Digital green transformation: technology-specific insights into advancing environmental sustainability[1]

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Giuseppe Lanfranchi - Antonio Crupi - Fabrizio Cesaroni

Abstract

Frame of the research: *Digital transformation and environmental sustainability have emerged as parallel strategic priorities in contemporary academic and managerial discourse. Nevertheless, existing studies frequently examine them in isolation, overlooking their potential complementarities. This fragmentation limits our understanding of how heterogeneous digital technologies, such as the Internet of Things, Artificial Intelligence, Robotics, and Cloud Computing, can generate differentiated environmental outcomes beyond their conventional efficiency-enhancing functions.*

Purpose of the paper: *The paper seeks to clarify how individual digital technologies contribute, both directly and indirectly, to environmental sustainability, with particular attention to the organisational logics, motivations, and adoption pathways through which firms operationalise them. By doing so, the study advances a technology-specific perspective on the twin transition, shedding light on the differentiated environmental affordances embedded in distinct digital tools and on how firms unintentionally generate sustainability gains while pursuing efficiency, quality, or competitiveness objectives.*

Methodology*: The analysis draws on a multiple case study of four Italian manufacturing firms, selected for their varied digital maturity and sustainability trajectories. Semi-structured interviews, document analysis, and on-site observations were combined to capture how managers interpret and deploy different digital technologies within their operational processes. This qualitative, in-depth design enables a granular examination of technology-specific mechanisms and provides contextualised insights into how environmental impacts emerge from concrete organisational practices.*

Findings: *Three key patterns emerge: (i) established technologies including Internet of Things, Artificial Intelligence and Robotics improve efficiency and competitiveness while simultaneously reducing water and energy consumption and limiting material waste; (ii) emerging solutions such as Augmented Reality / Virtual Reality and 3D printing are perceived as promising yet only marginally integrated into sustainability-oriented processes; and (iii) other tools, notably the metaverse, are widely considered irrelevant in industrial practice. Overall, managers interpret efficiency-driven digitalisation as an unexpected catalyst for environmental benefits, reinforcing the strategic value of these technologies.*

Research limits: *The study is based on a limited number of cases drawn from a single national context, which constrains the generalisability of the findings and calls for caution in extending the results to other industries or institutional environments. Furthermore, the analysis captures managerial perceptions and self-reported practices, suggesting that future research could integrate quantitative performance data or cross-country comparisons to validate and expand the proposed interpretations.*

Practical implications: *The study provides manufacturing firms with actionable guidance on how to design digital strategies that simultaneously advance efficiency and sustainability objectives. Specifically, it highlights which technologies generate the most immediate environmental returns, how firms can prioritise investments across mature and emerging solutions, and how to align digital roadmaps, process redesign, and resource allocation with broader sustainability ambitions. These insights can support more informed decision-making in contexts of technological uncertainty and budget constraints.*

Originality of the paper: *The paper offers a technology-specific interpretation of the twin transition, illuminating the heterogeneous pathways through which digital tools enable sustainability and highlighting indirect ecological benefits that emerge from efficiency-oriented digital adoption.*

Key words: D*igital technologies, environmental sustainability, manufacturing industry, digital green transformation.*

1. Introduction

The twin transition, digital and green, has become a central concern on global political and managerial agendas. International institutions, including the European Commission (2022), stress that the convergence of digital technologies and environmental sustainability (ES) is critical to addressing pressing challenges such as climate change, resource scarcity, and the need for more inclusive growth. Within the framework of the Sustainable Development Goals (SDGs), digital technologies are not only drivers of competitiveness but also enablers of innovative practices for resource management, emissions monitoring, and waste reduction (Mio *et al.*, 2020; Jibril *et al.*, 2024).

The academic literature has acknowledged this potential yet often treats digital transformation and ES in isolation or conceptualises digital transformation as a monolithic process, thereby neglecting the heterogeneity of individual technologies (Costa, 2024). Much research focuses on the aggregate effects of digitalisation in terms of economic performance or sustainable innovation (Hanelt *et al.*, 2017; George and Schillebeeckx, 2021; Schaltegger and Wagner, 2011), without extricating the specific trajectories through which different technologies, such as Internet of Things (IoT), Artificial Intelligence (AI), robotics, blockchain, or metaverse, affect ES. Although recent contributions have begun to explore this interface (Bhatia *et al.*, 2024; Camodeca and Almici, 2021), the picture remains fragmented and dominated by generic approaches that overlook the concrete mechanisms of environmental value creation.

This gap is significant for at least two reasons. First, digitalisation is far from homogeneous: each technology differs in maturity, implementation costs, side effects, and potential to generate positive or negative environmental externalities (Rejeb *et al.*, 2020; Bohnsack *et al.*, 2022). For example, IoT enables consumption monitoring and process optimisation, while 3D printing accelerates prototyping but raises concerns about material recyclability (Lanfranchi *et al.*, 2025; Javaid *et al.*, 2021). Second, the literature tends to privilege firms' strategic intentions, such as adopting explicitly "green" technologies, while devoting less attention to what managers actually perceive as the effective or unexpected outcomes of adopted technologies. Managerial perceptions are nonetheless a valuable lens, as they reveal how organisations recognise (or overlook) the environmental implications of their digital choices (Patton, 2002).

This study contributes to this debate by advancing a technology-specific perspective on the digital-green convergence. Its aim is to understand how managers perceive the environmental effects, intended or unintended, associated with specific digital technologies in the Italian manufacturing sector. This sector provides a particularly suitable context for analysis, given its high environmental impact (Conejo *et al.*, 2020) and the mounting regulatory and competitive pressures to adopt sustainable practices. At the same time, Italian manufacturing is a dynamic arena where firms of different sizes coexist, exhibiting heterogeneous levels of digitalisation, innovation, and sustainability orientation.

To investigate these dynamics, the research employs a multiple case study (Eisenhardt, 1989; Yin, 2018) of four manufacturing firms operating in distinct industries (automotive, logistics, shipbuilding, and safety equipment). The methodological design integrates the Analytic Hierarchy Process (AHP) with semi-structured interviews conducted with executives and innovation/sustainability managers, complemented by qualitative coding through NVivo (Richards, 1999). This approach enables the identification of both intentional trajectories and unexpected effects in the adoption of specific technologies.

The study's contributions are twofold. Theoretically, it develops a technology-specific reading of the twin transition, distinguishing among consolidated, emerging, and marginally relevant technologies. Managerially, it provides concrete insights into how efficiency and sustainability objectives can be jointly integrated into digital strategies, highlighting that the pursuit of efficiency frequently serves as an unexpected driver of environmental benefits.

The article is structured as follows: Section 2 outlines the theoretical background on digital transformation and environmental sustainability; Section 3 details the research methodology; Section 4 presents the empirical findings; Section 5 discusses the theoretical contributions and managerial implications; and Section 6 concludes with limitations and avenues for future research.

2. Theoretical Framework

2.1 Digital transformation and environmental sustainability

Digital transformation has been defined as "a process that aims to improve an entity by triggering significant changes in its properties through combinations of information, computing, communication, and connectivity technologies" (Vial, 2021, p. 118). It therefore extends well beyond the mere adoption of technological tools: it entails a profound reconfiguration of business models, internal processes, and relationships with customers, suppliers, and other stakeholders (Westerman *et al.*, 2014; Hanelt *et al.*, 2017). Digital transformation should thus be understood as a socio-technical phenomenon, one that integrates technological innovation with organisational, cultural, and strategic shifts, often characterised by complexity and non-linear dynamics (Crupi *et al.*, 2025; Lu *et al.*, 2023).

