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Industry 5.0: Transitioning Towards Human-centric, Sustainable, and Resilient Manufacturing Systems

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Abstract
Purpose: This study investigates the current state of Industry 5.0 awareness and initial receptiveness among manufacturing organizations, examining how this emerging paradigm, centered on human well-being, environmental sustainability, and organizational resilience, can complement Industry 4.0's technological gains and identify practical pathways for guiding the transition.
Design/methodology/approach: A mixed-methods design combined a structured quantitative survey, based on the SURE 5.0 self-assessment tool, with qualitative content analysis of open-ended responses. The survey targeted approximately 200 manufacturing organizations in northern Portugal, yielding 32 completed responses. Quantitative data were analyzed using descriptive statistics and reliability analysis (Cronbach's alpha = 0.794), complemented by a comprehensive review of theoretical frameworks, including the European Commission's three-pillar Industry 5.0 model and relevant ISO standards.
Findings: While 60% of respondents demonstrated receptiveness to Industry 5.0 principles, only 28% reported familiarity with the concept. Readiness varied across pillars: resilience achieved the strongest consensus (84%), human-centricity showed moderate strength (78%), and sustainability revealed the most critical implementation gaps. Workforce capability emerged as a decisive barrier, with 66% reporting only intermediate technology knowledge. Based on these findings, the study proposes a hybrid roadmap adapting the validated 6Ps framework, covering Product, Process, Platform, People, Partnership, and Performance, to integrate Industry 5.0 values with Industry 4.0 technologies.
Originality: The study provides empirical evidence on Industry 5.0 receptiveness in a significant European manufacturing region. Its main original contribution is the hybrid 6Ps Industry 4.0–5.0 roadmap, bridging established digital transformation methodology with Industry 5.0's human-centric, sustainable, and resilient value orientation.

Keywords: Industry 5.0; Human-centric manufacturing; Sustainability; Resilience; Smart society; Digital transformation

Paper type: Original Research Article

1. Introduction

The trajectory of industrial development has been marked by successive revolutionary phases, each fundamentally reshaping production systems, economic structures, and societal organization (Schwab, 2016). The first industrial revolution mechanized production through steam power; the second enabled mass production through electrical energy; the third introduced automation and computerization; and the fourth revolution–Industry 4.0–brought cyber-physical systems, artificial intelligence (AI), and the Internet of Things (IoT) to the manufacturing floor (Kagermann et al., 2013; Lasi et al., 2014). While Industry 4.0 has delivered remarkable improvements in operational efficiency and productivity, it has simultaneously raised critical concerns about technological unemployment, environmental sustainability, and the displacement of human expertise from production processes (Bonekamp & Sure, 2015; Xu et al., 2021).
In response to these challenges, the European Commission formally introduced the concept of Industry 5.0 in 2021, articulating a vision that transcends pure technological optimization to embrace broader societal values (European Commission, 2021). Industry 5.0 represents not a replacement of Industry 4.0 but rather its complement and evolution–a paradigm that seeks to harness advanced technologies in service of human well-being, environmental sustainability, and organizational resilience (European Commission, 2021; Xu et al., 2021). This human-centric approach recognizes that sustainable competitive advantage in manufacturing requires more than technological sophistication; it demands systems that amplify rather than supplant human creativity, judgment, and adaptability (Nahavandi, 2019; Javaid et al., 2022).
Despite its conceptual appeal, Industry 5.0 remains relatively nascent in both academic literature and industrial practice. Most manufacturing organizations continue to grapple with Industry 4.0 implementation, creating uncertainty about its practical implications (Maddikunta et al., 2022). Critical questions persist: How should organizations navigate the transition

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from Industry 4.0 to Industry 5.0? What specific capabilities and organizational changes does this transition require? To what extent are manufacturing organizations aware of and prepared for Industry 5.0 principles? This study addresses these questions through empirical investigation of manufacturing organizations in northern Portugal, a region characterized by substantial industrial activity and ongoing digital transformation efforts (Mourtzis, 2021; Golovianko et al., 2023).

The research presents three primary contributions: First, it provides empirical evidence regarding current Industry 5.0 awareness and initial receptiveness among manufacturing organizations, revealing significant knowledge gaps and key barriers to implementation. Second, it proposes a hybrid roadmap that adapts the validated 6Ps digital transformation model–a six-dimensional maturity framework developed under the CAPRI project, spanning Product, Process, Platform, People, Partnership and Performance dimensions–to integrate Industry 5.0 principles with existing Industry 4.0 technologies. Third, it identifies priority areas for organizational development, particularly emphasizing the critical role of workforce training and human-machine collaboration frameworks. These contributions address the practical needs of manufacturing organizations while advancing theoretical understanding of industrial evolution beyond technological determinism toward socio-technical integration.

2. Literature Review and Theoretical Framework

Understanding Industry 5.0 requires contextualizing it within the broader trajectory of industrial development. The first industrial revolution (circa 1760-1840) introduced mechanization through water and steam power, fundamentally altering agricultural and artisanal production systems (Mokyr, 2018). The second revolution (1870-1914) brought electrification, enabling mass production and assembly line manufacturing that dramatically expanded production capacity while creating new forms of labor organization (Chandler, 1990; Smil, 2017).

The third industrial revolution, beginning in the 1970s, introduced electronics, telecommunications, and computers to manufacturing, enabling programmable automation and the beginnings of digital integration (Rifkin, 2011). Industry 4.0, formally articulated at Germany's Hannover Fair in 2011, represents the current paradigm characterized by cyber-physical systems, IoT, cloud computing, big data analytics, and AI (Kagermann et al., 2013; Liao et al., 2017). These technologies enable unprecedented levels of connectivity, real-time data processing, and autonomous decision-making in manufacturing systems (Lee et al., 2015; Lu, 2017).

However, Industry 4.0's emphasis on automation and efficiency optimization has generated concerns about labor displacement, deskilling of workers, and environmental sustainability (Frey & Osborne, 2017; Sachs et al., 2015). Industry 5.0 emerged partly in response to these concerns, explicitly positioning human workers as collaborators rather than competitors with intelligent machines (Nahavandi, 2019). The European Commission's Industry 5.0 framework identifies three core pillars: human-centricity (placing worker well-being and development at the center of production), sustainability (integrating circular economy principles and environmental responsibility), and resilience (building adaptive capacity to withstand disruptions) (European Commission, 2021; Xu et al., 2021).

The human-centric pillar of Industry 5.0 represents a fundamental reconceptualization of the human-technology relationship in manufacturing. Rather than viewing automation as a means to reduce human involvement, Industry 5.0 seeks to create synergistic human-machine collaborations that leverage the complementary strengths of each (Nahavandi, 2019; Romero et al., 2016). Humans contribute creativity, contextual understanding, ethical judgment, and adaptability to novel situations–capabilities that remain difficult to automate (Brynjolfsson & McAfee, 2014). Machines provide precision, consistency, tireless execution, and rapid processing of vast data sets (Kaplan & Haenlein, 2019).

