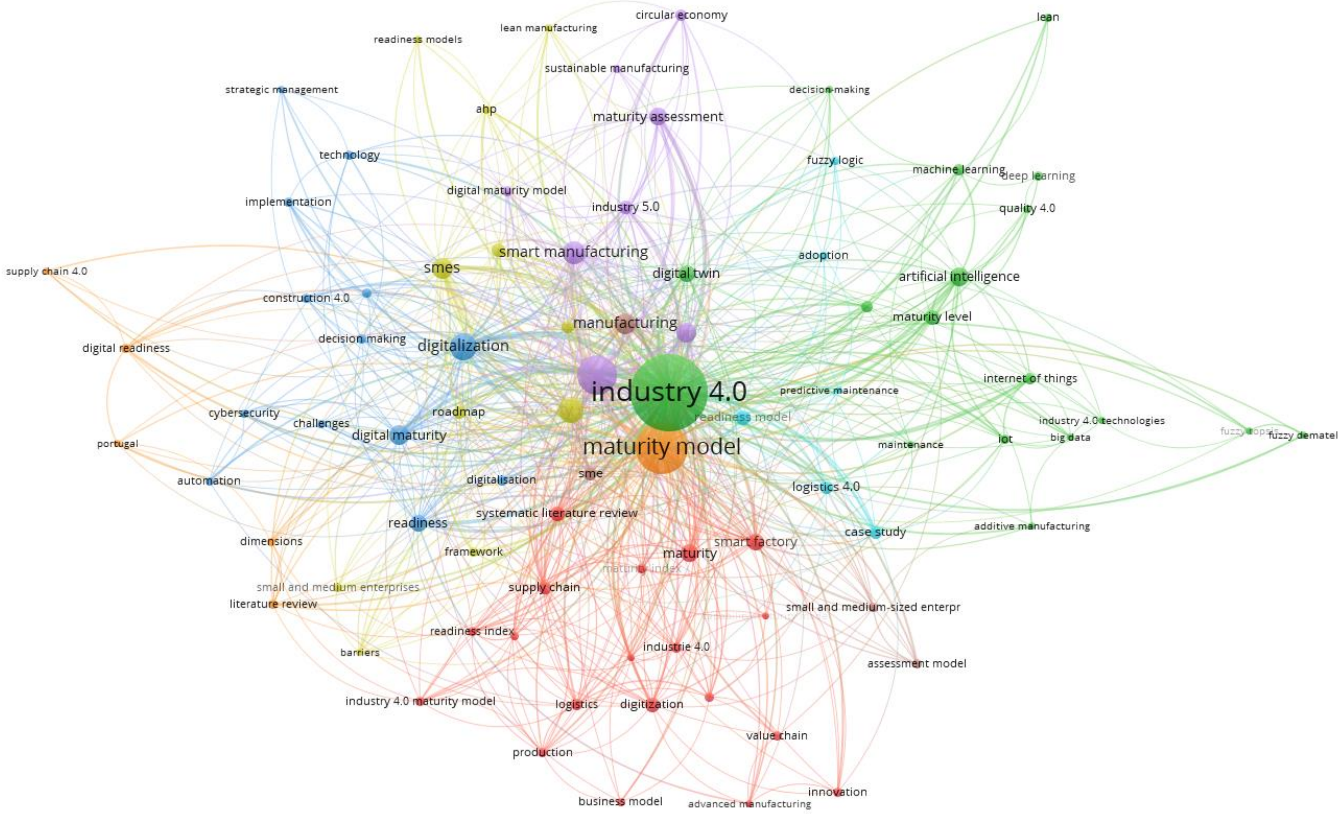


Fig. 1. VOSviewer – Scopus: "maturity model", "Industry 4.0", and "digital transformation" – over 800 publications (own elaboration based on bibliometric analysis using VOSviewer)

The following subsections present a review of existing Industry 4.0 maturity models, followed by frameworks and concepts related to ESG and sustainability maturity. Subsequently, studies attempting to integrate digital transformation and sustainability are discussed. This analysis leads to the identification of a clear research gap, which is addressed by the Digital Sustainability Maturity Framework (DSMF) proposed in this article.

2.1. Industry 4.0 Maturity Models and Digital Enablement Perspective

The literature offers numerous Industry 4.0 maturity and readiness models aimed at assessing the level of advancement of organizations in terms of digital transformation. These models primarily focus on the identification and measurement of technological and process capabilities that enable enterprises to implement the concept of smart manufacturing. The most frequently cited (da Rocha et al., 2020; Dwivedy, et al., 2025; Sunder, et al. 2024; Mendonca, et al., 2025; Othen, et al. 2025; Schuh, et al., 2019; Abate, et al., 2025; Binder, et al. 2025; Guimarães, et al. 2025; Sajjad et al., 2024; Durana et al., 2021) include the Industrie 4.0 Maturity Index developed by Acatech, the RAMI 4.0 reference model, as well as various commercial and academic digital maturity models proposed by consulting and research institutions.

Most existing Industry 4.0 maturity models encompass a similar set of assessment dimensions, such as process automation and robotization, the use of Internet of Things technologies and digital connectivity, real-time data integration, advanced analytics and artificial intelligence, integration of IT and OT systems, and digital supply chain integration. These models provide useful tools for diagnosing the level of digitalization of enterprises and their technological readiness to operate in an Industry 4.0 environment. However, it should be noted that this process does not occur uniformly across organizations. Difficulties in achieving higher levels of digital maturity often result from structural barriers, such as gaps in digital competencies and infrastructural limitations, which are particularly evident in the small and medium-sized enterprise (SME) sector (Ingaldi & Ulewicz, 2025). This perspective is consistent with prior research on the business value of digital technologies and dynamic capabilities.

At the same time, the literature indicates that dominant Industry 4.0 maturity models primarily focus on the technological dimension, treating technology as the main driver of organizational transformation. As a result, they rarely analyze the mechanisms through which technological capabilities translate into broader organizational outcomes, including sustainability performance. Environmental, social, and governance (ESG) aspects are either omitted or treated marginally in these models, and the relationship between digital maturity and sustainable organizational performance remains insufficiently explored.

In response to these limitations, it is increasingly emphasized that the mere availability of advanced Industry 4.0 technologies is not sufficient to generate sustainable organizational value. This distinction is consistent with recent research showing that the implementation gap in enterprise AI is driven not only by technology adoption itself, but also by deficiencies in strategic alignment, human capital readiness, and organizational integration capabilities (Sira, 2025). From the perspective of dynamic capabilities theory and research on the business value of information technologies, digital transformation yields results only when supported by complementary organizational capabilities. These include, among others, formal data governance and data quality management practices, employees' digital competencies, a data-driven organizational culture, integration of IT and operational processes, and an adequate level of cybersecurity.

The literature increasingly highlights the distinction between technological Industry 4.0 maturity and the capabilities enabling the effective use of digital technologies. Industry 4.0 maturity primarily refers to the scope and advancement of implemented technological solutions, whereas digital enablement factors describe the organizational, competency-based, and managerial conditions for their effective utilization. These factors act as mediating mechanisms between technology and organizational outcomes, enabling the transformation of technological potential into tangible operational and strategic effects.

Such an approach allows moving beyond a reductionist view of Industry 4.0 as merely a set of technologies and provides a foundation for further considerations on the role of digitalization in building ESG maturity and achieving sustainability performance outcomes, as reflected in the structure of the proposed Digital Sustainability Maturity Framework.

2.2. ESG and Sustainability Maturity Models

In recent years, issues related to ESG (Environmental, Social, Governance) have gained significant importance both in academic research and in management practice, primarily due to increasing regulatory pressure, stakeholder expectations, and global environmental and social challenges (Kucęba, 2025; Tancke, et al., 2023; Habek, 2025; Vijaya et al., 2026). In response to these conditions, numerous ESG reporting frameworks and standards have been developed, such as GRI, SASB, MSCI ESG Score, and the most recent European Sustainability Reporting Standards (ESRS), implemented under the Corporate Sustainability Reporting Directive (CSRD).

Dominant ESG frameworks primarily focus on the measurement and disclosure of information related to an organization's environmental impact (e.g., emissions, energy consumption, waste management), social aspects (e.g., occupational safety, employee well-being, equality), and governance elements, such as ethics, transparency, and risk management. In this approach, ESG is often treated as a set of reporting indicators, the main purpose of which is to ensure regulatory compliance and to meet stakeholders' information requirements.