The literature consistently highlights that digital transformation does not follow a uniform path but instead unfolds in sector-specific and context-dependent ways, shaped by technological maturity and firms' organisational capabilities (Jamwal *et al.*, 2025; Álvarez *et al.*, 2019). Some studies distinguish between incremental approaches, aimed at improving efficiency and automation, and radical approaches, which generate entirely new business models and redefine value chains (Ali *et al.*, 2025). In both cases, digitalisation is never purely technical: it requires substantial investment in human capital, the development of digital skills, and a sustained commitment to change management (Moncada *et al.*, 2025).

A further element of complexity lies in the heterogeneity of technologies encompassed by Digital transformation (V K *et al.*, 2025; McAfee, 2003). This spectrum includes mature solutions such as ERP systems or cloud computing, rapidly diffusing technologies such as IoT, AI, and robotics, and emerging solutions like 5G, blockchain, AR/VR, and additive manufacturing (Ghobakhloo and Fathi, 2020; Minoli and Occhiogrosso, 2019). Such heterogeneity implies highly differentiated impacts on firms' economic performance as well as on social and environmental outcomes. Yet mainstream literature continues to overlook the fact that each technology carries its own opportunities, risks, and implementation pathways (Crupi *et al.*, 2025; Appio *et al.*, 2021).

Finally, digital transformation is increasingly conceptualised as a dynamic and ongoing process, one that evolves in response to both external pressures (e.g., globalisation, regulatory demands, environmental crises) and internal drivers (e.g., growth strategies, capability development) (Jiang, 2025). This processual perspective underscores that Digital transformation is not a fixed destination but a trajectory of organisational learning and continuous experimentation, redefining competitive boundaries while opening new challenges linked to sustainability and social impact (Mozaffar & Candi, 2025).

In parallel, environmental sustainability (ES) has become a non-negotiable priority for firms and policy makers, driven by mounting pressures linked to climate change, the scarcity of natural resources, and the evolving expectations of stakeholders (Elder, 2025; Bansal and

Song, 2017). From a managerial perspective, ES has been defined as the ability of organisations to mitigate the negative impacts of their activities on ecosystems while simultaneously contributing to long-term socio-economic resilience (Tammaraksa *et al.*, 2025; Geissdoerfer *et al.*, 2017). Scholars emphasise that sustainability cannot be regarded as a peripheral activity; rather, it must be fully integrated into corporate strategy and everyday management practices (Palmiè *et al.*, 2025 MANCA IN BIBLIO; Schaltegger *et al.*, 2012). This requires moving beyond a reactive stance, oriented toward regulatory compliance and risk reduction, toward a proactive orientation in which sustainability becomes a source of innovation, reputation, and competitive advantage (Lichtentaler, 2025).

Nonetheless, firms face considerable structural barriers in implementing environmental practices. High implementation costs for green technologies and processes often represent the first obstacle (Kim *et al.*, 2025). Added to this are the persistent difficulties of establishing clear and widely accepted metrics for measuring environmental performance (Dade *et al.*, 2025; Hahn *et al.*, 2015). Many firms also struggle with a lack of internal expertise and specialised skills (Álvarez *et al.*, 2019; Oliveira *et al.*, 2022), compounded by cultural and organisational resistance to change (Ruiz-Palomino *et al.*, 2025; Lozano, 2013). These challenges are particularly acute in energy-intensive industries such as manufacturing, where environmental impacts translate into significant emissions, heavy resource consumption, and substantial production waste (Shaik *et al.*, 2025; Conejo *et al.*, 2020). As a result, these sectors are subject to heightened scrutiny by regulators, consumers, and civil society, all of whom demand tangible commitments to more sustainable production models (Sasso *et al.*, 2025).

Alongside these external pressures, internal dynamics also play a role. Many firms adopt environmental practices not only in response to regulation or stakeholder expectations but also as part of efforts to innovate their business models and exploit new market opportunities (Krishnan *et al.*, 2025). Examples include initiatives in the field of the circular economy (Kirchherr *et al.*, 2018) or the development of lean and "low-carbon" production systems (Wang *et al.*, 2024). Yet the translation of these strategies into concrete outcomes depends on the ability to reconcile sustainability with other business priorities, such as productivity, competitiveness, and risk management (Parida *et al.*, 2019).

Within this context, a fundamental tension emerges: while sustainability is increasingly perceived as a driver of value, managers continue to struggle with balancing environmental, economic, and social objectives (Islam, 2025; Hahn *et al.*, 2010). This tension often manifests in compromises, trade-offs, and processes of organisational learning that shape the capacity of firms to embed sustainability into their long-term practices (Porro and Lanfranchi, 2025).

2.2 The twin transition: the convergence between digital and green transition

In recent years, the notion of the twin transition has gained increasing prominence in both academic debates and public policy. The European Commission (2019; 2022) has stressed that the digital and green transitions must be understood as complementary and interdependent dimensions of industrial transformation. The future competitiveness of firms will depend largely on their ability to integrate the adoption of digital technologies with strategies oriented toward environmental sustainability (Cobbinah *et al.*, 2025; Annarelli *et al.*, 2021). The literature highlights a wide range of potential synergies between digitalisation and sustainability (Galvani *et al.*, 2025; Florek *et al.*, 2025). Digital technologies can enable environmental goals by facilitating real-time monitoring of resource consumption and emissions through IoT and AI (Muhoza *et al.*, 2023); by optimising production processes and improving energy efficiency via robotics and advanced automation (Ogbemhe *et al.*, 2017); by enhancing transparency and traceability across value chains through blockchain and big data (Xu *et al.*, 2025); and by supporting circular and low-carbon business models through technologies such as additive manufacturing and digital platforms (Devito *et al.*, 2024). These mechanisms have been documented across multiple sectors, including agriculture, transportation, and manufacturing (George and Schillebeeckx, 2021; Camodeca and Almici, 2021).

Specifically, recent contributions have begun to investigate this digital-green interface more explicitly. Li *et al.* (2018) examined how digitalisation supports circular economy practices in manufacturing firms, while Ali *et al.* (2024) introduced the concept of *Green Digital Transformation,* emphasising the integration of digital innovation with environmental objectives as an emerging strategic trajectory. Similarly, Alabdali *et al.* (2024) demonstrated empirically that digital technologies contribute to the achievement of the SDGs only when coupled with adequate organisational and institutional capabilities.

The literature also acknowledges the ambivalent nature of digitalisation. On the one hand, it has the potential to reduce waste, emissions, and energy consumption; on the other, it may generate negative externalities, such as increased demand for electricity, growth in electronic waste, and dependence on resource-intensive technological infrastructures (Bohnsack *et al.*, 2022). In this respect, digitalisation does not automatically represent a pathway to sustainability but rather a set of potentially divergent trajectories, contingent on the type of technology, the industrial context, and the capabilities of the adopting firms (Ghobakhloo and Fathi, 2020). More recent studies underscore that the twin transition remains a paradigm under construction, supported by limited empirical evidence. Bhatia *et al.* (2024), for example, show that digital technologies can accelerate progress toward carbon neutrality, but only under specific conditions of governance and inter-organisational collaboration. Therefore, literature on the twin transition continues to exhibit two critical limitations. First, it tends to privilege theoretical and conceptual contributions at the expense of robust empirical validation. Second, it frequently treats digital transformation as an aggregate phenomenon, overlooking the heterogeneity of individual technologies.