Collaborative robots (cobots) exemplify this principle, designed to work safely alongside human operators rather than in isolation (Bauer et al., 2016; Matheson et al., 2019). Unlike traditional industrial robots separated by safety cages, cobots incorporate sensors and control systems that enable physical interaction with humans while maintaining safety (Krüger et al., 2009; Villani et al., 2018). This enables flexible production systems that combine human judgment with robotic precision and endurance (El Zaatari et al., 2019).

Beyond physical collaboration, Industry 5.0 emphasizes cognitive augmentation–using AI and advanced analytics to enhance human decision-making rather than replace it (Jarrahi, 2018; Wilson & Daugherty, 2018). Digital twin technologies, for instance, enable workers to interact with virtual representations of physical systems, facilitating more informed maintenance decisions and process optimization (Grieves & Vickers, 2017; Tao et al., 2019). The ISO 27501:2019 standard on human-centered organizations provides guidelines for implementing such approaches, emphasizing employee well-being, skill development, and meaningful work (International Organization for Standardization, 2019a).

The sustainability pillar addresses the environmental impacts of industrial production, integrating circular economy principles into manufacturing systems (Ghobakhloo, 2020; Kristoffersen et al., 2021). Traditional linear production models–extract, produce, consume, dispose–generate substantial waste and environmental degradation (Ellen MacArthur Foundation, 2015). Industry 5.0 advocates for closed-loop systems that minimize waste through design, enable product life extension through

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maintenance and remanufacturing, and facilitate material recovery and recycling (Nascimento et al., 2019; Rosa et al., 2020). Digital technologies play a crucial enabling role in sustainable manufacturing. IoT sensors and analytics enable real-time monitoring of energy consumption, material flows, and emissions, facilitating optimization and waste reduction (Bonilla et al., 2018; Stock & Seliger, 2016). AI-powered predictive maintenance extends equipment lifespan while reducing energy consumption from equipment failures (Lee et al., 2014; Kang et al., 2016). Additive manufacturing enables on-demand production with minimal material waste and supports product customization that can extend product life by better matching user needs (Ford & Despeisse, 2016; Garmulewicz et al., 2018).

International standards provide frameworks for implementing sustainable practices. ISO 50001 establishes requirements for energy management systems, helping organizations systematically improve energy performance (International Organization for Standardization, 2018). ISO 14001 addresses broader environmental management, requiring organizations to identify environmental aspects, set improvement objectives, and monitor progress (International Organization for Standardization, 2015). Integration of these standards into Industry 5.0 implementations ensures systematic rather than ad hoc approaches to sustainability (Garetti & Taisch, 2012; Moldavska & Welo, 2017).

The COVID-19 pandemic starkly illustrated manufacturing's vulnerability to unexpected disruptions, spurring renewed attention to organizational resilience (Ivanov, 2020; Chowdhury et al., 2021). The resilience pillar of Industry 5.0 addresses this need, emphasizing adaptive capacity, flexibility, and preparedness for diverse threats, including pandemics, natural disasters, cyber-attacks, and supply chain disruptions (Rapaccini et al., 2020; Dolgui & Ivanov, 2021).

Resilient manufacturing systems exhibit several key characteristics: redundancy in critical capabilities, diversity in supply sources and production methods, modularity enabling reconfiguration, and connectivity facilitating rapid information flow and coordination (Christopher & Peck, 2004; Sheffi & Rice, 2005). Digital technologies enhance these capabilities through improved visibility, predictive analytics, and flexible automation (Ivanov et al., 2019; Belhadi et al., 2021). For instance, digital twins enable simulation of disruption scenarios and testing of response strategies before real-world implementation (Ivanov & Dolgui, 2021).

ISO 22301:2019 provides a framework for business continuity management systems, guiding organizations in identifying threats, assessing vulnerabilities, and developing response and recovery plans (International Organization for Standardization, 2019b). The related ISO 22316:2021 standard specifically addresses organizational resilience, offering principles and attributes for building adaptive capacity (International Organization for Standardization, 2021). These standards complement Industry 5.0 by providing structured approaches to resilience building rather than reactive crisis management (Duchek, 2020; Ponomarov & Holcomb, 2009).

Industry 5.0 exists within the broader context of Society 5.0, a concept introduced by Japan's Cabinet Office that envisions technology-enabled social systems balancing economic advancement with solutions to social challenges (Cabinet Office, 2016; Fukuyama, 2018). Society 5.0 represents the convergence of cyber and physical spaces to create human-centered societies that balance economic development with social problem-solving (Shiroishi et al., 2018; Deguchi et al., 2020).

This alignment between industrial and societal evolution reflects growing recognition that technological change must serve broad social objectives rather than narrow efficiency goals (Carayannis et al., 2021). Manufacturing organizations increasingly face expectations from workers, customers, investors, and regulators to demonstrate social responsibility beyond profit maximization (Porter & Kramer, 2011; Elkington, 2018). Industry 5.0 provides a framework for meeting these expectations while maintaining competitive advantage through innovation and adaptability (Mourtzis et al., 2022).

Despite growing attention to Industry 5.0 in policy documents and academic literature, significant gaps persist in understanding its practical implementation. Most existing research focuses on conceptual frameworks and technological capabilities rather than organizational readiness, implementation barriers, and transition pathways (Maddikunta et al., 2022; Golovianko et al., 2023). Furthermore, limited empirical evidence exists on how manufacturing organizations currently perceive and prepare for Industry 5.0, particularly in regions with strong industrial traditions such as northern Portugal.

This study addresses these gaps through three primary objectives: (1) Assess current awareness and understanding of Industry 5.0 principles among manufacturing organizations in northern Portugal, with particular attention to the three core pillars of human-centricity, sustainability, and resilience; (2) Identify key barriers and enablers for Industry 5.0 implementation, including technological capabilities, workforce readiness, organizational culture, and strategic orientation; (3) Develop a practical roadmap for Industry 5.0 transition that integrates established digital transformation frameworks with Industry 5.0 principles, providing actionable guidance for organizations at different maturity levels.

3. Research Methodology

This study employs a mixed-methods research design combining quantitative survey data with qualitative content analysis to achieve a comprehensive understanding of Industry 5.0 readiness in manufacturing organizations (Creswell & Plano Clark, 2017). The approach aligns with established practices in industrial engineering research where both numerical measurement and contextual understanding are essential for actionable insights (Edmondson & McManus, 2007).

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The quantitative component utilizes structured questionnaires with Likert-scale responses, enabling statistical analysis of attitudes, awareness, and perceived capabilities across Industry 5.0 dimensions. The qualitative component captures open-ended responses regarding organizational challenges, improvement suggestions, and future directions, providing contextual richness that purely quantitative methods cannot achieve (Bryman, 2006). This integration of methods follows an exploratory sequential design, in which qualitative insights inform the interpretation of quantitative patterns (Creswell, 2014).

The study focuses on manufacturing organizations in the Porto and Braga districts of northern Portugal, regions characterized by significant industrial activity and ongoing digital transformation initiatives. These districts were selected for their concentration of manufacturing firms, ranging from traditional sectors (textiles, footwear, metal products) to advanced manufacturing (electronics, pharmaceuticals, automotive components), providing the diversity necessary for generalizable insights (Etikan et al., 2016).