However, the literature increasingly emphasizes the need to distinguish between ESG reporting and ESG maturity understood as a systematic organizational capability. ESG maturity refers not only to the scope of disclosed data, but above all to the degree of integration of environmental, social, and governance aspects into decision-making processes, organizational strategy, and day-to-day operations. In this perspective, key elements include data quality and reliability, transparency of decision-making processes, consistency of actions with applicable regulations, and the ability to manage ESG risks in an active and proactive manner.

The concept of data-driven sustainability is also gaining increasing attention in the literature, indicating that effective ESG management requires access to up-to-date, integrated, and comparable data that enable monitoring, analysis, and decision-making in near real time. Despite this, most existing ESG frameworks do not systematically consider the technological and organizational conditions that enable the achievement of higher levels of ESG maturity. Digital technologies and the organizational capabilities related to their use remain largely outside the scope of analysis in these models.

Consequently, although numerous tools are available for assessing ESG performance and disclosure levels, there is a lack of approaches that treat ESG as a dynamic organizational capability linked to digital transformation, the development of technological competencies, and the ability to leverage data in management processes. This limitation constitutes an important starting point for further considerations on the integration of digital maturity and ESG within a coherent analytical model.

2.3. Integrating Digital Transformation and ESG

In recent years, an increasing number of studies have examined the relationships between digital transformation and organizational sustainability. Authors indicate that Industry 4.0 technologies can serve as a significant tool to support the achievement of environmental, social, and governance objectives. The literature emphasizes (Hien, et al., 2026; Zhao, et al., 2026; Wu, et al., 2026; Sun, et al., 2026; Dung, et al. 2026), in particular, the potential of digital technologies to improve resource efficiency, increase process transparency, and mitigate operational and regulatory risks.

Empirical research shows that the application of Internet of Things (IoT) technologies and sensor systems enables real-time monitoring of energy consumption, emissions, and waste, contributing to the reduction of resource losses and improving environmental efficiency. Advanced data analytics and artificial intelligence-based solutions support demand forecasting, production process optimization, and data-driven decision-making, leading to improvements in both economic and environmental outcomes.

The literature also highlights the role of digital twins and simulation tools in analyzing the environmental impact of industrial processes and designing more sustainable production solutions. Automation and robotics, in turn, are recognized as factors that enhance workplace safety, improve ergonomics, and reduce employees' exposure to hazards, directly contributing to the social dimension of sustainability.

Increasing attention is also being paid to the significance of digital technologies for corporate governance, particularly in terms of enhancing transparency in decision-making processes, improving the quality of non-financial reporting, ensuring regulatory compliance, and managing risks. Information systems that support data integration, process auditability, and internal control are identified as key enablers for effective ESG management. This perspective is further supported by recent evidence showing that sustainability-oriented operational practices do not always translate into performance through simple direct paths, but may depend on mediating organizational mechanisms such as resilience (Songkhwan et al., 2025).

Despite the growing body of research confirming the potential of digital technologies in the ESG domain, most studies focus on selected technologies or individual dimensions of sustainability. The relationships between digital transformation, organizational capabilities, and systematic ESG management are analyzed in a fragmented manner, often without clear reference to organizational maturity levels and without a coherent analytical structure enabling their joint assessment.

Building upon these insights, ESG maturity can also be viewed as a direct driver of sustainable performance outcomes. Mature ESG systems enhance resource efficiency, improve employee well-being, and strengthen organizational resilience and regulatory compliance. The integration of digital technologies with management systems enables a significant improvement in occupational safety indicators, forming a foundation of the social pillar of ESG. Empirical evidence suggests that the systematic implementation of optimization tools, such as 5S and work standardization, positively affects employee attitudes and reduces operational risk (Sá et al., 2025).

These observations indicate that ESG should not be treated solely as a reporting or compliance framework, but rather as a data-driven managerial capability that translates into measurable organizational outcomes.

2.4. Research Gap Identification

The literature review indicates that while advanced Industry 4.0 maturity models, numerous ESG frameworks and standards, and a growing body of research analyzing the relationships between digital technologies and sustainability exist, there is a lack of an integrated approach. Specifically, no framework enables the simultaneous assessment of an organization's technological maturity, the organizational capabilities required for effective use of digital technologies, ESG maturity, and the actual outcomes of sustainable organizational performance.

Despite the growing body of literature on Industry 4.0 maturity models and ESG performance, existing research remains fragmented. Classical maturity models, such as those proposed by Schumacher et al. (2016) and Bibby and Dehe (2019), primarily focus on assessing technological and organizational readiness for digital transformation. More recent approaches, such as Zoubek et al. (2021), begin to incorporate environmental aspects into maturity assessment, indicating a gradual shift towards sustainability-oriented perspectives.

At the same time, empirical studies increasingly confirm the positive relationship between digital transformation and ESG performance. For example, Chen and Wang (2024) and Liu and Wang (2025) demonstrate that digital transformation significantly enhances ESG outcomes and innovation capabilities, while Marczewska et al. (2025) provide evidence that digitalization contributes to sustainable performance in European enterprises. Furthermore, recent research highlights the growing importance of integrated ESG data systems and interoperability in sustainability governance (Vijaya et al., 2026), as well as the specific challenges faced by SMEs in implementing ESG practices (Steidle et al., 2025).

However, despite these advances, the literature still lacks a unified analytical framework that systematically integrates Industry 4.0 maturity, digital enablement capabilities, ESG maturity, and measurable sustainability performance outcomes within a single cause-and-effect structure. Existing studies tend to analyze these relationships separately or focus on selected dimensions, without providing a comprehensive diagnostic architecture.

Existing Industry 4.0 maturity models primarily focus on technological and process-related aspects, without systematically considering environmental, social, and governance dimensions. Conversely, ESG frameworks mainly emphasize reporting, disclosure, and regulatory compliance, overlooking the technological and organizational conditions necessary to achieve higher levels of ESG maturity. Moreover, prior research rarely examines the synergistic effects between digital maturity and ESG in terms of measurable sustainability outcomes, such as resource efficiency, workplace safety, or management transparency.

The absence of such an integrated perspective hinders both researchers and practitioners from assessing whether and to what extent investments in Industry 4.0 technologies support the achievement of sustainability goals or remain weakly aligned with them. Consequently, organizations make decisions regarding digital transformation and ESG in a fragmented manner, without tools that allow for a holistic evaluation of their interdependencies.

To synthetically illustrate the scope and limitations of existing Industry 4.0 maturity models and ESG frameworks, Table 1 presents a comparison of selected, most frequently cited approaches applied in the literature and practice.

Table 1. Comparison of Selected Industry 4.0 and ESG Maturity Frameworks (own elaboration based on Cahan et al., 2025; Blaber & Gougoumanova, 2024; Hąbek, 2025; Bux, et al. 2025; Heldmann, et al., 2025; Kagermann, et al., 2016; Hassanpourroudbeneh & Zangeneh, 2026; Steidle, e al., 2025; da Rocha et al., 2020; Dwivedy, et al., 2025; Sunder, et al. 2024; Mendonca, et al., 2025; Othen, et al. 2025; Schuh, et al., 2019; Abate, et al., 2025; Binder, et al. 2025; Guimarães, et al. 2025; Sajjad et al., 2024; Durana et al., 2021)

Model	Type	Scope	Strengths	Limitations
IMPULS Industry 4.0 Readiness	I4.0	6 maturity dimensions	Practical, widely used	No link to ESG
ACATECH Maturity Index	I4.0	4 phases of digitalization	Strong theoretical foundation	Complex, mainly for large enterprises
PwC Digital Operations Maturity	I4.0	Operational transformation	Useful for benchmarking	Lacks social dimension
Deloitte Smart Factory Model	I4.0	Process integration	Modern, holistic	No environmental linkage
GRI Standards	ESG	Environmental and social disclosures	Most globally recognized standard	Does not assess digital maturity
SASB Standards	ESG	Industry-specific ESG metrics	High sectoral relevance	Less popular in Europe
CSRD/ESRS	ESG	Mandatory EU reporting	Comprehensive, regulatory	Burden for SMEs
MSCI ESG Score	ESG	Company evaluation metrics	External comparability	No digital methodology included

The comparative analysis presented in Table X confirms the fragmented nature of existing approaches to assessing organizational maturity. Industry 4.0 models primarily focus on technological and operational dimensions, without addressing environmental, social, and governance aspects. Conversely, ESG frameworks and reporting standards concentrate on disclosure and regulatory compliance, overlooking the technological and organizational capabilities necessary to achieve higher levels of ESG maturity.