To further position this study within the existing body of knowledge, Table 1 summarizes the most relevant contributions addressing the intersection between digital transformation and ES. For each study, the context, method, main findings, and contribution to the literature are reported. The review highlights that, while a growing number of studies acknowledge the potential of digital technologies to foster sustainable practices, the majority of contributions remain either conceptual or quantitative in nature. Only a limited number of works (e.g., Pflaum and Gölzer, 2018; Javaid *et al.*, 2021) focus on technology-specific trajectories. This gap provides the foundation for the present research, which aims to disentangle the differentiated pathways through which digital technologies contribute, directly or indirectly, to environmental sustainability (Reuter, 2021).

Tab. 1: Key studies on Digital Transformation and Environmental Sustainability

Author(s) (Year)	*Method*	*Main Findings*	*Contribution to the Literature*
Li *et al.* (2018)	Quantitative survey	Digital transformation strengthens organizational and entrepreneurial capabilities	Shows the role of dynamic capabilities as a foundation for digital adoption, with implications for sustainability
Ali *et al.* (2024)	Conceptual/ empirical (cases and models)	Digital transformation, combined with circular business models, enhances green innovation and resilience	Introduces the perspective of sustainable tech entrepreneurship
Alabdali *et al.* (2024); Crupi *et al.*, 2025	Quantitative survey / Conceptual study	Green digital transformation contributes to SDGs when supported by leadership and a digital-green culture	Highlights organizational conditions for the digital-green convergence
Appio *et al.* (2021)	Review	DT is still treated as a generic phenomenon, with little focus on specific impacts	Provides a research agenda to explore DT and innovation in more detail
George and Schillebeeckx (2021)	Conceptual	Digital innovations support the fight against climate change	Defines the emerging field of digital sustainability
Bohnsack *et al.* (2022)	Literature review	Digitalisation has both intended and unintended sustainability effects	Emphasizes trade-offs and ambivalences in the twin transition
Camodeca and Almici (2021)	Document analysis	Digital practices support SDGs implementation	Provides empirical evidence from the Italian context
Bhatia *et al.* (2024)	Survey and review	DT can accelerate carbon neutrality, but faces barriers and risks	Explores drivers and obstacles in the twin transition
Pflaum and Gölzer (2018); Lanfranchi *et al.*, (2025)	Conceptual/Review	IoT fosters data-driven models	Demonstrates the IoT-efficiency link, with indirect green effects
Javaid *et al.* (2021)	Review	3D printing reduces time and material use but raises recycling challenges	Shows ambivalent sustainability impacts of additive manufacturing
Rejeb *et al.* (2020)	Review	AR improves traceability and transparency	Highlights opportunities and limitations in energy/ organizational terms
Lu (2017)	Literature survey	Maps enabling technologies for Industry 4.0	Provides a foundation to distinguish the heterogeneous impacts of different technologies
Hanelt *et al.* (2017)	Empirical survey	IS supports eco-innovation performance	Links DT adoption to environmental performance
Engert and Baumgartner (2016)	Conceptual	ES must be integrated into corporate strategies	Bridges the gap between sustainability strategy and implementation

Source: Author's own work

3. Methodology

3.1 Research context

This study is situated within the Italian manufacturing sector, a context of critical economic and occupational relevance that simultaneously faces pressing challenges in terms of environmental impact and digital transformation. Manufacturing remains one of the cornerstones of the national production system, contributing substantially to overall value added and exports, and thus provides a fertile ground for examining the dynamics of convergence between digitalisation and sustainability. From an environmental perspective, manufacturing is characterised by high energy intensity, elevated levels of emissions, and significant consumption of natural resources alongside substantial waste generation (Conejo *et al.*, 2020). These features have subjected the sector to growing regulatory and societal pressures, both at the national and European levels, to adopt sustainable practices and pursue decarbonisation strategies (Costantini and Mazzanti, 2012). At the same time, the digital landscape of Italian manufacturing is highly heterogeneous: while some firms have already integrated consolidated technologies such as IoT, AI, and robotics, others are experimenting with emerging solutions, including additive manufacturing and augmented reality. This heterogeneity makes the sector a privileged setting for exploring how managers perceive the differentiated impacts of specific digital technologies on both efficiency and sustainability.

Within this context, four firms were selected through purposive sampling (Eisenhardt, 1989; Yin, 2018), designed to ensure technological variety, environmental relevance, and access to data. The selection criteria included: adoption of heterogeneous digital technologies, ranging from established (IoT, AI, robotics) to emerging (AR/VR, additive manufacturing); exposure to significant environmental challenges and regulatory pressures; representation of distinct industrial domains (automotive, logistics, shipbuilding, and safety equipment) to enable cross-sectoral comparison; and willingness of managers to participate in in-depth interviews and provide internal documentation. This strategy ensured both theoretical relevance and empirical richness, allowing for an investigation into how the adoption of different digital technologies is perceived to translate into environmental sustainability outcomes. Both companies operate within the manufacturing industry, specializing in the production of high-quality components and machines for diverse industries, including automotive and aerospace. The first company is renowned for its technological prowess and unwavering commitment to innovation. This company has held a strong reputation in the market for decades. The second company is actively engaged in the production and distribution of manufacturing products, catering to a wide array of sectors. With a comprehensive supply chain and logistics network, this company is well-equipped to deliver tailored solutions and services to its clientele. The third company specializes in the production of components for the nautical industry. With a focus on high-quality materials and precision engineering, this company provides essential parts and accessories for various types of vessels, ensuring durability and performance in marine environments. The fourth company is dedicated to the development and manufacturing of fire-rated doors and safety devices. Known for their rigorous testing standards and innovative safety solutions, this company supplies essential products that enhance fire protection and security in residential, commercial, and industrial settings (Table 2)

Tab. 2: details of firms subject to the study

Company	Employees	Revenues	Market
A	>1000	>300 mln €	Manufacturing for automotive
B	>600	>120 mln €	Manufacturing for logistics
C	>500	>100 mln €	Manufacturing for vessels
D	>400	>110 mln €	Manufacturing for safety

Source: Author's own work

3.2 Data collection and analysis

The research design adopted for this study is the multiple case study (Yin, 2018), a methodology particularly suited to exploring complex and under-investigated phenomena such as the intersection of digital transformation and environmental sustainability. The objective was not statistical generalisation but rather analytical generalisation, that is, the construction of concepts and theoretical propositions derived from systematic comparison across heterogeneous cases. The adoption of this methodology was driven by its capacity to provide a thorough and profound understanding of the underlying processes and dynamics through which phenomena occur, enabling meticulous and detailed interpretation (Bansal and Corley, 2012). Moreover, qualitative methods are particularly adept for exploring uncharted research domains (Eisenhardt, 1989).

Data collection relied primarily on semi-structured interviews conducted between 2022 and 2023. In total, fifteen interviews were carried out, approximately four per firm, including one meeting that involved two managers simultaneously. The interviewees included CEOs, CTOs, production managers, sustainability officers, and R&D managers. Each interview lasted an average of 90 minutes, was conducted in Italian, fully transcribed, and subsequently translated into English. To complement these primary data, secondary sources such as corporate reports, internal documentation, and official websites were also gathered, enabling triangulation and reducing the risk of bias linked to managerial perceptions alone.