Initial sampling identified approximately 200 organizations through industrial association databases, with contacts distributed via email, professional networks, social media (LinkedIn), and industrial association partnerships. The survey remained active for 60 days (August 15 to October 13, 2024), ultimately yielding 32 completed responses representing a 16% response rate. While this response rate is modest, it falls within acceptable ranges for organizational surveys in industrial contexts where response burden and confidentiality concerns often limit participation (Baruch & Holtom, 2008). A plausible source of non-response bias should be acknowledged: organizations less familiar with Industry 5.0 may have been less likely to complete a questionnaire on the topic, as it would not seem professionally relevant to them. This is corroborated by the fact that 94% of actual respondents reported at least intermediate knowledge of Industry 5.0 concepts, suggesting self-selection toward more digitally aware organizations. Findings should therefore be interpreted cautiously, as the sample is likely to overrepresent firms already engaged in digital transformation. Importantly, this also implies that true awareness of Industry 5.0 across the broader population of manufacturing firms in northern Portugal may be even lower than the 28% familiarity rate observed here.

The questionnaire was developed based on the SURE 5.0 project's self-assessment tool, designed to support European SMEs in Industry 5.0 transition (SURE 5.0 Consortium, 2023). A preliminary version of this study was presented at the CENTERIS 2025 conference, where the instrument's reliability and the main descriptive findings were first reported (Palinhas et al., 2026). The present article extends that work through a more comprehensive analysis of readiness, barriers, and the proposed transition roadmap. The instrument comprises seven sections with 36 questions (34 mandatory), structured as follows:

a) Section 1 (S1): Organizational and respondent profile - 5 questions capturing location, business sector, employee count, technological knowledge level, and functional area.
b) Section 2 (S2): Smart factory and intelligent production systems - 6 questions assessing familiarity with Industry 4.0/5.0 concepts, attitudes toward advanced technologies (AI, IoT, robotics), and current technological investments.
c) Section 3 (S3): Organizational strategy - 4 questions examining strategic orientation toward customization, data sharing practices, technology adoption, and data-driven decision-making.
d) Section 4 (S4): Sustainability and environment - 3 questions addressing waste reduction, circular economy practices, sustainability policies, and environmental metrics.
e) Section 5 (S5): Human-centricity - 3 questions evaluating worker health and safety, well-being indicators, and workforce competencies for data handling.
f) Section 6 (S6): Resilience - 2 questions assessing business continuity planning and crisis management structures.
g) Section 7 (S7): Feedback and improvement suggestions - 4 questions (2 optional) capturing qualitative input on organizational improvements, future focus areas, implementation willingness, and questionnaire relevance.

Sections 2-6 employed five-point Likert scales (1=Strongly Disagree to 5=Strongly Agree) to enable quantitative analysis while capturing nuanced attitudes. Section 7 used the Net Promoter Score (NPS) methodology, with a 10-point scale, for two questions assessing implementation willingness and questionnaire relevance. All questions were framed positively to minimize acquiescence bias (DeVellis, 2016).

Quantitative data analysis utilized descriptive statistics, including frequencies, percentages, means, standard deviations, and variance. Reliability analysis employed Cronbach's alpha to assess internal consistency of multi-item scales, with alpha values above 0.70 indicating acceptable reliability (Nunnally & Bernstein, 1994). Microsoft Forms provided initial descriptive analytics, supplemented by Minitab statistical software for advanced analysis, including correlation matrices, item analysis, and distribution assessments.

Qualitative responses underwent content analysis, systematically coding open-ended responses to identify recurring themes, patterns, and relationships (Hsieh & Shannon, 2005). Coding followed an iterative process: initial familiarization with responses, development of preliminary codes, systematic application of codes to all responses, and thematic synthesis. This approach enables both frequency analysis (counting theme occurrences) and interpretive analysis (understanding meaning

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and context) (Krippendorff, 2018).

Several limitations should be acknowledged. First, the sample size (n=32) and 16% response rate limit statistical power and generalizability, though the sample provides valuable exploratory insights. Given the likely non-response bias toward more digitally aware organizations, all findings should be treated as indicative of the more advanced segment of the manufacturing population rather than representative of the sector as a whole. Second, the cross-sectional design captures a single point in time during rapid conceptual development of Industry 5.0, meaning organizational awareness and attitudes may evolve quickly. Third, self-reported data introduces potential biases: social desirability may lead respondents to overreport positive attitudes toward well-being and environmental responsibility. At the same time, the absence of objective verification means the study captures how companies describe their awareness and priorities, not necessarily how they actually operate in practice. Fourth, geographic focus on northern Portugal may limit transferability to regions with different industrial structures, regulatory environments, or cultural contexts. Future research should address these limitations through larger samples, longitudinal designs, multi-method verification, and cross-regional comparisons.

4. Results

4.1. Sample characteristics

The 32 respondents represent diverse organizational and individual profiles. Geographically, 69% of respondents were from Braga district organizations, while 31% represented Porto district firms, reflecting stronger response from Braga despite equal initial sampling (Figure 1).

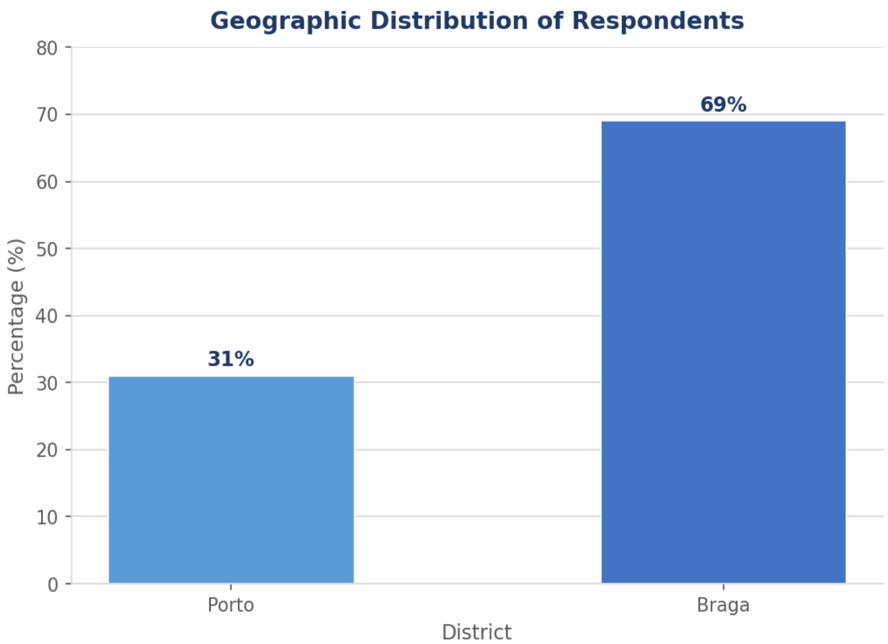

Figure 1. Geographic distribution of survey respondents across the Porto and Braga districts

Business sectors showed considerable diversity: 47% identified as ‘Other’ beyond the 16 predefined categories, indicating Portugal’s varied manufacturing landscape. Health sector representation reached 13%, followed by construction (9%) and pharmaceuticals/chemicals (6%). The 70% industrial versus 30% service-sector split aligned with sampling priorities focused on manufacturing transformation.