Moreover, even sustainability-oriented approaches do not provide a coherent framework that integrates digital maturity, digital enablement factors, and measurable sustainability outcomes. This highlights a clear research gap in the development of systemic maturity models that link digital transformation with ESG.

The identified research gap justifies the need for the development of the Digital Sustainability Maturity Framework (DSMF), which integrates four levels: Industry 4.0 maturity, digital enablement factors, ESG maturity, and organizational sustainability outcomes. This framework creates a coherent analytical structure for the systematic assessment of the relationships between digital transformation and sustainability, providing a foundation for further empirical validation.

Existing studies and maturity models address selected aspects of digital transformation, sustainability, or ESG assessment; however, they rarely integrate technological maturity, organizational digital capabilities, ESG maturity, and measurable sustainability outcomes within one coherent maturity-based analytical structure. Therefore, the gap addressed in this article concerns not the absence of all related approaches, but the lack of a unified framework that operationalizes these dimensions jointly and links them through an explicit causal logic.

The contribution of this study does not lie in identifying the relationship between digital transformation and ESG, which has already been empirically confirmed, but in proposing an integrated maturity-based framework that enables a systemic assessment of these interdependencies and provides a foundation for future empirical validation.

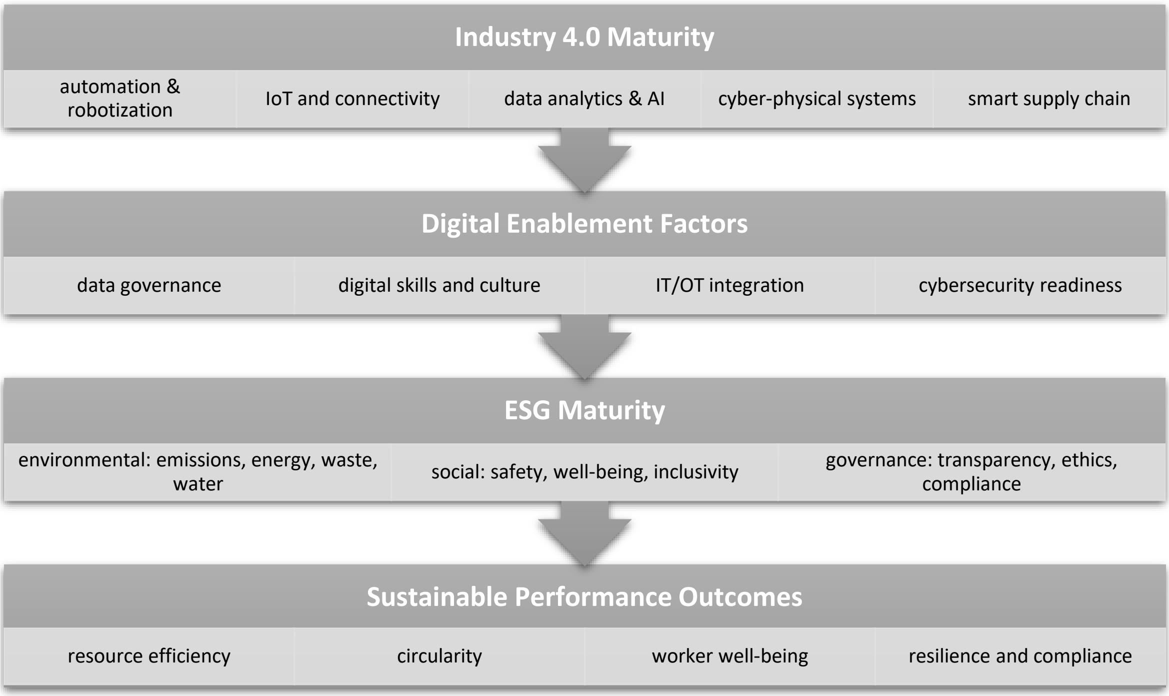
3. Proposal of the Digital Sustainability Maturity Framework (DSMF)

The proposed Digital Sustainability Maturity Framework (DSMF) integrates Industry 4.0 technology maturity, digital enablement factors, ESG maturity, and organizational sustainability outcomes into a coherent cause-and-effect structure. The model is systemic and exploratory in nature, based on the assumption that digital transformation serves as a key mechanism enabling the effective implementation of sustainability practices and the achievement of lasting organizational outcomes.

The proposed model integrates two domains: digital maturity (Industry 4.0) and sustainability maturity (ESG). It consists of four layers (Fig. 2):

1. Industry 4.0 Maturity,
2. Digital Enablement Factors,
3. ESG Maturity,
4. Sustainable Performance Outcomes.

This concept assumes that greater digital maturity translates into greater ESG maturity and leads to better performance.



Rys. 2. Digital Sustainability Maturity Framework (DSMF) (own elaboration)

In contrast to many ESG frameworks, this study deliberately excludes risk management from governance capabilities. In conventional ESG frameworks, risk management is typically treated as a governance capability. In the present study, however, it is conceptualized as part of sustainable performance outcomes, as the focus is placed on the observable organizational effects of digital and ESG integration, such as resilience, regulatory responsiveness, and the effectiveness of risk mitigation. This conceptual choice reflects the outcome-oriented logic of the proposed model and should be interpreted as model-specific and analytical, rather than as a general redefinition of governance within ESG research.

It should be noted that risk management is conceptualized here as a component of sustainable performance outcomes, reflecting organizational resilience and regulatory compliance enabled by Industry 4.0 and ESG maturity, rather than as an element of governance capability. This approach differs from traditional ESG frameworks, where risk is typically treated as a governance capability.

In the first stage, the DSMF model assumes that Industry 4.0 maturity, encompassing process automation and robotics, the use of Internet of Things (IoT) technologies, real-time data availability, data analytics and artificial intelligence, cyber-physical systems integration, and digital supply chain integration, constitutes the technological foundation for organizational transformation. These elements reflect the level of sophistication of technological solutions implemented in the organization, independent of the organizational capabilities required to leverage them effectively.

At the second level, the DSMF identifies Digital Enablement Factors, which serve as a bridge between Industry 4.0 technological maturity and the organization's capacity to effectively implement ESG practices. These factors include data governance, digital skills and organizational culture, IT/OT process integration at the organizational level, and cybersecurity readiness. They reflect not the technological sophistication itself, but the organization's ability to consciously, safely, and coherently utilize digital technologies in decision-making and operational processes. Digital Enablement Factors are conceptualized as organizational capabilities rather than technological assets.

In this study, Digital Enablement Factors are conceptualized as organizational capabilities that enable the effective and consistent use of Industry 4.0 technologies.

Within Industry 4.0 maturity, IT/OT integration represents the technological infrastructure, whereas in Digital Enablement Factors it captures the organizational capability to manage and align digital and operational processes.

In the next stage, the DSMF model assumes that both Digital Enablement Factors and Industry 4.0 maturity support the development of ESG maturity, understood as the organization's capability to systematically and integratively manage environmental, social, and governance aspects based on reliable data, transparency, and regulatory compliance. The model allows for both indirect and direct effects of Industry 4.0 maturity on ESG maturity, indicating a partially mediated relationship between digital transformation and sustainability.

The final level of the DSMF model comprises organizational sustainability outcomes, treated as the results of the synergy between Industry 4.0 maturity and ESG, rather than as additional maturity levels. These outcomes include resource efficiency, process circularity, employee well-being, and organizational resilience and regulatory compliance. Conceptualizing outcomes as the terminal component of the model allows for an assessment of the tangible effects of digital transformation and ESG implementation, emphasizing their complementary and mutually reinforcing nature.

The proposed model includes both direct and indirect relationships, enabling the assessment of partial mediation effects between constructs.