As a preliminary step to qualitative analysis, the study employed a mixed-methods approach incorporating the Analytic Hierarchy Process (AHP) (Saaty, 1990), a multi-criteria technique designed to evaluate alternatives through comparative judgments (Hülle *et al.*, 2011). In this context, AHP was used to assess the degree of knowledge and familiarity managers held with different digital technologies[2]. Participants were asked

[2] Appendix A provides the full details of the Analytic Hierarchy Process.

to provide pairwise comparisons across technologies, which generated composite scores for each technology in terms of perceived awareness. This procedure allowed for a clearer distinction between perceptions grounded in direct experience and less consolidated opinions, thereby providing a robust basis for the subsequent qualitative analysis.

Consequently, we employed a qualitative analysis, using semi-structured interviews that are, as noted by Bansal and Corley (2012), characterized by a set of predefined questions but allowed room for follow-up questions based on participants' responses. The comprehensive details of the interview and interviewers are meticulously documented in Appendices B and C.

For the textual analysis of interviews, data were processed using NVivo software (Richards, 1999) and examined through the Gioia Methodology (Gioia *et al.*, 2013). This inductive approach unfolds in three stages: (i) identification of first-order concepts in the language of participants; (ii) clustering of these into second-order themes with theoretical relevance; and (iii) synthesis into aggregate dimensions, which form the foundation of the final conceptual framework. Coding was carried out by three researchers, who conducted double coding on a subset of interviews to test reliability and collectively discussed any discrepancies.

This combination allowed us to capture both the relative awareness of managers toward specific technologies (via AHP) and the deeper interpretive patterns emerging from their narratives. Additionally, the integration of AHP, inductive coding, triangulation with secondary sources, and iterative researcher comparison ensured methodological rigor and internal consistency. This approach enabled the emergence of robust conceptual categories that are firmly grounded in empirical evidence.

4. Findings

4.1 Digital technologies awareness and knowledge among manufacturing firms (AHP)

The preliminary analysis conducted through the AHP (Table 3) enabled a comparative assessment of managers' familiarity with major digital technologies. The results reveal a clear pattern: while Italian manufacturing firms demonstrate solid knowledge of established technologies such as the IoT, AI, Cloud Computing, and Robotics, they also exhibit marked uncertainty and scepticism toward more experimental or recently introduced solutions. Established technologies are generally perceived as already embedded in business processes, supporting production monitoring, predictive maintenance, and cost optimisation. As the CTO of Firm A remarked, "*The adoption of IoT has transformed our production monitoring, allowing us to identify inefficiencies in real time*". Similarly, the Chief Technology Officer of Firm B emphasised AI as a competitive asset: "*Integrating AI into decision-making processes has given us a significant competitive advantage*".

By contrast, emerging technologies such as the metaverse, blockchain, and 5G are viewed with substantial skepticism, with managers struggling to envision concrete applications in the manufacturing context. The stance is often unequivocal, as illustrated by the Chief Technology Officer of Firm C: "*The metaverse does not exist for us; we are a company that manufactures physically, we live on the shop floor. For me, the metaverse is pure fantasy in our industry*". Such statements underscore the gap between the hype surrounding certain technologies and their actual transferability into industrial practice. Overall, the AHP analysis allowed the identification of three categories of technologies. First, consolidated technologies (IoT, AI, Cloud, Robotics), which combine operational efficiency with initial indirect environmental benefits. Second, advanced technologies (3D printing, AR/VR) are regarded as promising but are still selectively applied. Third, emerging technologies (metaverse, blockchain, web 4.0) are largely perceived as marginal or of limited utility in the short term.

This classification forms the basis for the subsequent thematic analysis, showing that managers' familiarity and hands-on experience not only shape adoption trajectories but also condition their ability to recognise the potential indirect environmental impacts of specific technologies. It is also worth noting that the interviewed firms differ substantially in size, from small and medium enterprises (SMEs) to large corporations, which influenced the scope and pace of their digital-green transformation. Larger firms benefitted from greater resource availability and structured sustainability departments, whereas SMEs relied more on external collaborations and incremental experimentation. This heterogeneity should be considered when interpreting the findings.

Tab. 3: Calculating Criteria Weights

Factors	*Criteria Weights*	*Criteria weight (%)*
IoT	0,2689	27
Big Data	0,1455	15
AI	0,1308	13
Cloud Computing	0,0534	5
3D Printers	0,0615	6
Robotics	0,1595	16
AR	0,0457	5
Blockchain	0,0246	2
Machine Learning	0,0648	6
Metaverso	0,0146	1
Materiali Intelligenti	0,0307	3

Source: Author's own work

4.2 Thematic analysis

The thematic analysis, conducted with the support of NVivo and guided by the Gioia Methodology (Gioia *et al.*, 2013), enabled the transformation of managerial perceptions into structured analytical categories. Beginning with first-order concepts, that is, the recurring expressions used by participants, the analysis identified a set of second-order themes that captured theoretically relevant dimensions. These themes were subsequently consolidated into broader aggregate dimensions, among which the most salient to emerge was the notion of Digital Green Transformation. The following sections present the results organised around the main thematic clusters, illustrated with selected excerpts from the interviews.

4.2.1 Consolidated digital transformation technologies

The first theme concerns consolidated digital transformation technologies, including IoT, AI, Big Data, and Cloud Computing. These solutions are widely perceived as integral to business processes and as strategic levers for enhancing efficiency, competitiveness, and, indirectly, sustainability. As the Head of Plant of Firm A remarked, "*The adoption of IoT has transformed our production monitoring, allowing us to identify inefficiencies in real time*". Echoing this perspective, the Head of Plant of Firm B highlighted the role of digital data in waste reduction: "*Our familiarity with Big Data has enabled us to optimise operations and cut down on waste*".

AI, in particular, is described as a technology capable not only of improving decision-making but also of supporting more sustainable practices. As the Corporate Social Responsibility Officer of Firm C explained, "*We discovered that AI can predict machine failures with remarkable accuracy, reducing downtime and production waste*". A similar point was raised by the Managing Director of Firm D: "*We are aware that decarbonisation is a priority, and we are investing in technologies that help us reduce emissions*".

Taken together, these insights illustrate how consolidated technologies, though often adopted primarily for efficiency and competitiveness, also generate significant indirect environmental benefits, contributing to reductions in energy consumption, waste, and emissions. Their centrality in the digitalisation trajectory of manufacturing firms constitutes a first step toward the broader convergence between digital transformation and sustainability, which is further examined in the subsequent sections.

4.2.2 Advanced manufacturing technologies

A second cluster emerging from the thematic analysis concerns advanced manufacturing technologies, including robotics, additive manufacturing (3D printing), and augmented/virtual reality (AR/VR). These technologies are widely perceived as high-potential tools capable of accelerating processes and reducing errors, yet their adoption remains limited and strongly contingent upon product characteristics and production line configurations.

Among this group, robotics stands out as the most consolidated, associated with tangible benefits in both productivity and workplace safety. As the Head of Plant of Firm B noted, "*Robotics has significantly reduced production times while at the same time improving operator safety*".

Similarly, the CTO of Firm A remarked, "*We have observed that robotics not only increases efficiency but also enhances safety in the factory*".

In the case of 3D printing, managers primarily emphasise its value in prototyping and new product development. The Head of Innovation of Firm C explained, "*The introduction of 3D printing has been useful for speeding up prototyping and reducing design errors*". At the same time, adoption remains selective: "*The use of 3D printing varies greatly depending on the type of product and its specific requirements*".