The organizational size distribution revealed 22% from firms with 10–50 employees (small enterprises), 13% from 50–250 employee firms (medium enterprises), and 13% from organizations with more than 250 employees (large enterprises). The remaining 52% correspond to micro enterprises with fewer than 10 employees–a category prevalent in Portugal’s manufacturing landscape but often excluded from standard SME classifications (IAPMEI, 2023). This high share of microenterprises should be considered when interpreting the findings, as resource constraints and organizational capabilities differ substantially from those of larger firms.

Respondent technological knowledge levels present a critical finding: 66% reported intermediate knowledge, 22% advanced

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knowledge, and only 6% claimed expert-level technological capabilities. Merely 6% characterized their knowledge as basic. This intermediate-heavy distribution suggests widespread basic familiarity with digital technologies but limited deep expertise–a potential barrier to advanced Industry 5.0 implementation requiring a sophisticated understanding of human-machine collaboration, AI systems, and digital twin technologies.

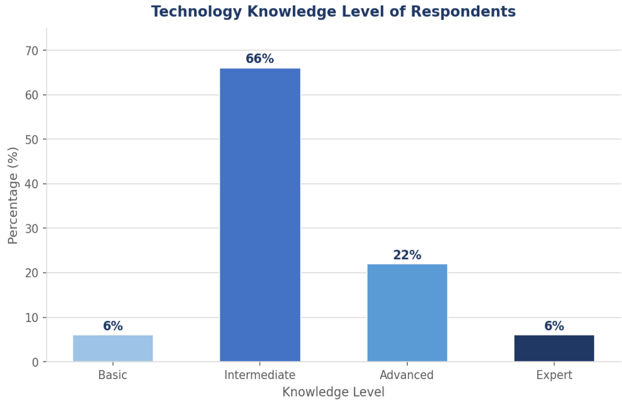

Figure 2. Technology knowledge levels among survey respondents

Functional roles of respondents revealed unexpected patterns: 28% worked in production/maintenance, 22% held management positions, 22% occupied 'Other' roles (commercial, development, administrative), and 13% specialized in quality management. Surprisingly, only 9% came from project management/planning roles despite these functions' expected centrality in strategic change initiatives (Figure 2). The strong production/maintenance representation suggests frontline workers' direct engagement with technological transformation, while substantial management participation indicates executive-level attention to Industry 5.0 concepts.

4.2. Overall reliability and response patterns

Reliability analysis of the 18 Likert-scale items (Sections 2-6) yielded Cronbach's alpha = 0.794, indicating acceptable internal consistency (Nunnally & Bernstein, 1994). This confirms that items reliably measure related constructs despite spanning diverse Industry 5.0 dimensions. Item-total correlations ranged from 0.07 to 0.65, with most items showing moderate to strong correlations, though some items (particularly Q_2.5 and Q_5.3) showed weaker associations, suggesting they may capture distinct constructs.

Aggregate response patterns across Sections 2-6 reveal important insights: 36% of responses indicated 'Moderately Agree' and 24% 'Strongly Agree', yielding 60% positive agreement with Industry 5.0-related statements. However, 26% chose neutral responses, suggesting substantial uncertainty or lack of knowledge. Negative responses ('Moderately Disagree' and 'Strongly Disagree') totaled only 15%, indicating limited active opposition but considerable ambivalence (Figure 3).

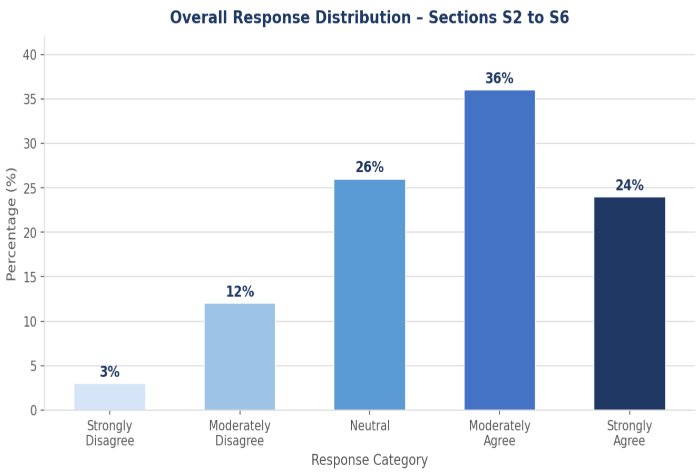

Figure 3. Overall response distribution across Industry 5.0 assessment dimensions (Sections 2-6)

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This pattern–majority receptiveness but substantial neutrality–suggests organizations recognize Industry 5.0's potential importance without yet possessing a clear understanding or implementation strategies. The high neutral percentage stands out in particular, potentially reflecting either genuinely undecided opinions or a lack of knowledge preventing definitive responses.

4.3. *Smart factory and technology awareness (section 2)*

Industry 4.0 familiarity (Q_2.1) showed 46.8% agreement that organizations understand Industry 4.0 fundamentals, while 28.1% disagreed and 25% remained neutral. This mixed pattern suggests uneven Industry 4.0 maturity–some organizations have substantially engaged with digitalization, while others remain in early stages. The mean score of 3.22 (SD=1.01) confirms moderate overall familiarity with considerable variability.

Advanced technology importance (Q_2.2: AI, robotics, IoT, big data, augmented reality) garnered 56.2% agreement regarding future organizational importance, with only 12.4% disagreement. The 31.2% neutral responses likely reflect uncertainty about specific technology applications rather than outright skepticism. A mean score of 3.63 (SD=1.13) indicates moderately positive attitudes toward advanced technology adoption, though the variability suggests divergent readiness levels.

Critically, Industry 5.0 familiarity (Q_2.3) revealed substantial knowledge gaps: only 28.1% agreed their organizations understand Industry 5.0 fundamentals, while 34.4% disagreed and 37.5% remained neutral. The mean score of 2.88 (SD=1.10)–the lowest across all items–indicates limited Industry 5.0 awareness. This finding confirms Industry 5.0's nascent status in organizational consciousness and highlights the urgent need for education and knowledge dissemination. The high neutral percentage suggests many respondents lacked sufficient information to form opinions, underscoring knowledge gaps.

4.4. *Organizational strategy and digital integration (section 3)*

Customer-centric solution development (Q_3.1) achieved strong support: 71.8% agreed organizations invest in personalized solutions aligned with customer needs and market trends, with only 12.5% disagreement. Mean score of 3.91 (SD=1.00) indicates this aspect of Industry 5.0–mass customization and customer focus–resonates strongly with organizational strategies. This finding suggests existing business imperatives (customer satisfaction, competitive differentiation) align with Industry 5.0 personalization principles, potentially facilitating adoption.

Data sharing practices (Q_3.2) revealed more hesitation: 43.8% remained neutral about sharing digital logistics and inventory data with customers and suppliers, while 31.2% agreed and 25% disagreed. This hesitation likely reflects concerns about competitive intelligence, data security, and loss of control–common barriers to supply chain transparency (Treiblmaier, 2018). The high neutral percentage suggests organizations recognize potential benefits but remain uncertain about implementation risks.