The causal logic of the DSMF model is based on the sequence:

Digital Capabilities → ESG Capabilities → Sustainable Performance Outcomes

where both Industry 4.0 maturity and Digital Enablement Factors (DEF) can exert direct and indirect effects on sustainable performance outcomes.

Hypotheses of the model:

H1: Industry 4.0 → Digital Enablement: Industry 4.0 maturity positively influences digital enablement factors.
Rationale: Automation, IoT, and system integration drive the development of data governance, digital skills, and cybersecurity.
Path: I4.0 → DEF

H2: Digital Enablement → ESG Maturity: Digital enablement factors positively influence ESG maturity.
Rationale: Without data governance, digital skills, and IT/OT integration, organizations lack:

- reliable ESG data,
- transparency,
- compliance.

Path: DEF → ESG

H3: Industry 4.0 → ESG Maturity (direct): Industry 4.0 maturity has a direct positive effect on ESG maturity.
Rationale: IoT, analytics, and automation enable:

- measurement of emissions, energy, and occupational safety,
- governance supported by real-time data.

This represents partial mediation of the I4.0 → ESG relationship through DEF.
Path: I4.0 → ESG

H4: ESG Maturity → Sustainable Performance Outcomes: ESG maturity positively influences sustainable performance outcomes.
Rationale: Mature ESG capabilities:

- improve resource efficiency,
- enhance employee well-being,
- strengthen organizational resilience and regulatory compliance.

Note: risk management is treated as an outcome rather than a governance capability.
Path: ESG → SPO

H5: Digital Enablement → Sustainable Performance Outcomes: Digital enablement factors positively influence sustainable performance outcomes.
Rationale: Data governance, digital skills, and cybersecurity:

- reduce reaction time,
- improve decision-making,
- increase organizational resilience.

Path: DEF → SPO

H6: Industry 4.0 → Sustainable Performance Outcomes: Industry 4.0 maturity positively influences sustainable performance outcomes.
Rationale: Some effects (e.g., resource efficiency, occupational safety) result directly from technology, independently of formal ESG practices.
This completes the model as a partial mediation framework.
Path: I4.0 → SPO

Summary of hypothesized relationships:
H1: I4.0 → DEF
H2: DEF → ESG
H3: I4.0 → ESG
H4: ESG → SPO
H5: DEF → SPO
H6: I4.0 → SPO

The final arrangement is presented in Figure 3.

Fig. 3 Causal logic of the DSMF model (own elaboration)

The structural model assumes that Industry 4.0 maturity influences Digital Enablement Factors, which in turn affect ESG maturity. ESG maturity acts as a key driver of sustainable performance outcomes. Additionally, Industry 4.0 maturity and Digital Enablement Factors exert both direct and indirect effects on sustainable performance, resulting in a partially mediated model.

The proposed DSMF model has been operationalized in the form of a survey instrument designed to assess the level of organizational maturity across the different areas of the model. The survey is intended not only to identify the presence of selected technological solutions or managerial practices but also to capture their level of advancement and consistency in the context of the organization's overall functioning (Appendices 1 and 2). The instrument was developed based on the theoretical foundations discussed in Chapters 2 and 3, particularly the concept of Industry 4.0 maturity, ESG maturity frameworks, and Digital Enablement Factors embedded in the DSMF model.

The questionnaire is intended to allow for a systematic evaluation of organizational maturity in four dimensions of the model: Industry 4.0 technological maturity, Digital Enablement Factors, ESG maturity, and sustainable performance outcomes. The maturity-based approach assumes that organizations may be at different stages of development in each of these areas, and advancing to a higher level of maturity requires not only technology adoption but also the development of relevant organizational capabilities and the integration of sustainable management practices.

The survey instrument combines items adapted from established maturity model and ESG literature with items developed specifically for the DSMF context. The adaptation process was guided by the need to ensure consistency with existing theoretical constructs while capturing the specific relationships embedded in the proposed framework. At the same time, several items were developed by the authors to reflect the integration between digitalization and ESG, which is not sufficiently represented in existing instruments.

Each item was selected to represent an observable manifestation of the intended construct, while avoiding the mere declaration of policy existence. The questionnaire focuses on the actual implementation and operational use of technologies and practices rather than formal compliance or strategic declarations. The seven-point Likert scale (1–7) was adopted due to its widespread use in organizational and maturity model research, as it provides an appropriate balance between measurement sensitivity and respondent cognitive load. Compared to shorter scales, it allows for finer differentiation of maturity levels, which is particularly important when assessing complex and multi-dimensional constructs such as digital capabilities and ESG maturity. At the same time, it avoids excessive granularity that could reduce response reliability.

The scale is interpreted as reflecting the intensity and consistency of implementation, ranging from very low or nonexistent practices (1) to fully implemented and systematically integrated practices (7). Although the scale follows established methodological standards, formal cognitive pre-testing of the instrument constitutes a direction for future research.

The seven maturity levels should be interpreted as an analytical progression describing increasing integration between digitalization and sustainability. The structure of seven levels was adopted to reflect a gradual transition from ad hoc and fragmented practices to fully integrated, data-driven and autonomous organizational systems, in line with the logic of existing maturity models.

At the current stage, these levels are conceptual and descriptive rather than empirically calibrated. Their future operational use will require the development of explicit scoring rules and threshold criteria based on empirical data. Therefore, the proposed maturity levels should be treated as a theoretical framework supporting interpretation, rather than as a finalized measurement scale.

In the survey instrument tables, the column labeled "Theoretical Basis" refers to the conceptual justification of each indicator and its linkage to the underlying construct, as derived from the literature on Industry 4.0 maturity, digital capabilities, and ESG frameworks. It does not refer to the assessment process within the enterprise, but rather to the theoretical grounding that supports the inclusion of a given item in the measurement model.

This column reflects the alignment of each indicator with established research streams, ensuring content validity of the instrument, rather than indicating a single direct source or empirical reference.

Using the survey enables a self-assessment of the organization from the perspective of individuals with knowledge of technological, organizational, and managerial processes. Respondents evaluate the level of advancement of individual elements of the model based on the current state of the organization rather than declared plans or aspirations. This approach allows capturing the actual level of organizational maturity in the assessed areas.

The questionnaire also serves as a comparative tool, allowing for the analysis of differences between organizations and the identification of characteristic maturity profiles. The collected data enable the examination of relationships between technological maturity, organizational capabilities, ESG maturity, and sustainable performance outcomes, providing a foundation for the empirical validation of the proposed research model.

Additionally, the survey helps identify areas requiring further development, highlighting potential gaps between technology implementation and the organization's ability to effectively leverage these technologies in the context of sustainability. In this sense, the questionnaire can serve not only as a research tool but also as a reference point for practitioners interested in diagnosing the maturity level of their organizations.

The adopted survey format is consistent with the prevailing approach in maturity model research within digital transformation, where organizational self-assessment is a recognized method for measuring the advancement of complex organizational constructs. At the same time, the design of the instrument enables further empirical validation of the DSMF model using structural equation modeling (SEM) methods, allowing for the assessment of relationships between individual dimensions of maturity.

The proposed model structure allows for empirical verification both at the level of measuring individual constructs and at the level of causal relationships between them, using SEM techniques.

4. Conceptual verification and future empirical validation

The term "validation" used in this study should be interpreted as conceptual and content-oriented rather than as formal statistical or expert-based validation. No structured expert panel, Delphi procedure, or quantitative content validity indices (e.g., CVI or Lawshe's method) were applied at this stage. The primary objective of this phase was to ensure internal conceptual consistency and alignment with existing theoretical constructs, while full empirical validation is planned as a subsequent stage of the research.

Due to the conceptual and methodological nature of this study, the validation of the DSMF is limited to conceptual validation and the development of a procedure for future empirical verification. No statistical empirical validation has been conducted at this stage.

The validation of the Digital Sustainability Maturity Framework (DSMF) was designed as a multi-stage process, encompassing both the assessment of the conceptual soundness of the proposed model and the development of a procedure for its future empirical verification. Due to the conceptual and methodological nature of this article, the analysis focused on conceptual validation of the model and the construction of the measurement instrument, while statistical empirical validation represents the next stage of the planned research.

4.1. Conceptual validation of the Model and Survey Design

The first stage in validating the DSMF involved conceptual validation, aimed at confirming that the proposed theoretical constructs and their corresponding survey indicators adequately reflect the assumptions of the model and are consistent with the current state of scientific knowledge. To this end, an analysis was conducted to assess the alignment between the structure of the DSMF, the literature review findings, and the survey items.