Immersive technologies such as AR and VR are considered to be at an early stage in manufacturing, though managers acknowledge promising applications, particularly for workforce training and remote maintenance. As the Head of Innovation of Firm D observed, "*We are evaluating the use of augmented reality to improve operator training, but for now these remain pilot projects*".

Overall, these opinions suggest that advanced manufacturing technologies are regarded as promising but still experimental. Their sustainability contribution is perceived in terms of reducing design errors, lowering material use in prototyping, and improving working conditions, yet not as a systemic or large-scale impact. This differentiates them clearly from consolidated technologies, positioning them as potential drivers of the twin transition, though still distant from full integration into production processes.

4.2.3 Emerging technologies

The third cluster concerns emerging technologies, including blockchain, the metaverse, advanced machine learning, web 4.0, and 5G. Although these solutions are frequently highlighted in debates about the future of digitalisation, within the manufacturing context under study, they are generally met with scepticism and regarded as having limited short-term relevance for production processes.

This scepticism is most visible in the case of the metaverse. As the Chief Technology Officer of Firm C stated unequivocally, "*The metaverse does not exist for us; we are a company that manufactures physically, we live on the shop floor. For me, the metaverse is pure fantasy in our industry*". A similar view was echoed by the Chief Technology Officer of Firm B: "*We do not see how the metaverse could have a real impact on our operations, except in scenarios that are very distant*".

Other frontier technologies are also struggling to find meaningful applications. The Managing Director of Firm D commented, "*Blockchain is widely discussed, but for us it has no direct applicability in manufacturing production*". Likewise, the Head of Plant of Firm A observed, "*We know that 5G will have important impacts in the future, but at the moment we do not see an immediate return on investment*".

Such remarks highlight a significant gap between the hype surrounding emerging technologies and their actual transferability to industrial practice. From an environmental standpoint, moreover, these technologies are not perceived as delivering tangible benefits: unlike IoT or AI, there is no evidence here of positive spillovers in terms of reduced consumption, emissions, or waste.

Taken together, the findings suggest that while managers acknowledge the potential long-term role of blockchain, the metaverse, and 5G, these technologies currently remain at the margins of corporate strategies. Their status is that of "awaiting validation", distant from contributing meaningfully to the twin transition.

4.2.4 ES as a transversal dimension

Another thematic cluster concerns ES, which emerged as a transversal dimension across all interviews. Although it was not identified as the primary motivation for adopting digital technologies, sustainability consistently appeared as an unexpected yet significant benefit, gradually recognised by managers as an integral component of corporate strategies.

Several respondents stressed the growing importance of decarbonisation and emission reduction. As the Head of Innovation Firm D explained, "*We are aware that decarbonisation is a priority, and we are investing in technologies that help us reduce emissions*". Similarly, the Head of Plant of Firm B highlighted the contribution of digital monitoring: "*Digital tracking allows us to monitor energy consumption and intervene more quickly to reduce it*".

Consolidated technologies were frequently associated with indirect environmental impacts. The Managing Director of Firm C noted, "*Our digitalisation strategy aims to balance operational efficiency with environmental sustainability*". Echoing this perspective, the Chief Sustainability Officer of Firm A observed, "*We have seen that the use of IoT and robotics not only reduces costs but also helps to limit material waste*".

The theme of sustainability was also linked to waste and energy management. The Head of Innovation of Firm C pointed out, "*Our familiarity with big data has enabled us to optimise operations and reduce waste*". Likewise, the Head of Plant of Firm B emphasised the integration of economic and environmental objectives: "*Decarbonisation and efficiency are not separate goals, digital technologies help us achieve them together*".

While digital adoption in manufacturing firms was initially driven by considerations of competitiveness and efficiency, managers have increasingly recognised its capacity to advance environmental sustainability objectives. This intertwining of economic and ecological performance reinforces the idea that digitalisation, even when motivated by business imperatives, functions as an unexpected driver of the green transition.

4.2.5 Human factors and competences

Another second-order code concerns human factors and competences, which managers consistently identified as essential conditions for fully realising the potential of digital technologies. Digitalisation is not perceived merely as a technical process but as an organisational transformation that requires new skills, adaptability, and careful attention to employee well-being.

The theme of continuous training was repeatedly emphasised across interviews. As the Head of Innovation of Firm C explained, "Our digital transition is supported by constant training programmes; without them, technologies would never be fully exploited". Similarly, the Plant Manager of Firm B observed, "Managers' familiarity with digital technologies has facilitated a smoother transition to new processes".

The issue of competences also intersects with organisational adaptability. The Head of Plant of Firm D noted, "Advanced technologies cannot be adopted without developing organisational agility; we must be ready to change models and processes quickly".

A particularly salient aspect is the link between digitalisation and worker well-being. The CTO of Firm A highlighted, "Robotics not only improves productivity but also reduces risks for operators, enhancing overall workplace safety". Additionally, several firms are moving towards open innovation approaches to address competence gaps. The Managing Director of Firm C explained, "We have launched experimental projects with universities and technology partners to acquire know-how that we can later internalise".

These quotes show that the success of sustainable digitalisation depends not only on the availability of new technologies but also on firms' ability to develop skill readiness and manage change inclusively. The twin transition is thus also a human transition, one that intertwines competences, organisational culture, and worker welfare.

4.3 Aggregate theme: Technology-specific pathways to the Digital Green Transformation

The thematic analysis revealed that the integration of digitalisation and sustainability does not follow a uniform trajectory but rather unfolds as a technology-specific pathway, in which each technology contributes differently, and with varying intensity, to the green transition. This result, summarised in Figure 1, illustrates the progression from managers' language (*first-order concepts*) to *second-order themes* and ultimately to the aggregate theme.

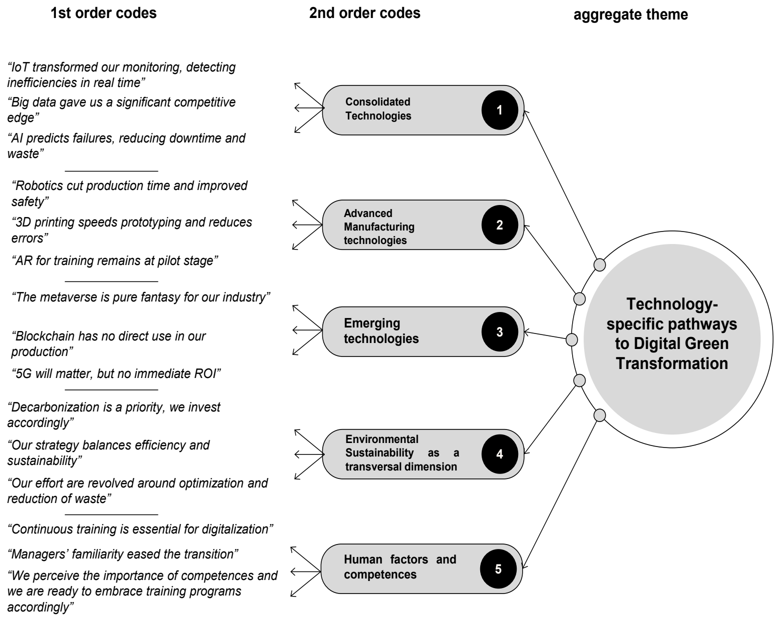
Consolidated technologies, such as IoT, AI, Big Data, and Cloud, emerge as the principal drivers of digital and green transformation. Although primarily adopted for efficiency and competitiveness, they also generate unexpected environmental benefits, including reductions in energy consumption, waste minimisation, and enhanced workplace safety. Advanced technologies, robotics, additive manufacturing, and AR/VR occupy an intermediate position. They are regarded as promising and already demonstrate positive effects on prototyping, error reduction, and workforce training. Yet their diffusion remains context-dependent, and they are still distant from systemic integration.