Technology investment patterns (Q_3.3, Q_3.4) showed moderate adoption: 59.4% confirmed investments in robotics, automation, wireless tracking, and cloud systems, while 28.1% remained neutral. Similarly, 56.2% reported using data analytics for decision support, though 43.7% either disagreed or remained neutral. These patterns suggest partial digital transformation–organizations have begun technology adoption but haven't achieved comprehensive integration. The neutral responses may indicate ongoing implementation projects not yet yielding clear results.

4.5. *Sustainability and environmental management (section 4)*

Waste reduction and material reuse (Q_4.1) achieved 50% agreement, with 37.5% neutral and 12.5% disagreement. The substantial neutral percentage suggests either inconsistent practices or a lack of formal circular economy policies. Service sector respondents may have contributed to neutrality/disagreement due to limited direct material handling, though waste reduction applies across sectors.

Sustainability policies (Q_4.2) garnered 71.9% agreement regarding energy efficiency, water consumption, and waste management initiatives, yet concerning gaps persist: 18.8% remained neutral, and 9.3% disagreed. Given sustainability's regulatory requirements and public expectations, these figures suggest some organizations lack even basic environmental management systems–a significant barrier to Industry 5.0's sustainability pillar.

Environmental metrics monitoring (Q_4.3) showed 59.4% agreement about tracking sustainability indicators, though 21.9% remained neutral and 18.7% disagreed. This pattern suggests that while most organizations have implemented some sustainability measures, systematic monitoring and performance tracking remain incomplete. Without robust metrics, organizations cannot effectively manage improvement or communicate sustainability performance to stakeholders (Searcy, 2012). This finding is corroborated at the firm level by a case study of a Portuguese metalworking company, where

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commitment to sustainable materials was strong, but the strategic potential of sustainability as a driver of new market opportunities remained largely unrecognized (Costa et al., 2026). An important contextual factor is the EU's mandatory Corporate Sustainability Reporting Directive (CSRD), which requires large enterprises and listed companies to report detailed ESG metrics. Inspection of the sample by company size reveals that large enterprises (exceeding 250 employees, 13% of the sample) showed notably higher rates of environmental monitoring, consistent with regulatory obligations. Medium and small enterprises showed considerably lower adoption. In contrast, micro enterprises (<10 employees) reported the lowest monitoring rates–a pattern suggesting that mandatory reporting requirements are a meaningful driver of environmental metrics implementation, and that voluntary adoption remains limited without such obligations. This finding reinforces the case for extending regulatory incentives and support mechanisms to smaller firms to accelerate the sustainability pillar of Industry 5.0.

4.6. Human-centric practices (section 5)

Worker health, safety, and well-being (Q_5.1) achieved the second-highest agreement: 78.1% confirmed organizations prioritize these aspects in objectives and strategies. However, concerning gaps remain: 15.6% neutral and 6.2% disagreement indicate some organizations inadequately address worker well-being despite legal requirements and its centrality to Industry 5.0. Mean score of 4.22 (SD=0.94) indicates strong but not universal commitment.

Well-being indicators (Q_5.2) revealed more variation: 50% agreed organizations maintain performance and well-being metrics, while equal percentages (25% each) disagreed or remained neutral. This split suggests that while organizations implement safety measures, systematic measurement and communication of well-being indicators remain underdeveloped. This disconnect between policy and measurement limits organizations' ability to demonstrate human-centricity tangibly. It is consistent with evidence from a firm-level assessment in the Portuguese metalworking sector, where employee participation was strongly valued (mean 4.105). However, investment in ergonomic workstations and occupational health conditions remained the lowest-scoring dimension (mean 3.056) (Costa et al., 2026).

Data handling competencies (Q_5.3) showed 56.2% agreement that production workers possess sufficient skills for data manipulation and presentation, yet 18.7% disagreed–a significant minority lacking essential digital competencies. Combined with earlier findings showing 66% of the workforce with intermediate technology knowledge, these results highlight workforce development as critical to Industry 5.0 success. Effective human-machine collaboration requires workers who can interpret system outputs, identify anomalies, and make informed decisions (Romero et al., 2016).

4.7. Resilience and business continuity (section 6)

Business recovery management (Q_6.1) generated the strongest consensus: 84.3% agreed all organizations should implement recovery plans for external disruptions, with only 6.2% disagreement. Mean score of 4.38 (SD=0.75)–the highest across all items–reflects the COVID-19 pandemic's lasting impact on organizational consciousness. This near-universal recognition of resilience's importance suggests favorable conditions for implementing Industry 5.0's resilience pillar, though recognition doesn't guarantee the capability to implement it.

Risk management structures (Q_6.2) similarly achieved strong support: 81.2% agreed organizations should establish internal structures for risk management and business continuity, with only 6.2% disagreement. Mean score of 4.28 (SD=0.92) confirms widespread recognition that resilience requires dedicated resources and clear responsibilities rather than ad hoc responses. However, agreement about what should be done does not necessarily translate to implementation–future research should examine actual resilience capabilities versus aspirations (Figure 4).

Figure 4. Agreement levels across Industry 5.0 core pillars show variation in organizational readiness

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4.8. *Improvement priorities and future directions (section 7)*

Qualitative analysis of improvement suggestions (Q_7.1) identified clear priorities: Training and skills development emerged as the dominant theme (25%), emphasizing both technical skills for new technologies and soft skills for adaptation and problem-solving. Process improvement ranked second (16%), focusing on workflow optimization, communication enhancement, and waste reduction. Human resource focus ranked third (13%), focusing on employee engagement, well-being initiatives, and organizational culture. Work flexibility (9%) and salary conditions (3%) received less emphasis, suggesting organizations recognize training and systemic improvements as more fundamental than compensation adjustments (Figure 5).

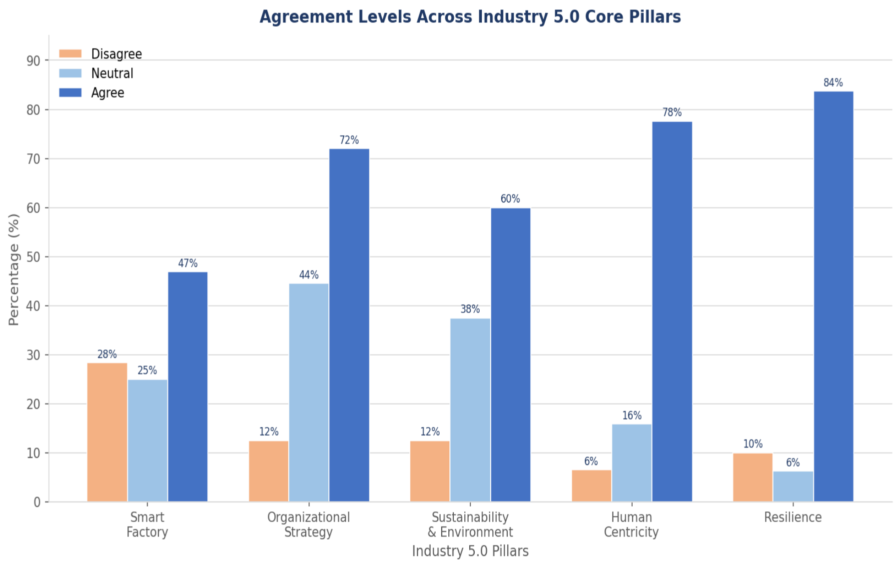

Figure 5. Priority areas for organizational improvement based on open-ended suggestions

These priorities align remarkably well with Industry 5.0 principles, particularly the emphasis on human-centricity, worker development, and meaningful work (European Commission, 2021). The prominence of training aligns with Saniuk et al.'s (2022) findings on workforce development as Industry 5.0's critical success factor. The process improvement emphasis reflects lean manufacturing's enduring influence in Portuguese industry while showing awareness that efficiency must integrate with sustainability and human well-being.