The model constructs were defined based on recognized Industry 4.0 maturity models, ESG frameworks, and the literature on organizational capabilities and the business value of digital technologies. Each construct was subsequently operationalized through a set of survey indicators designed to measure the level of organizational maturity, rather than merely the declarative presence of technological solutions or formal procedures.

Particular attention was paid to separating the technological layer (Industry 4.0 Maturity) from the organizational capability layer (Digital Enablement Factors), which helped avoid construct overlap and ensured the logical consistency of the model. Similarly, ESG maturity was defined as a systematic managerial capability based on data, transparency, and regulatory compliance, whereas elements such as risk management and regulatory compliance were conceptualized as components of sustainable performance outcomes, rather than as separate governance capabilities. In line with the adopted conceptualization, Digital Enablement Factors were operationalized as organizational capabilities rather than technological assets, ensuring clear discriminant validity between constructs.

The conducted conceptual validation confirmed the alignment between the theoretical assumptions of the DSMF and the structure of the designed questionnaire, providing a foundation for the subsequent empirical verification of the proposed causal relationships.

4.2. Planned Empirical Validation of the Model

The next stage of the research will involve empirical validation of the DSMF using survey data collected via the CAWI method from representatives of industrial enterprises. Respondents will be individuals with knowledge of the technological, organizational, and ESG-related processes operating within the surveyed organizations.

Structural Equation Modeling (SEM) using the Partial Least Squares approach (PLS-SEM) is planned for data analysis. This method is particularly suitable for exploratory models, complex causal structures, and the presence of higher-order constructs. PLS-SEM enables the simultaneous assessment of the measurement model quality and the structural relationships between constructs.

Empirical validation will include the evaluation of reliability and validity of the measurement model, including internal consistency (Cronbach's alpha, composite reliability), convergent validity (AVE), and discriminant validity (Fornell–Larcker criterion and HTMT ratio). Additionally, multicollinearity analysis (VIF) and assessment of the significance of structural paths using a bootstrapping procedure will be performed.

Hypotheses H1–H6 will be tested to empirically assess both direct and indirect relationships between Industry 4.0 maturity, digital enablement factors, ESG maturity, and sustainable performance outcomes. Special emphasis will be placed on analyzing mediating effects, allowing the evaluation of digital transformation as a mechanism supporting the achievement of sustainable development outcomes.

5. Discussion

This study contributes to the literature by proposing an integrated maturity-based framework that combines Industry 4.0 maturity, digital enablement capabilities, ESG maturity, and sustainability performance outcomes within a unified analytical structure.

An important conceptual contribution of the DSMF is the treatment of risk as a measurable outcome rather than a governance capability. This perspective reflects organizational resilience and the ability to respond to dynamic environmental and regulatory conditions.

In conventional ESG frameworks, risk management is typically treated as a governance capability. In the present study, however, it is conceptualized as part of sustainable performance outcomes, as the focus is placed on observable organizational effects such as resilience, regulatory responsiveness, and the effectiveness of risk mitigation. This distinction reflects the outcome-oriented logic of the model and should be interpreted as analytical rather than as a general redefinition of ESG governance.

The aim of this section is to position the proposed Digital Sustainability Maturity Framework (DSMF) within the context of existing maturity models and conceptual frameworks related to digital transformation and sustainable development. The literature features numerous approaches for assessing organizational digital maturity as well as frameworks for measuring ESG performance, yet these are rarely analyzed together within a single, coherent analytical scheme. In response to this gap, the DSMF proposes an integrated perspective on the relationships between Industry 4.0 maturity, organizational capabilities enabling digitalization, ESG maturity, and sustainable performance outcomes.

For a synthetic comparison of the proposed DSMF with selected Industry 4.0 maturity models and ESG frameworks, Table 2 presents the key criteria differentiating the scope, underlying logic, and assessment methods of each approach.

Table 2. Comparison of DSMF with Existing Industry 4.0 and ESG Maturity Models (own elaboration based on Cahan et al., 2025; Blaber & Gougoumanova, 2024; Hąbek, 2025; Bux, et al. 2025; Heldmann, et al., 2025; Kagermann, et al., 2016; Hassanpourroudbeneh & Zangeneh, 2026; Steidle, e al., 2025)

Criterion	DSMF (proposed)	IMPULS (I4.0)	ACATECH (I4.0)	GRI / ESRS / CSRD (ESG)
Main objective	Integrated assessment of digital and sustainable maturity (I4.0 + ESG).	Assessment of enterprise readiness for Industry 4.0.	Assessment of the degree of digital transformation and system integration.	Standardization of ESG reporting and non-financial disclosures.
Scope	Technology + data management + ESG + environmental and social outcomes.	Processes, technologies, data, and organization (excluding ESG).	Infrastructure, organization, systems, people (excluding ESG).	Emissions, energy, waste, people, ethics, governance (excluding technology).
Number of domains	4 (I4.0, Digital Enablement, ESG, Sustainable Performance).	6 domains (e.g., strategy, production, IT, products).	3 main levels (resources – processes – systems).	E (environmental), S (social), G (governance).
Maturity levels	7 levels (Ad hoc → Smart Sustainable Enterprise).	6 levels (0–5).	6 levels (Level 1–6).	No levels — reporting standards, not a maturity model.
Integration of I4.0 and ESG	Full integration (maturity alignment).	No integration with ESG.	No integration with ESG.	No integration with I4.0 technologies.
Data orientation	Operational + environmental + social + governance data (full synergy).	Operational and process data; weak integration with other data types.	Digital and process data; ESG context missing.	ESG data (emissions, environmental, social); no technological data.
Analytics levels	Up to AI, digital twins, and ESG prediction.	Up to data integration and automation (excluding ESG).	Advanced technologies, but no sustainability component.	ESG reporting and analysis, but no process analytics or AI.
Assessment method	Questionnaire + SEM/cluster analysis (proposed study).	IMPULS questionnaire.	Audit based on infrastructure and processes.	Indicators and disclosures (E1–E5, S1–S4, G1–G4).
Outcome	Assessment of Digital × ESG alignment and identification of maturity profile.	Assessment of digital readiness for I4.0.	Assessment of technological transformation.	Compliance with reporting requirements.
Uniqueness	The only model integrating I4.0 and ESG in a coherent maturity framework.	Primarily a technology-focused model.	Technical-organizational model.	Reporting standard, not a transformation model.

The comparison results reveal fundamental differences between DSMF and existing models, which require deeper interpretation. Unlike classical Industry 4.0 maturity models, such as IMPULS or the Industrie 4.0 Maturity Index (acatech), which primarily focus on the implementation level of digital technologies and the technical readiness of organizations, DSMF extends the analytical perspective to include digital enablement factors and ESG maturity. This shift moves the focus from the question "Which technologies are implemented?" to "How are technologies utilized to generate sustainable value?".

Existing Industry 4.0 models typically do not systematically account for organizational capabilities that enable effective use of digital technologies or their linkage to environmental and social outcomes. In the proposed model, the Digital Enablement Factors layer plays a crucial mediating role, capturing the difference between mere availability of advanced technological solutions and the organization's ability to use them practically, safely, and responsibly. In this sense, DSMF aligns with research on dynamic capabilities and the business value of digital technologies while extending it with a sustainability perspective.

Conversely, ESG frameworks and sustainability assessment models, such as GRI, ESRS, or CSRD, focus primarily on reporting, regulatory compliance, and formal aspects of corporate governance. Digital technologies are often treated as an external context rather than as an integral part of the ESG management system. As a result, many organizations achieve formal reporting compliance without simultaneously possessing the operational capabilities to meaningfully improve environmental and social performance. DSMF addresses this limitation by treating ESG maturity as an organizational capability based on data, transparency, and process integration, whose development is directly supported by digital transformation.

Another distinguishing feature of DSMF is the adoption of sustainable performance outcomes as the terminal element of the model, rather than as an additional maturity level. Unlike many existing models that concentrate on internal levels of process or organizational sophistication, DSMF allows for the assessment of actual effects of digital transformation and ESG implementation. These include resource efficiency, process circularity, employee well-being, organizational resilience, and regulatory compliance. This distinction prevents the conflation of organizational maturity with its outcomes and provides a foundation for empirically evaluating the effectiveness of digitalization and sustainability initiatives.