Emerging technologies, including blockchain, the metaverse, and 5G, are generally perceived as marginal or irrelevant to the current manufacturing context. They represent the more speculative side of digitalisation, still awaiting empirical validation and rarely associated with concrete environmental outcomes.

Across these categories, the sustainability cluster highlights that environmental objectives are seldom the primary motivation for adoption.

Instead, sustainability typically emerges as an indirect and unintended outcome of digitalisation: managerial pursuit of efficiency often translates into lower emissions, reduced consumption, and less waste, thereby turning the business case into a lever for environmental performance. Similarly, the human and competences cluster underscores that the twin transition cannot be realised without adequate human capital: continuous training, organisational agility, and attention to employee well-being are indispensable conditions for enabling these trajectories. The overarching theme is captured by the notion of Technology-Specific Pathways to the Digital Green Transformation. The digital-green transition does not advance as a single, homogeneous phenomenon but through differentiated trajectories shaped by the maturity and applicability of individual technologies. Italian manufacturing firms thus demonstrate that digital efficiency can act as an unexpected driver of sustainability, provided it is supported by appropriate competences and by the strategic reframing of environmental benefits arising from digital technology adoption. Figure 1 presents the results of the Gioia methodology applied in this study. Illustrative first-order concepts, derived from managers' quotes, were grouped into five second-order themes: consolidated technologies, advanced manufacturing technologies, emerging technologies, environmental sustainability, and human factors and skills. These themes converge into the aggregate dimension of "Technology-specific pathways to the Digital Green Transformation," highlighting how digital technologies contribute to sustainability outcomes in differentiated ways depending on their level of maturity and contextual applicability.

Fig. 1: Technology-specific pathways to the Digital Green Transformation



Source: Author's own work

5. Discussion

5.1 Theoretical implications

Our study advances the debate on the intersection between digital transformation and environmental sustainability in three connected ways. First, we contribute by developing a technology-specific interpretation of the twin transition in the Italian manufacturing sector. Whereas much of the extant literature treats digital transformation as a unitary and homogeneous process (e.g., Guandalini, 2022; Bohnsack *et al.*, 2022), our multiple case study shows that this view risks obscuring the heterogeneity of digital technologies. By analysing managerial perceptions, we demonstrate that consolidated technologies such as IoT, AI, Big Data, and Cloud Computing already deliver tangible environmental benefits, often introduced under the guise of efficiency; that advanced technologies such as robotics, 3D printing, and AR/VR remain promising but are selectively deployed (Markowitz *et al.*, 2018; Wang *et al.*, 2021); and that emerging technologies such as the metaverse, blockchain, and 5G are perceived as marginal. This contextualised evidence underscores that the twin transition does not evolve as a uniform phenomenon but grows through multiple, uneven trajectories shaped by the maturity and applicability of each technology (Lu, 2018; Hanelt *et al.*, 2017; Camodeca and Almici, 2021). By disaggregating the digital into its component technologies, our study challenges the dominant all-inclusive perspective and provides a more nuanced framework for understanding how specific tools enable sustainability in manufacturing.

Second, our findings highlight efficiency as a hidden driver of sustainability. In line with managerial sensemaking, most digital initiatives were motivated by efficiency, competitiveness, and cost reduction rather than by explicit environmental objectives. Nevertheless, managers consistently reported positive spillovers in the form of reduced waste, lower emissions, and greater energy efficiency. This extends prior research that has framed sustainability largely as a strategic orientation or a response to regulatory and social pressures (Hart and Milstein, 1999; Costantini and Mazzanti, 2012; Hahn *et al.*, 2015; George and Schillebeeckx, 2021). Our contribution lies in showing that sustainability frequently emerges unintentionally as a by-product of efficiency-oriented digital adoption. In doing so, we add an important layer to the business-case logic in sustainability research (Porter and Kramer, 2011; Engert and Baumgartner, 2016), demonstrating that environmental outcomes, though initially unintended, can be strategically leveraged by firms.

Third, we bring the human dimension into the debate on digital-green convergence. Our analysis reveals that technologies alone do not guarantee sustainability outcomes; their effectiveness depends critically on the availability of skills, organisational agility, and attention to employee well-being. Digital investments generated meaningful sustainability effects only when accompanied by continuous training, managerial competence development, and collaborative initiatives with external partners such as universities and research centres. This finding resonates with prior work on the role of human capital and dynamic capabilities in enabling organisational change (Eisenhardt and Martin, 2000; Engert and Baumgartner, 2016; Chesbrough, 2006) but extends it by positioning human readiness as a fundamental enabler of technology-specific sustainability pathways. In this way, our study bridges the literature on digital sustainability (Seele and Lock, 2017; Guandalini, 2022) with research on skills and organisational resilience, highlighting that the twin transition is as much a social and cognitive process as it is a technological one (Crupi *et al.*, 2025). Taken together, these contributions suggest that the Digital Green Transformation is a mosaic of technology-specific pathways shaped by efficiency imperatives, organisational competences, and managerial sensemaking.

Interpreting technology-specific pathways through the RBV and DC lens

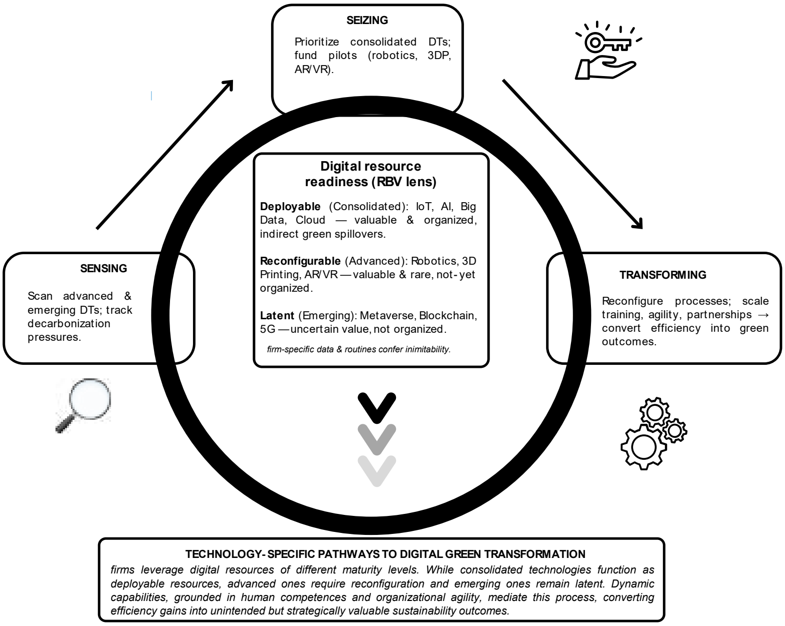
To better grasp the essence of our findings, we interpreted them through the lens of the Resource-Based View, which posits that firms achieve sustained competitive advantage by mobilising resources that are valuable, rare, inimitable, and organisationally embedded (Barney, 1991; Peteraf, 1993).