Future focus areas (Q_7.2) showed more uncertainty: 63% provided no response, suggesting either a lack of strategic clarity or a reluctance to commit publicly to specific directions. Among those responding, process automation (16%) and technology implementation (9%) dominated, indicating continued Industry 4.0 orientation. Sustainability received 6% mention, while human-centricity themes remained largely absent. This disconnect between improvement priorities (emphasizing training and people) and stated future focus (emphasizing technology) may reflect strategic confusion about balancing Industry 4.0 completion with Industry 5.0 principles.

4.9. *Implementation willingness and survey relevance*

Net Promoter Score (NPS) methodology assessed implementation willingness (Q_7.3) and questionnaire relevance (Q_7.4) on 10-point scales. Willingness to implement yielded a mean score of 7.37 (on a 1-10 scale, where 1-6 are detractors, 7-8 are passives, and 9-10 are promoters), indicating moderately positive readiness to implement Industry 5.0 principles. Distribution showed clustering in the 6-8 range (representing cautious positivity), with few strong promoters (9–10) or definite detractors (1–6). This pattern suggests conditional readiness dependent on a better understanding of implementation requirements, resource availability, and demonstrated benefits.

Professional relevance (Q_7.4) scored slightly higher at 7.66, indicating respondents found the questionnaire professionally valuable and relevant. Despite the average completion time of 11.5 minutes exceeding the 7-minute target, this positive perception suggests the topic resonates with organizational concerns. The professional relevance score exceeding implementation willingness may indicate awareness of Industry 5.0 importance despite uncertainty about implementation approaches–recognizing the destination without a clear roadmap (Figure 6).

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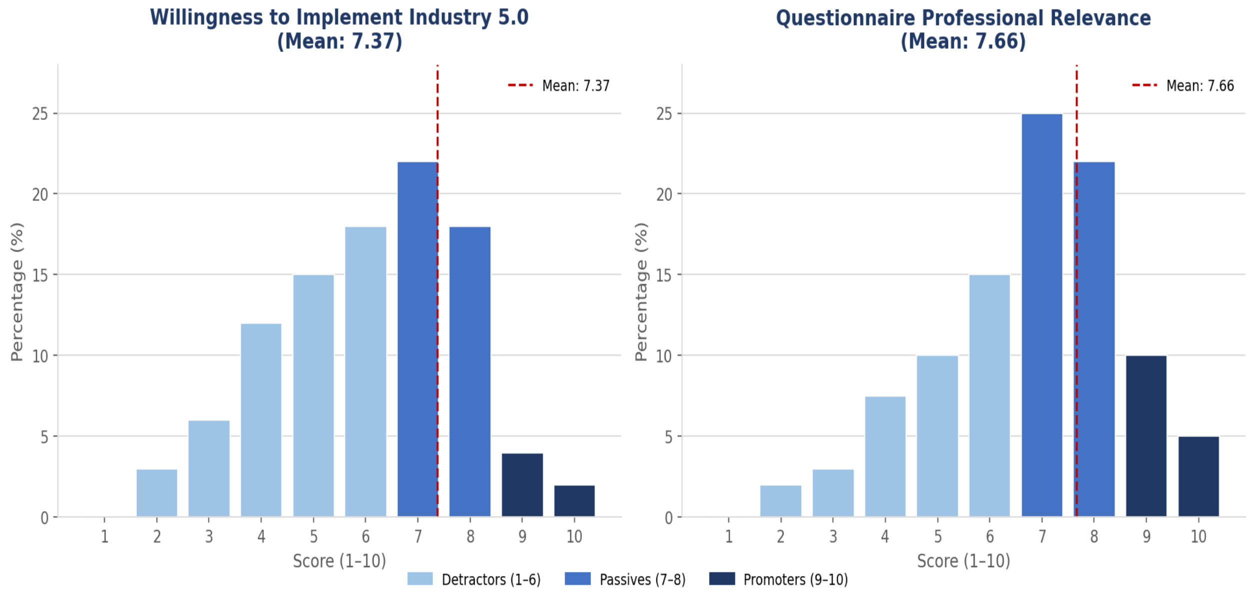

Qualitative feedback (Q_7.5) reinforced these themes: respondents emphasized people focus, working conditions, and Industry 5.0 novelty. Several explicitly acknowledged unfamiliarity with Industry 5.0 concepts despite recognizing their apparent importance. This honest acknowledgment of knowledge gaps validates the questionnaire's educational function while highlighting dissemination challenges for emerging industrial paradigms.

5. Discussion: towards an industry 5.0 roadmap

5.1. The need for structured transition frameworks

Survey findings reveal substantial gaps between Industry 5.0 principles and current organizational capabilities. While receptiveness exists (60% positive responses), guidance for systematic implementation remains lacking. Organizations recognize the importance of sustainability yet incompletely measure it; they value worker well-being yet inadequately monitor it; they acknowledge the necessity of resilience yet often lack formal capabilities. This pattern–widespread principle acceptance without clear implementation pathways–creates frustration and potentially delayed action.

Structured roadmaps address this gap by translating abstract principles into concrete actions sequenced according to organizational readiness and resource availability (Schumacher et al., 2016). Effective roadmaps do not prescribe universal solutions but provide frameworks that organizations can adapt to their contexts, technologies, and strategic priorities (Müller et al., 2018). This study proposes such a framework by adapting the established 6Ps digital transformation model to integrate Industry 5.0 values with Industry 4.0 technologies. The roadmap is grounded in both the literature review and the empirical survey findings: survey data directly informed the selection of priority dimensions (notably workforce development, identified by 25% of respondents as the top improvement area), the framing of sustainability gaps (incomplete measurement despite high policy adoption), and the emphasis on resilience as an entry point given its strong organizational recognition. Where specific survey evidence is limited, the roadmap draws on established theoretical frameworks, and this distinction is explicitly acknowledged in the discussion of each phase.

5.2. The 6Ps framework as a foundation

The CAPRI project's 6Ps digital transformation roadmap provides a validated methodology for assessing and guiding manufacturing digitalization (CAPRI Consortium, 2022). The framework organizes transformation across six dimensions grouped into technical pillars (Product, Process, Platform) and socio-economic pillars (People, Partnership, Performance). Each dimension progresses through five maturity levels from minimal digital integration (Level 1) to state-of-the-art implementation (Level 5).

Product dimensions address digital integration in product design, including sensors, connectivity, and smart functionality, enabling products to serve as data sources. Process dimension examines production system digitalization through automation, analytics, and optimization. Platform dimension focuses on digital infrastructure for data management, integration, and value creation through data exploitation.