The comparison also highlights DSMF's advantage in terms of logical integration across domains. The model is based on a clearly defined cause-and-effect sequence, in which Industry 4.0 maturity influences the development of organizational digital capabilities, which in turn support the institutionalization of ESG practices, ultimately leading to improved sustainable performance outcomes. Simultaneously, the model allows for direct relationships between digital maturity and performance outcomes, reflecting the partially mediated nature of the relationship between digitalization and sustainability.

In this context, DSMF can be seen as a bridge between technology-focused maturity models and sustainability frameworks, offering an integrated approach to assessing organizational maturity under digital transformation and increasing regulatory requirements. The model contributes to the literature by combining technological, organizational, and sustainability perspectives into a single operational analytical framework. At the same time, it lays the groundwork for further empirical research on mechanisms linking digital transformation with measurable sustainable performance, as reflected in the concluding sections of the study.

It should be noted that the proposed framework represents a conceptual structure, and its practical applicability requires empirical validation, which constitutes the next stage of the research.

6. Summary and conclusion

The aim of this article was to develop an integrated maturity model that combines the perspective of Industry 4.0 digital transformation with the sustainability requirements framed by ESG. In response to the identified research gap, the Digital Sustainability Maturity Framework (DSMF) was proposed as a conceptual and methodological tool that enables the assessment of alignment between technological maturity, organizational capabilities, ESG maturity, and sustainable performance outcomes.

The theoretical contribution of this article lies in the introduction of a new, integrated maturity model that unites the Industry 4.0 digital transformation perspective with ESG maturity in a single, coherent analytical framework. DSMF extends previous research on Industry 4.0 beyond technological capabilities, incorporating environmental, social, and governance dimensions as integral elements of organizational maturity. At the same time, the article contributes to the literature on sustainability by embedding ESG practices within the context of technological and organizational enablers for their effective implementation.

A notable methodological contribution of the study is the development of a survey instrument that operationalizes the DSMF for empirical research. The questionnaire, based on a maturity-based approach, allows for the assessment of organizational advancement across the four dimensions of the model and provides a foundation for further empirical validation using structural equation modeling (SEM). Consequently, DSMF serves not only as a conceptual framework. The DSMF is proposed as a potential diagnostic tool that may support managers in assessing the alignment between digitalization and ESG performance, subject to future empirical validation.

From a practical perspective, DSMF may provide managers and decision-makers with a tool to assess organizational readiness for digitally-enabled sustainable transformation. The application of the model allows for the identification of ESG gaps arising from insufficient digital maturity or limited organizational capabilities. Moreover, the model's structure can function as a roadmap to support strategic prioritization of digital investments aimed at achieving measurable environmental, social, and governance outcomes.

The proposed DSMF should be interpreted as a conceptual and methodological contribution rather than a fully validated diagnostic tool. Its practical application depends on future empirical studies aimed at testing the proposed relationships and validating the measurement instrument.

Additional limitations concern the potential overlap between conceptually adjacent constructs, particularly between digital enablement factors and ESG maturity, despite efforts to ensure discriminant validity at the conceptual level. Furthermore, the study relies on a self-reported survey instrument, which may introduce response bias and limit the objectivity of the measurement. The absence of objective operational and environmental indicators constitutes another limitation, as the framework is currently based on perceptual data.

A potential limitation concerns the wording of selected items within the Sustainable Performance Outcomes construct, where references to digital technologies may partially overlap with explanatory variables. This may introduce a risk of construct contamination and artificially strengthen observed relationships in future empirical analyses. Therefore, future research should refine the measurement of outcomes to focus more explicitly on organizational effects independent of their technological drivers.

Moreover, the proposed model may function differently across industries characterized by varying levels of digital maturity, regulatory pressure, and organizational complexity. These contextual differences are not explicitly captured in the current version of the model and should be addressed in future empirical research.

This study has a conceptual-methodological nature, which constitutes its primary limitation. The proposed DSMF has not yet undergone empirical validation, and its operationalization relies on a survey instrument based on self-assessment, which may be subject to measurement bias. Furthermore, the model is static and does not account for the dynamics of digital transformation and sustainability over time. The model's scope was also deliberately limited to industrial enterprises, which may constrain its direct generalizability to other economic sectors.

Future research should focus on the empirical validation of the DSMF using structural equation modeling techniques, particularly PLS-SEM, as well as on the analysis of mediating effects between Industry 4.0 maturity, digital enablement factors, and ESG maturity. Further studies may also include cross-sector comparisons, investigations assessing the dynamics of organizational maturity, and extensions of the model to incorporate contextual factors such as regulatory pressure, organizational strategy, or corporate culture. The use of methodological triangulation, combining survey data with objective operational and environmental indicators, could further enhance the validity and practical utility of the proposed framework. Future research may extend the model by incorporating contextual variables such as organizational size, industry specificity, and regulatory pressure.

Acknowledgements

Research and publication were financed by the statutory research fund of the Czestochowa University of Technology.

Reference

Abate, R., Gallo, M., Guizzi, G., Santillo, L.C., 2025. Dynamic Sustainability Assessment: Enhancing the RAMI 4.0 Model for Environmental Integration in Industry 4.0. IFAC-PapersOnLine, 59, (10), 1964-1969. DOI: 10.1016/j.ifacol.2025.09.330.

Awotunde, J.B., Muduli, K., Brahma, B. (Eds.). (2025). Computational Intelligence for Analysis of Trends in Industry 4.0 and 5.0 (1st ed.). Auerbach Publications. DOI: 10.1201/9781003533023.

Blaber, Z., Gougoumanova, G.,2024. Analytical Thinking in Accounting Education: Student Use of the Sustainability Accounting Standards Board (SASB) Navigator Database, Springer Proceedings in Business and Economics [In:] Tankiso. M., Babu. G. (ed.), Towards Digitally Transforming Accounting and Business Processes, 853-863, Springer, DOI: 10.1007/978-3-031-46177-4_46.

Binder, C., Riedmann, S., Neureiter, C., Vollmar, J., Gupta, R., Calà, A. Lüder,A., 2025. Bridging the Gap: Deriving Specific Reference Architectures from RAMI 4.0 for Flexible Production Systems. IFAC-PapersOnLine, 59(10), 1119-1124. DOI: 10.1016/j.ifacol.2025.09.189.

Boulitama, O., Lhamidi, S., Taifi, R., & Sabiri, B. (2025). Digital transformation and supply chain capabilities: a sectoral maturity perspective in Morocco. Polish Journal of Management Studies, 31(2), 61-80. DOI: 10.17512/pjms.2025.32.1.04

Bux, C., Geatti, P., Sebastiani, S., Del Chicca, A., Giungato, P., Tarabella, A., & Tricase, C., 2025. Toward an Experimental Common Framework for Measuring Double Materiality in Companies. Sustainability, 17(14), 6518. DOI: 10.3390/su17146518.

Cahan, S.F., Chen, L., Wei, Y., 2025. Do sustainability standards improve the information environment? Evidence from the influence of SASB standards on disagreement among ESG rating agencies. Meditari Accountancy Research, ahead-of-print, DOI: 10.1108/MEDAR-08-2024-2600.

Czerwińska, K., Pacana, A. 2022. Analysis of the maturity of process monitoring in manufacturing companies. Production Engineering Archives, 28(3), 2022. 246-251. DOI: 10.30657/pea.2022.28.30.

da Rocha, T., Szejka, A.L., Osiris Canciglieri Junior. O., Rocha Loures E. da F., 2020. A Preliminary Discussion of the ACATECH 4.0 and AHP to Measure Enterprise Maturity Level Index. [In:] Pokojski J., et al. (Eds.). Transdisciplinary Engineering for Complex Socio-technical Systems – Real-life Applications, Proceedings of the 27th ISTE International Conference on Transdisciplinary Engineering, July 1 – July 10, 2020, 143-150, doi:10.3233/ATDE200071.

Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting (Text with EEA relevance) https://eur-lex.europa.eu/eli/dir/2022/2464/oj/eng (Access 15.12.2025).