As stated in the previous paragraph, within Italian manufacturing firms, digital technologies clearly emerge as heterogeneous resources. Consolidated technologies, such as IoT, AI, Big Data, and Cloud Computing, already function as deployable resources embedded in operational routines, generating efficiency and, often unintentionally, environmental benefits. Advanced manufacturing technologies, including robotics, 3D printing, and AR/VR, constitute resources with strong potential, but their application remains limited and contingent on product and process characteristics. Emerging technologies, such as the metaverse, blockchain, and 5G, are not yet incorporated into firms' resource bases and are therefore perceived as minor. This resource-based interpretation underscores that the digital-green nexus cannot be conceptualised in aggregate terms; rather, it depends on the distinct features and maturity levels of the technologies firms command.

Yet, as the Dynamic Capabilities perspective reminds us, the mere possession of resources does not suffice to sustain competitive advantage (Teece *et al.*, 1997; Eisenhardt and Martin, 2000). What matters is the capacity to integrate, reconfigure, and transform these resources in response to shifting environmental and market conditions. Our findings confirm the need for dynamic capabilities of sensing, seizing, and transforming. Firms must: sense advanced and emerging technologies while interpreting environmental pressures such as decarbonisation; seize opportunities by allocating resources to consolidated technologies while financing targeted experiments with advanced ones; transform processes by scaling training, fostering organisational agility, and engaging in external partnerships so that efficiency gains can be converted into tangible environmental outcomes. In this perspective, human and organisational competences act as the micro-foundations of dynamic capabilities that enable the transformation of digital resources into sustainability pathways.

The final component of the framework synthesises this central insight: Digital Green Transformation unfolds as a constellation of technology-specific pathways, shaped by the maturity of digital resources and by firms' dynamic capabilities. Sustainability, in this view, emerges as an unintended but strategically significant outcome of efficiency-driven digital adoption. Building on this integrated perspective, we advance a framework (Figure 2) that conceptualises technology-specific pathways to the Digital Green Transformation.

Fig. 2: Framework for achieving the Digital Green Transformation



Source: Author's own work

5.2 Managerial implications

The findings of this study provide valuable insights for manufacturing firms seeking to embrace Digital Green Transformation and enhance their ES practices. First, our analysis delivers a snapshot of the technologies currently most relevant to the Italian manufacturing sector, highlighting their varying degrees of maturity and adoption. Managers should capitalise on these outcomes, making them visible to stakeholders and translating efficiency gains into legitimacy and competitive advantage. Second, advanced technologies call for targeted experimentation and selective investment. Their value extends beyond efficiency, offering opportunities to redesign processes and products while improving workplace safety. To achieve systemic impact, however, managers must complement experimentation with investments in organisational capabilities and pathways for scaling successful initiatives. Third, emerging technologies still show limited applicability in manufacturing. A prudent approach is recommended: firms should monitor these technologies through sensing activities and pilot testing only where clear returns are foreseeable, avoiding premature investments that may divert resources from more mature and impactful solutions.

Finally, across all clusters, human competences and organisational agility are the decisive levers for turning technologies into tangible outcomes. Continuous training, cross-functional learning, and stronger collaborations enable firms to build the dynamic capabilities required to align digital innovation with ES objectives. Therefore, managers should view digital transformation as a pattern of differentiated technological trajectories. By assessing the current state of the sector, prioritising investments wisely, and developing the necessary organisational competences, firms can steer the Digital Green Transformation toward pathways that simultaneously enhance competitiveness and create environmental value.

5.3 Limitations and future research directions

This study is not without limitations, which at the same time open up promising directions for future research. First, the analysis is narrowed to the context of Italian manufacturing, which inevitably limits the generalisability of the findings to other industries or to geographical contexts characterised by different industrial structures. Comparative studies at the international level could enrich our understanding of digital-green trajectories across more heterogeneous production systems. Furthermore, the classification of technologies into three clusters provides a useful analytical map, but one that remains necessarily streamlined. Certain technologies may fall into more than one category depending on sectoral and organisational conditions. More fine-grained analyses, conducted on individual technologies or specific supply chains, would allow for deeper insights into their peculiarities and interdependencies. Additionally, the study does not capture the temporal dimension of technological adoption. Longitudinal approaches would be valuable to trace how pathways of Digital Green Transformation evolve over time, particularly in response to external shocks or new policy interventions (e.g., the Italian PNRR or the European Green Deal). A further limitation concerns the timeliness of data collection, which took place in 2022. Considering the fast-evolving nature of digital and green technologies, as well as the regulatory and market pressures shaping sustainability strategies, some contextual conditions may have changed since then. Accordingly, the results should be interpreted with caution, recognising that more recent developments could influence firms' digital-green trajectories. Future studies may therefore update or replicate this analysis using new data to capture the dynamic evolution of digital-green initiatives over time. Finally, although this research highlights the importance of competences and dynamic capabilities, it does not fully explore the organisational, cultural, and institutional factors that may either enable or constrain adoption. Future investigations, potentially drawing on qualitative methodologies, could shed light on these dimensions, offering a more comprehensive understanding of the mechanisms underpinning transformation. At the same time, this study highlights the need for quantitative studies capable of systematically measuring the effects of different clusters of digital technologies on firms' environmental performance at the point of adoption.

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Academic or professional position and contacts

Giuseppe Lanfranchi
Post-Doctoral Researcher in AI, Technology and Innovation Management
Visiting Researcher Bayes Business School
City University of London
e-mail: giuseppe.lanfranchi@studenti.unime.it

Antonio Crupi
Associate Professor of Digital Transformation Management
University of Messina - Italy
e-mail: crupi.antonio@unime.it

Fabrizio Cesaroni
Full Professor of Strategic Management
University of Messina - Italy
e-mail: fabrizio.cesaroni@unime.it

A – APPENDIX

Utilizing the AHP's methodology process, we refined the scaling system and mathematical operations to suit the specific needs of our study, ensuring precise calculations. The scoring spectrum, ranging from 1 (the lowest possible score) to 9 (the highest), was derived from participant responses, indicating the potential impact of each technology.

Judgments	Numerical Value
Extremely superior	9
Strongly superior	7
Moderately superior	5
Superior	3
Equal	1

Based on the simulation outcomes, we established a classification system to interpret these scores: a value of 9 indicates that Technology A revealed to be extremely more useful and well-known compared to Technology B. A value of 7 represents a significantly higher level of awareness and utility. A value of 5 signifies a moderate superiority of Technology A over Technology B. Lastly, a value of 3 indicates a slight superiority of Technology A over Technology B. If a value of 1 is assigned, it signifies that the technologies have an equal level of perceived awareness and utility.