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People dimension assesses workforce digital competencies, change management, and organizational culture. Partnership dimension evaluates collaboration with external stakeholders, including suppliers, customers, and technology providers. Performance dimension examines business model innovation enabled by digitalization and new value creation mechanisms (CAPRI Consortium, 2022).

This comprehensive framework captures digitalization's technical and social dimensions, making it suitable for Industry 5.0 adaptation. However, its Industry 4.0 focus requires modification to explicitly integrate human-centricity, sustainability, and resilience - Industry 5.0's defining characteristics.

5.3. Hybrid industry 4.0-5.0 integration model

Critical debate surrounds Industry 5.0's relationship to Industry 4.0: replacement, coexistence, or hybrid integration? Ivanov (2023) argues for hybrid models combining Industry 4.0's technological capabilities with Industry 5.0's value orientation. This approach recognizes that abandoning Industry 4.0 investments would be economically irrational, while pursuing technology without human-centric and sustainability considerations increasingly fails to meet stakeholder expectations (Maddikunta et al., 2022).

The hybrid model reframes Industry 5.0 not as a technological revolution but as a re-orientation of existing and emerging technologies toward broader social and environmental objectives (Xu et al., 2021). AI and machine learning–Industry 4.0 technologies–become Industry 5.0 tools when deployed to reduce worker exposure to hazardous conditions, optimize energy consumption, or enhance production resilience. Similarly, IoT sensors serve Industry 5.0 when monitoring environmental impacts and worker safety rather than only production metrics (Javaid et al., 2022).

This study's roadmap adopts this hybrid perspective, modifying each 6Ps dimension to embed Industry 5.0 principles while maintaining Industry 4.0 technological progression. For instance, the Product dimension now explicitly considers products' lifecycle environmental impacts, repairability, and recyclability alongside smart functionality. The Process dimension incorporates worker well-being metrics and collaborative robotics alongside automation efficiency. The People dimension emphasizes meaningful work and worker agency rather than merely technological skill acquisition.

5.4. Roadmap structure and application guidelines

The proposed roadmap maintains the 6Ps structure while integrating Industry 5.0 assessment criteria at each maturity level. Organizations should approach implementation through three phases:

a) Phase 1: Assessment and Baseline Establishment - Organizations evaluate current maturity across all six dimensions using Industry 5.0-enhanced criteria. This assessment identifies strengths, gaps, and priorities, establishing a baseline for measuring progress. Assessment should involve diverse stakeholders–not only technical specialists but also frontline workers, sustainability managers, and strategic leaders–to capture a comprehensive organizational reality.
b) Phase 2: Strategy Development and Prioritization - Based on assessment results, organizations develop transformation strategies aligned with their strategic objectives, competitive context, and resource constraints. Rather than pursuing uniform advancement across dimensions, organizations prioritize based on business impact, stakeholder expectations, and existing capabilities. For instance, organizations with strong environmental commitments might prioritize Process and Partnership dimensions for sustainability integration, while those facing talent attraction challenges might emphasize the People dimension for human-centric work design.
c) Phase 3: Implementation and Continuous Improvement - Organizations execute prioritized initiatives while establishing feedback mechanisms for learning and adaptation. Industry 5.0 implementation rarely follows a linear progression–organizations may advance rapidly in some dimensions while plateauing in others. Continuous reassessment enables strategy adjustment as technologies mature, standards evolve, and organizational capabilities develop.

Critical success factors emerged from the literature review and survey findings. First, executive commitment and visible leadership prove essential for cultural transformation toward human-centric values (Bonekamp & Sure, 2015). Second, workforce development requires systematic attention–survey findings showed 66% possess only intermediate technology knowledge, limiting advanced implementation. Third, cross-functional collaboration prevents siloed approaches that fragment Industry 5.0's integrated vision. Fourth, measurement systems must balance traditional performance metrics with sustainability indicators and human well-being measures. Fifth, external partnerships provide access to expertise, technologies, and best practices that organizations cannot develop internally (Müller et al., 2018; Mourtzis et al., 2022).

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5.5. Addressing identified barriers

Survey findings identified specific barriers the roadmap must address. Limited Industry 5.0 awareness (only 28.1% familiar) requires extensive education and knowledge dissemination. The roadmap includes explicit learning objectives at each maturity level, gradually building understanding through practical experience rather than assuming prior knowledge. Organizations begin with foundational concepts (human-centricity principles, circular economy basics) before advancing to sophisticated applications (cognitive automation, predictive resilience).

Workforce capability gaps demand systematic competency development. The roadmap's People dimension explicitly sequences skill-building from basic digital literacy through advanced data analytics to human-AI collaboration expertise. Rather than expecting workers to independently acquire capabilities, organizations must invest in structured training programs, mentoring relationships, and experiential learning opportunities (Saniuk et al., 2022). Survey respondents' emphasis on training (25% of improvement suggestions) confirms this priority's organizational salience.

Sustainability implementation gaps–where many organizations have policies but incomplete measurement–require integrated metrics frameworks. Statistical analysis of the survey data reveals that organizations investing in waste reduction tend systematically to develop more structured environmental policies ($r = 0.786$, $p < 0.001$), and that formalization of those policies is in turn associated with greater control of environmental metrics ($r = 0.665$, $p < 0.001$), suggesting a coherent maturity progression rather than isolated initiatives (Palinhas et al., 2026). The roadmap capitalizes on this progression by emphasizing baseline measurement before improvement targets, ensuring organizations can track progress rather than pursuing unmeasured initiatives. Integration with established standards (ISO 14001; ISO 50001) provides structured approaches backed by extensive best practices (Garetti & Taisch, 2012).

Strategic ambiguity–reflected in 63% non-response to future focus questions–suggests many organizations lack clear transformation visions. The roadmap addresses this through explicit articulation of maturity level characteristics, enabling organizations to envision progression stages. Concrete examples at each level illustrate what progression entails, reducing abstraction that may paralyze decision-making (Schumacher et al., 2016).

5.6. Industry 5.0 standards integration

The roadmap explicitly incorporates relevant international standards supporting Industry 5.0 principles. ISO 27501:2019 (human-centered organizations) provides guidelines for organizational cultures prioritizing employee well-being, capability development, and meaningful work (International Organization for Standardization, 2019a). ISO 14001:2015 and ISO 50001:2018 establish frameworks for environmental and energy management, respectively, operationalizing sustainability commitments (International Organization for Standardization, 2015, 2018). ISO 22301:2019 and ISO 22316:2021 address business continuity and organizational resilience, essential for Industry 5.0's resilience pillar (International Organization for Standardization, 2019b, 2021).

These standards serve multiple functions: they provide structured implementation guidance refined through global best practice; they enable third-party certification demonstrating commitment to stakeholders; they facilitate benchmarking against peers and competitors; and they ensure systematic approaches rather than ad hoc initiatives (Moldavska & Welo, 2017). The roadmap maps standards to relevant maturity levels, indicating when particular frameworks become most valuable. For instance, basic environmental awareness might precede formal ISO 14001 certification pursued at intermediate maturity levels.