Dung, L.T., Binh, N.T., 2026. From Digital Roots to Sustainable Routes: Integrating Sharing Economy and ESG for SMEs' Sustainable Export Competitiveness. Corporate Social Responsibility and Environmental Management, 1-25. DOI: 10.1002/csr.70468.

Durana, P., Perkins, N., Valaskova, K., 2021. Artificial Intelligence Data-driven Internet of Things Systems, Real-Time Advanced Analytics, and Cyber-Physical Production Networks in Sustainable Smart Manufacturing. Economics, Management, and Financial Markets, 16(1), 20–30. DOI: 10.22381/emfm16120212.

Dwivedy, M., Pandit, D., Khatter, K., 2025. Assessment of Smart Manufacturing Readiness for Small and Medium Enterprises in the Indian Automotive Sector. Sustainability, 17(18), 8096. DOI: 10.3390/su17188096.

European Sustainability Reporting Standards) (https://www.unepfi.org/impact/interoperability/european-sustainability-reporting-standards-esrs/) (Access 10.12.2025).

Guimarães, A., Reis, P., Pereira, T., Marques Cardoso, A.J., 2025. Industry 4.0 in Portugal: validation of a readiness assessment model through an empirical approach. Benchmarking: An International Journal, ahead-of-print. DOI: 10.1108/BIJ-02-2025-0121.

Hąbek, P. (2025). Evaluating ESG Software Solutions for Sustainability Reporting in the Manufacturing Sector. Management Systems in Production Engineering, 33(3), 420-432. DOI: 10.2478/mspe-2025-0041.

Hassanpourroudbeneh, F., Zangeneh, P., 2026. Sustainability assessment of Las Bambas copper mine: Reviewing disclosures. The Extractive Industries and Society, 25, 101787, DOI: 10.1016/j.exis.2025.101787.

Heldmann, J., Dang,H.D., Brückner, T., 2025. Investing in a low-carbon transition: Carbon footprint savings with green MSCI indices. Journal of Environmental Management, 393, 126022, DOI: 10.1016/j.jenvman.2025.126022.

Hien, H.T., Thanh, LV., Phi, SN., Le T.-A., 2026. Bibliometric analysis of corporate social responsibility and tax avoidance. Discover Sustainability 7, 105. DOI: 10.1007/s43621-025-02420-1.

Ingaldi, M., Ulewicz, R. 2025. Sustainable development and technological advancements in Industry 4.0: Overcoming barriers in SME sector integration. Management Systems in Production Engineering, 33(2), 144–162, DOI: 10.2478/mspe-2025-0015.

Kagermann, H., Anderl, R., Gausemeier, J., Schuh, G., Wahlster W. 2016. Industrie 4.0 in a Global Context – Strategies for Cooperating with International Partners. acatech – National Academy of Science and Engineering. Munich: Herbert Utz Verlag. https://en.acatech.de/publication/industrie-4-0-in-a-global-context-strategies-for-cooperating-with-international-partners/ (Access 16.12.2025).

Kucęba, R., 2025. The Impact of ESG Reporting on the Multidimensional Activities of Modern Companies. System Safety: Human - Technical Facility - Environment, 7(1), 19-28. DOI: 10.2478/czoto-2025-0003.

Li, T.-T., Wang, K., Sueyoshi, T., Wang, D.D., 2021. ESG: Research progress and future prospects. Sustainability, 13(21), 11663. DOI: 10.3390/su132111663.

Marszałek-Kotzur, I., 2025. Artificial intelligence in industry – Ethical challenges. Production Engineering Archives, 31(4), 550–564. DOI: 10.30657/pea.2025.31.51.

Mazur, M., Ingaldi, M., 2025. Strategies for Solar Energy Utilization in Businesses: A Business Model Canvas Approach. Energies, 18(24), 6533. DOI: 10.3390/en18246533.

Mendonca, R.S., Medeiros, R.L.P., Silva, L.E.S.e., Silva, R.G.G., Santos, L.G.S., de Lucena, V.F., Jr., 2025. Enabling Technologies of Industry 4.0 for the Modernization of an Industrial Process. Processes, 13(8), 2488. DOI:10.3390/pr13082488.

Othen, R., Padberg, J., Möbitz, C., Gries, T. 2025. Digital transformation in the paper industry: Assessing maturity, challenges, and opportunities. Sustainability, 17(2), 770. DOI: 10.3390/su17020770.

Rosak-Szyrocka, J., 2025. From CSR to ESG – The new era in corporate responsibility. System Safety: Human - Technical Facility - Environment, 7(1), 234–246. DOI: 10.2478/czoto-2025-0022.

Rosak-Szyrocka, J., Knop, K., 2024. Navigating the Fourth Industrial Revolution: insights from a comprehensive bibliometric study on Industry 4.0. Production Engineering Archives, 30(4), 501-519. DOI: 10.30657/pea.2024.30.47.

Sá, J. C., Oliveira, A., Hines, P., Mourão, Filipa, McDermott, O., Marques, P. A., Zouari, A., Pathania, A., Ulewicz, R., 2025. The effects of Lean and people's behaviours on Occupational Safety. Production Engineering Archives, 31(1), 1–14. DOI: 10.30657/pea.2025.31.1.

Sajjad, A., Ahmad, W., Hussain, S., Chuddher, B.A., Sajid, M., Jahanjaib, M., Ali, M.K., Jawad, M.,2024. Assessment by Lean Modified Manufacturing Maturity Model for Industry 4.0: A Case Study of Pakistan's Manufacturing Sector. IEEE Transactions on Engineering Management, 71, 6420-6434, DOI: 10.1109/TEM.2023.3259005.

Schuh, G., Bleider, M., Hoffmann, J., Hartard, E., Heisenberger, P., Zeller. V., 2019. Systematic Analysis of IT Complexity Challenges Hindering the Implementation of Industrie 4.0 Roadmaps. [In:] Proceedings of the 5th International Conference on e-Society, e-Learning and e-Technologies (ICSLT '19). Association for Computing Machinery, New York, NY, USA, 104–108. DOI: 10.1145/3312714.3312716.

Sira, M., 2025. A gap analysis framework for enterprise AI implementation. Production Engineering Archives, 31(3), 291–310. DOI: 10.30657/pea.2025.31.28.

Songkhwan, S., Meathawiroon, C., & Thunyachairat, A., 2025. The influence of lean manufacturing and green supply chain management on firm performance: The mediating role of supply chain resilience. Production Engineering Archives, 31(1), 41–53. DOI: 10.30657/pea.2025.31.4.

Steidle, C., Ostojic, S., Achterfeldt, S., Traverso, M., 2025. Small players, big impact? Unveiling practices and challenges of sustainability reporting by German SMEs. Discovery Sustainability, 6, 780. DOI: 10.1007/s43621-025-01727-3.

Sun, Y., Lu, Y., Wu, Y., Xu, C., Davey, H., 2026. Synergizing ESG and Digital Transformation for Corporate Decarbonization. Business Strategy and the Environment, 35, (2), 2581–2599. DOI: 10.1002/bse.70262.

Sunder, V.M., Prashar, A., Tortorella, G.L., Sreedharan, V.R., 2024. Role of Organizational Learning on Industry 4.0 Awareness and Adoption for Business Performance Improvement. IEEE Transactions on Engineering Management, 71, 4904-4917, DOI: 10.1109/TEM.2023.3235660.

Ślusarczyk, B. (2025). Analysis of the benefits of implementing the industry 4.0 concept in enterprises. *Polish Journal of Management Studies*, 32(1), 231-250, DOI: 17512/pjms.2025.32.1.14

Tancke, L., Užík, M., Block, S., Glova, J., Boha H., 2023. Managerial perspective on ESG and financial performance of car manufacturers. Polish Journal of Management Studies, 28(1), 330–343. DOI: 10.17512/pjms.2023.28.1.19.

Vijaya, A., Dzaudan Qadri, F.D., Angreani, L.S., Wicaksono, H., 2026. From fragmentation to interoperability: How semantic models transform environmental, social, governance (ESG) reporting, knowledge, and sustainability governance. Journal of Innovation & Knowledge, 13, 100924. DOI: 10.1016/j.jik.2025.100924.