Table A. Pair wise comparison matrix

Factors	Iot	Big Data	AI	Cloud Computing	3D Printers	Robotics	AR	Block chain	Machine Learning	Metaverso	Materiali intelligenti
Iot	1	5	3	7	7	1	7	9	5	9	5
Big Data	1/5	1	1	5	5	1	3	7	3	9	5
AI	1/3	1	1	5	3	1	3	7	1	9	5
Cloud Computing	1/7	1/5	1/5	1	1	1	1	3	1	5	1
3D Printers	1/7	1/5	1/3	1	1	1	3	3	1	5	1
Robotics	1	1	1	1	1	1	7	9	5	9	5
AR	1/7	1/3	1/3	1	1/3	1/7	1	5	1	5	1
Block chain	1/9	0	1/7	1/3	1/3	1/9	0	1	1	3	1
Machine Learning	1/5	1/3	1	1	1	1/5	1	1	1	7	5
Metaverso	1/9	1/9	1/9	1/5	1/5	1/9	1/5	1/3	1/7	1	1
Materiali Intelligenti	1/5	1/5	1/5	1	1	1/5	1	1	1/5	1	1
Sum	**3,58**	**9,52**	**8,32**	**23,53**	**20,87**	**6,77**	**27,40**	**46,33**	**19,34**	**63,00**	**31,00**

Subsequently, after entering the values for the comparison between individual technologies and obtaining the sum of perceived values for each technology, we proceeded to normalize the values to ensure a fair and meaningful comparison among the technologies. Normalization allowed us to standardize the values and bring them within a common range, enabling a more accurate assessment and comparison of their relative importance and utility.

sinergie
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Vol. 43, Issue 3, 2025

Table B. Normalized Pair wise comparison matrix

Factors	Iot	Big Data	AI	Cloud Computing	3D Printers	Robotics	AR	Block chain	Machine Learning	Metaverso	Materiali intelligenti	Sum	Criteria Weights
Iot	0,2790	0,5252	0,3605	0,2975	0,3355	0,1478	0,2555	0,1942	0,2585	0,1429	0,1613	2,9578	0,2689
Big Data	0,0558	0,1050	0,1202	0,2125	0,2396	0,1478	0,1095	0,1511	0,1551	0,1429	0,1613	1,6007	0,1455
AI	0,0930	0,1050	0,1202	0,2125	0,1438	0,1478	0,1095	0,1511	0,0517	0,1429	0,1613	1,4387	0,1308
Cloud Computing	0,0399	0,0210	0,0240	0,0425	0,0479	0,1478	0,0365	0,0647	0,0517	0,0794	0,0323	0,5877	0,0534
3D Printers	0,0399	0,0210	0,0401	0,0425	0,0479	0,1478	0,1095	0,0647	0,0517	0,0794	0,0323	0,6767	0,0615
Robotics	0,2790	0,1050	0,1202	0,0425	0,0479	0,1478	0,2555	0,1942	0,2585	0,1429	0,1613	1,7548	0,1595
AR	0,0399	0,0350	0,0401	0,0425	0,0160	0,0211	0,0365	0,1079	0,0517	0,0794	0,0323	0,5022	0,0457
Block chain	0,0310	0,0150	0,0172	0,0142	0,0160	0,0164	0,0073	0,0216	0,0517	0,0476	0,0323	0,2702	0,0246
Machine Learning	0,0558	0,0350	0,1202	0,0425	0,0479	0,0296	0,0365	0,0216	0,0517	0,1111	0,1613	0,7132	0,0648
Metaverso	0,0310	0,0117	0,0134	0,0085	0,0096	0,0164	0,0073	0,0072	0,0074	0,0159	0,0323	0,1605	0,0146
Materiali Intelligenti	0,0558	0,0210	0,0240	0,0425	0,0479	0,0296	0,0365	0,0216	0,0103	0,0159	0,0323	0,3374	0,0307
												11	1

Once the values were normalized, we proceeded to calculate their consistency ratio. The consistency ratio provided a measure of the reliability and consistency of the pairwise comparisons made during the analysis. It ensured that the obtained rankings are not affected by inconsistencies or random variations in the decision-making process. By calculating the consistency ratio, we can assess the reliability of the obtained results and ensure that they accurately reflect the perceived differences in the utility and awareness of the technologies being compared.

Table C. Calculating Consistency Ratio

C.W.	0,2689	0,1455	0,1308	0,0534	0,0615	0,1595	0,0457	0,0246	0,0648	0,0146	0,0307			
Factors	Iot	Big Data	AI	Cloud Computing	3D Printers	Robotics	AR	Block chain	Machine Learning	Metaverso	Materiali intelligenti	Weighted sum value	Criteria Weights	WSV/CW
Iot	0,2689	0,7276	0,3924	0,3740	0,4306	0,1595	0,3196	0,2211	0,3242	0,1314	0,1534	3,5026	0,2689	13,03
Big Data	0,0538	0,1455	0,1308	0,2671	0,3076	0,1595	0,1370	0,1719	0,1945	0,1314	0,1534	1,8525	0,1455	12,73
AI	0,0896	0,1455	0,1308	0,2671	0,1846	0,1595	0,1370	0,1719	0,0648	0,1314	0,1534	1,6356	0,1308	12,51
Cloud Computing	0,0384	0,0291	0,0262	0,0534	0,0615	0,1595	0,0457	0,0737	0,0648	0,0730	0,0307	0,6560	0,0534	12,28
3D Printers	0,0384	0,0291	0,0436	0,0534	0,0615	0,1595	0,1370	0,0737	0,0648	0,0730	0,0307	0,7647	0,0615	12,43
Robotics	0,2689	0,1455	0,1308	0,0534	0,0615	0,1595	0,3196	0,2211	0,3242	0,1314	0,1534	1,9692	0,1595	12,34
AR	0,0384	0,0485	0,0436	0,0534	0,0205	0,0228	0,0457	0,1228	0,0648	0,0730	0,0307	0,5642	0,0457	12,36
Block chain	0,0299	0,0208	0,0187	0,0178	0,0205	0,0177	0,0091	0,0246	0,0648	0,0438	0,0307	0,2984	0,0246	12,15
Machine Learning	0,0538	0,0485	0,1308	0,0534	0,0615	0,0319	0,0457	0,0246	0,0648	0,1022	0,1534	0,7705	0,0648	11,88
Metaverso	0,0299	0,0162	0,0145	0,0107	0,0123	0,0177	0,0091	0,0082	0,0093	0,0146	0,0307	0,1731	0,0146	11,86
Materiali Intelligenti	0,0538	0,0291	0,0262	0,0534	0,0615	0,0319	0,0457	0,0246	0,0130	0,0146	0,0307	0,3843	0,0307	12,53
													L.max=	12,37

L.max - n	1,37
n - 1	10
CI	0,14
CR	0,09

RI=1.51

B – APPENDIX

Semi-structured questions
Could you describe the company's structure, including the number of manufacturing plants, the number of employees, and its international relations?
Does the company have a research and development (R&D) department? If yes, how many people work in that department?
Does the company have a dedicated department for environmental sustainability?
Is the R&D department currently conducting experiments related to the potential of digital technologies? If yes, what types of experiments?
Is the company currently initiating projects specifically dedicated to sustainability?
In which functional areas do you believe significant achievements in environmental sustainability can be made?
Which of these digital technologies are you familiar with and find interesting for future developments in the mechanical industry?
- Internet of Things (IoT)
- Big Data and Analytics
- Artificial Intelligence
- Cloud Computing
- 3D Printers
- Robotics
- Augmented Reality
- Blockchain
- Machine Learning
- Metaverse
- Virtual Reality
- Smart Materials
- Web 4.0
- 5G
- Agility

C – APPENDIX

Interviewed	***Company***	***Age***	***Gender***
Head of Business Development	A	30-40	Male
Chief Technology Officer	A	40-50	Male
Chief Sustainability Officer	A	30-40	Male
Head of Plants	A	40-50	Male
Chief Technology Officer	B	40-50	Male
Chief Sustainability Officer	B	30-40	Male
Head of Plants	B	40-50	Male
Head of Innovation	C	30-40	Female
CSR manager	C	40-50	Female
Managing Director	C	30-40	Female
Chief Technology Officer	C	40-50	Male
Managing Director	D	20-30	Male
Head of Innovation	D	30-40	Male
Head of Plants	D	40-50	Male

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