6. Conclusions and Future Directions

6.1. Key findings and contributions

This research investigated Industry 5.0 awareness and initial receptiveness among northern Portuguese manufacturing organizations, revealing several critical findings. First, substantial knowledge gaps persist: only 28% of respondents reported familiarity with Industry 5.0 concepts despite the majority (60%) being receptive to its principles once explained. This disconnect between potential acceptance and current awareness indicates significant knowledge dissemination challenges for this emerging paradigm. It is more accurate to characterize these findings as evidence of initial receptiveness rather than implementation readiness–organizations show openness to the principles of Industry 5.0 but lack the knowledge, metrics, and structured capabilities to operationalize them systematically.

Second, organizations demonstrate uneven readiness across Industry 5.0's three pillars. Resilience generated the strongest consensus (84% agreement on business continuity importance), likely due to COVID-19's lasting impact. Human-centricity showed moderate strength with 78% valuing worker well-being, but only 50% systematically measuring it. Sustainability revealed concerning implementation gaps, with 72% having policies but only 59% monitoring environmental metrics. These

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patterns suggest widespread principle acknowledgment without consistent translation to systematic practice.

Third, workforce capabilities present critical barriers. Sixty-six percent of respondents possessed only intermediate technology knowledge, potentially limiting sophisticated Industry 5.0 implementation, requiring an advanced understanding of AI, digital twins, and human-machine collaboration frameworks. Furthermore, 19% reported insufficient production worker competencies for data handling–essential for data-driven decision-making in smart manufacturing environments.

Fourth, training and skills development emerged as the dominant improvement priority (25% of suggestions), followed by process improvement (16%) and people focus (13%). This emphasis aligns closely with Industry 5.0's human-centric orientation while recognizing that technological transformation requires capable, engaged workforces rather than technology deployment alone.

The study contributes both empirically and methodologically. Empirically, it provides evidence regarding current Industry 5.0 awareness and readiness in a significant manufacturing region, identifying specific knowledge gaps and capability deficits requiring attention. Methodologically, it demonstrates how validated digital transformation frameworks can be adapted to integrate Industry 5.0 principles, providing practical guidance for organizations navigating this transition. The hybrid 6Ps roadmap offers a structured approach balancing Industry 4.0 technological capabilities with Industry 5.0 value orientation.

6.2. Practical implications for organizations and policymakers

For manufacturing organizations, findings suggest several actionable priorities. First, invest systematically in workforce development covering both technical competencies (data analytics, AI fundamentals, digital twin operation) and adaptive capabilities (change management, cross-functional collaboration, continuous learning orientation). Survey results indicate this investment enjoys strong employee support and addresses critical capability gaps.

Second, establish comprehensive measurement systems for sustainability and human well-being alongside traditional operational metrics. Without measurement, organizations cannot manage improvement, communicate performance to stakeholders, or identify high-impact intervention points. Integrate relevant ISO standards (14001, 50001, 27501) to leverage established frameworks rather than creating proprietary approaches.

Third, recognize Industry 5.0 as a complement to rather than a replacement of Industry 4.0. Organizations should continue to benefit from digitalization while consciously reorienting technology deployment toward human-centric, sustainable, and resilient objectives. This hybrid approach avoids false dichotomies between technological advancement and social responsibility.

For policymakers and industrial associations, findings highlight knowledge dissemination as a critical priority. With only 28% familiar with Industry 5.0, extensive education efforts targeting diverse organizational roles (executives, engineers, production workers) prove necessary. Support mechanisms might include training programs, demonstration centers showcasing Industry 5.0 implementations, and knowledge networks facilitating peer learning.

Additionally, policymakers should ensure regulatory frameworks and incentive structures support Industry 5.0 principles. Current policies often inadvertently reward narrow efficiency optimization over broader social and environmental considerations. Revised frameworks might incorporate human-centricity and sustainability criteria into innovation funding, provide preferential treatment for circular economy practices, and establish recognition programs celebrating exemplar implementations (European Commission, 2021).

6.3. Limitations and future research directions

Several limitations constrain interpretation and generalizability. The modest sample size (n=32) and 16% response rate limit statistical power and representativeness. As discussed in Section 3, the likely self-selection of digitally aware respondents means findings should be understood as exploratory evidence of initial receptiveness rather than a definitive account of Industry 5.0 readiness across manufacturing firms broadly. While providing valuable preliminary insights, findings require validation through larger samples, enabling more sophisticated statistical analysis, including factor analysis, structural equation modeling, and cluster analysis, to identify distinct organizational types.

Cross-sectional design captures a single snapshot during rapid Industry 5.0 conceptual evolution, potentially missing important temporal dynamics. Longitudinal research tracking organizations over time could illuminate implementation trajectories, the effectiveness of different approaches, and how organizational learning proceeds. Such research might identify critical transition points, common pitfalls, and success patterns informing more refined guidance.

Self-reported data introduces potential biases, including social desirability bias (overreporting positive practices) and a lack of objective verification. Future research should incorporate multiple data sources–document analysis, direct observation, performance metrics–enabling triangulation and validation of self-reported information (Yin, 2018). Comparative analysis across different cultural and regulatory contexts would illuminate how national institutions shape Industry 5.0 adoption patterns.

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Most critically, the proposed roadmap requires empirical validation through pilot implementations. Longitudinal case studies tracking organizations applying the framework would assess its practical utility, identify refinement needs, and develop implementation guidelines grounded in real-world experience. Action research partnerships between researchers and implementing organizations could generate both theoretical insights and practical knowledge.

Additional research directions include: (1) Developing sector-specific adaptations recognizing that discrete manufacturing, process industries, and service sectors face distinct challenges; (2) Investigating SME-specific considerations given that resource constraints and organizational characteristics differ substantially from large enterprises; (3) Examining human factors in greater depth, particularly worker acceptance of collaborative robotics and AI-augmented decision-making; (4) Analyzing economic impacts and business model innovations Industry 5.0 enables; (5) Exploring environmental impact measurement methodologies suitable for diverse manufacturing contexts.

6.4. Concluding remarks

Industry 5.0 represents more than incremental technological advancement–it embodies a fundamental reconceptualization of manufacturing's societal role. After decades in which efficiency and productivity dominated industrial discourse, Industry 5.0 recenters on human well-being, environmental responsibility, and social value creation. This shift responds to growing recognition that purely technological optimization generates unsustainable outcomes–environmental degradation, social displacement, and organizational fragility in the face of disruptions.

However, paradigm transitions require more than compelling visions–they demand practical implementation pathways accessible to organizations with diverse capabilities, resources, and contexts. This study contributes to these pathways through an empirical assessment of current readiness and the development of adaptable roadmaps that integrate Industry 5.0 principles with established transformation frameworks. By revealing specific knowledge gaps, capability deficits, and priority areas, research enables targeted interventions rather than diffuse exhortations.

The path forward requires sustained commitment from multiple stakeholders. Manufacturing organizations must invest in workforce development, measurement systems, and strategic reorientation toward human-centric values. Policymakers must create supportive frameworks through education, funding, and regulation. Technology providers must develop solutions explicitly designed for human-machine collaboration rather than human replacement. Researchers must generate actionable knowledge bridging conceptual frameworks and implementation realities. Through such collective effort, Industry 5.0 can fulfill its promise: manufacturing systems leveraging advanced technology not for technological sophistication's sake but in service of human flourishing, environmental stewardship, and resilient prosperity.

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