Wu, Q., Gao, X., Lipovka, A. 2026. Integration of Artificial Intelligence into Human Resource Management in Manufacturing Enterprises: A Systematic Literature Review of Challenges, Approaches, and Evolution (2000–2025). Sustainability, 18(5), 2618. DOI: 10.3390/su18052618.

Yoo, S., Managi, S. 2022. Disclosure or action: Evaluating ESG behavior towards financial performance. Finance Research Letters, 44 (C), 102108. DOI: 10.1016/j.frl.2021.102108.

Zhao, X., Chen, X., Lee, C.-C., 2026. Towards green transformation: Digital finance and green technology innovation in renewable energy enterprises. Renewable Energy, 259, 125037, DOI: 10.1016/j.renene.2025.125037.

Schumacher, A., Erol, S., Sihn, W., 2016. A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises. Procedia CIRP, 52, 161–166. DOI: 10.1016/j.procir.2016.07.040.

Zoubek, M., Poor, P., Broum, T., Basl, J., Simon, M., 2021. Industry 4.0 Maturity Model Assessing Environmental Attributes of Manufacturing Company. Applied Sciences, 11(11), 5151. DOI: 10.3390/app11115151.

Chen, D., Wang, S.,(2024. Digital transformation, innovation capabilities, and servitization as drivers of ESG performance in manufacturing SMEs. Scientific Reports, 14, 24516. DOI: 10.1038/s41598-024-76416-8.

Liu, X., Wang, L., 2025. Digital transformation, ESG performance and enterprise innovation. Scientific Reports, 15, 23874. DOI: 10.1038/s41598-025-08850-1.

Marczewska, M., Hegerty, S.W., Panwar, R., Kostrzewski, M., 2025. Digital transformation, ESG, and companies' performance: an exploratory study of the European food sector. The Journal of Technology Transfer, 50, 883–907, DOI: 10.1007/s10961-025-10247-1.

Steidle, C., Ostojic, S., Achterfeldt, S., Traverso, M., 2025. Small players, big impact? Unveiling practices and challenges of sustainability reporting by German SMEs. Discover Sustainability, 6, 780. DOI: 10.1007/s43621-025-01727-3.

Vijaya, A., Dzaudan Qadri, F.D., Angreani, L.S., Wicaksono, H., 2026. From fragmentation to interoperability: How semantic models transform environmental, social, governance (ESG) reporting, knowledge, and sustainability governance. Journal of Innovation & Knowledge, 13, 100924. DOI: 10.1016/j.jik.2025.100924.

Agrawal K., Nargund, N., 2024. Deep Learning in Industry 4.0: Transforming Manufacturing Through Data-Driven Innovation. [In:] Distributed Computing and Intelligent Technology: 20th International Conference, ICDCIT 2024, Bhubaneswar, India, January 17–20, 2024, Proceedings. Springer-Verlag, Berlin, Heidelberg, 222–236. DOI: 10.1007/978-3-031-50583-6_15.

Bibby, L., Dehe, B., 2019. An Industry 4.0 maturity model proposal. Journal of Manufacturing Technology Management, 31(5), 1023–1043. DOI: 10.1108/JMTM-09-2018-0284.

Appendix

Appendix A: Quantitative Survey Instrument for the DSMF Model

Appendix A presents the survey instrument developed to operationalize the theoretical constructs and hypotheses of the Digital Sustainability Maturity Framework (DSMF) model.
LIKERT SCALE: 1–7 1 = strongly disagree / very low level 7 = strongly agree / very high level

Table A. Industry 4.0 Maturity

Code	Indicator	Survey Item (CAWI)	Scale	Theoretical Basis
A1	Automation	Our production processes are highly automated.	1–7	
A2	Robotics	We utilize collaborative or autonomous robots.	1–7	
I1	IoT	We have a broad network of IoT sensors and devices.	1–7	
I2	Data	Machine data is available in real-time.	1–7	
D1	Analytics	We apply predictive analytics or AI.	1–7	
T1	IT/OT	Production systems are integrated with digital systems, enabling real-time monitoring and control.	1–7	
SC1	Supply Chain	Our supply chain is digitally integrated end-to-end.	1–7	

Table B. Digital Enablement Factors

Code	Indicator	Survey Item (CAWI)	Scale	Theoretical Basis
DG1	Data Governance	Our organization has formal data management policies.	1–7	
C1	Culture	Employees demonstrate high digital competencies.	1–7	
C2	IT/OT Integration	IT and operational processes are aligned.	1–7	
CY1	Cybersecurity	The level of cybersecurity is adequate to the risk.	1–7	

Table C1. ESG Maturity: Environmental

Code	Indicator	Survey Item (CAWI)	Scale	Theoretical Basis
E1	Emissions	We monitor and report CO2 emissions (Scope 1–3).	1–7	
E2	Energy	We measure energy consumption and the share of renewable energy.	1–7	
E3	Waste	We monitor and reduce waste generation.	1–7	
E4	Water	We conduct water footprint analysis.	1–7	

Table C2. ESG Maturity: Social

Code	Indicator	Survey Item (CAWI)	Scale	Theoretical Basis
S1	Safety	We continuously monitor workplace safety.	1–7	
S2	Well-being	We implement initiatives to support employee well-being.	1–7	
S3	Inclusivity	We follow principles of equality and inclusiveness.	1–7	

Table C3. ESG Maturity: Governance

Code	Indicator	Survey Item (CAWI)	Scale	Theoretical Basis
G1	Transparency	The organization ensures transparency through regular and reliable non-financial disclosures.	1–7	
G2	Ethics	The organization has a formal ethics and compliance system with enforcement mechanisms.	1–7	
G3	Compliance	The organization effectively ensures compliance with ESG regulations and standards (e.g., CSRD, GRI).	1–7	

Table D. Sustainable Performance Outcomes (SPO)

Code	Indicator	Survey Item (CAWI)	Scale	Theoretical Basis
SP1	Resource Efficiency 1	In recent years, we have improved the efficiency of resource use (energy, materials, water).	1–7	
SP2	Resource Efficiency 2	Digital technologies support real-time monitoring and optimization of resource consumption.	1–7	
SP3	Circularity 1	Digital solutions support waste reduction and resource reuse.	1–7	
SP4	Circularity 2	The organization implements circular economy principles in operational processes.	1–7	
SP5	Worker Well-being 1	The use of digital technologies has improved workplace safety.	1–7	
SP6	Worker Well-being 2	Industry 4.0 solutions positively impact employee well-being and comfort.	1–7	
SP7	Resilience and Compliance 1	The organization effectively identifies and manages operational and regulatory risks using digital data.	1–7	
SP8	Resilience and Compliance 2	Digital technologies support compliance with regulatory and ESG requirements.	1–7	

Appendix B: DSMF Maturity Levels

Table E. Model DSMF: Levels and Definitions

Level	Name	Definition
1	Ad hoc	The organization lacks a formal digital or ESG strategy. Processes are manual, data collection is unsystematic, and environmental/social activities are incidental or absent.
2	Awareness	The organization recognizes the importance of digitalization and ESG, but initiatives are fragmented and reactive. Early digital or environmental initiatives exist, but are not strategy-linked. Process and environmental data are collected sporadically.
3	Digital Silos	Selected Industry 4.0 technologies are implemented (e.g., isolated IoT sensors, robots, document digitization), but initiatives are scattered and unintegrated. No coherent data management system. ESG operates as a separate area, unlinked to digitalization.
4	ESG Compliance	The organization meets minimum regulatory requirements (e.g., CSRD, GRI), conducts basic environmental and social measurements, and implements compliance mechanisms. Digital technologies support only reporting and monitoring. ESG data is not integrated with industrial systems.
5	Integrated Systems	Data from digital systems (ERP, MES, SCADA, IoT) is integrated with environmental and social data. The organization uses data for operational and strategic decision-making. Digitalization and ESG begin to mutually reinforce each other.
6	Advanced Analytics	The organization uses advanced analytics, predictive models, and AI to optimize efficiency, emissions, energy, waste, and safety. Digital twins and environmental impact simulations are implemented. Data is processed in real-time.
7	Smart Sustainable Enterprise	Full synergy between Industry 4.0 and ESG. The organization autonomously monitors and optimizes environmental, social, and operational performance. High resilience, transparency, and competitiveness. Decisions are data-driven, and environmental impact is actively minimized using intelligent technologies.