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Article

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Unravelling human-centric tensions towards Industry 5.0: Literature review, resolution strategies and research agenda

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ABSTRACT

In recent years, heightened attention has been directed towards the emerging Industry 5.0 (I5.0) paradigm, advocating intelligent collaboration between human workers and machines to enhance efficiency, productivity, customization, and product quality in manufacturing. However, despite its potential to revolutionize current industrial practices, the I5.0 transition also imposes several known and unknown tensions that require attention for effective adaptation. This study aims to investigate the main human-centric tensions and resolution strategies in manufacturing arising in the transition towards I5.0. The research methodology developed a three-step approach. First, the study conducted a literature review of academic papers to gain insights into the human-centricity challenges arising from the adoption of I5.0. Second, based on these findings, we develop a theoretical framework that organizes these central human-centricity tensions in the manufacturing context, resulting in 20 tensions identified. The identified tensions are categorized into learning, organizing, belonging, performing and their interrelationships, according to the paradox theory. Third, based on the literature findings, the study develops a novel framework with resolution strategies to address these tensions. The findings show that salient tensions emerge mainly in dimensions such as automation, well-being, safety, education, and value creation. The study provides valuable insights for manufacturing companies in the preparation or I5.0 realization, emphasizing the pivotal roles of shop floor workers in the interaction with machines. The study provides valuable insights for both researchers and practitioners, representing a pioneering effort to understand the tensions and resolution strategies of I5.0 within the manufacturing environment.

1. Introduction

In recent years, there has been an increased interest in the emergent Industry 5.0 (I5.0) paradigm. The next wave of industrial revolution of I5.0 aims to intelligently elevate the collaboration between human workers and machines to improve efficiency, productivity, customization, and product quality (Pizoń & Gola, 2023; Santhi & Muthuswamy, 2023). Our research refers to the I5.0 concept as “a combination of organizational principles and technologies to design and manage operations and supply chains as resilient, sustainable, and human-centric systems” (Ivanov, 2023, p. 1683). However, while the new I5.0 paradigm has considerable potential for revolutionizing the current industrial and manufacturing practices, it has many challenges that it needs to cover to gravitate towards the future of manufacturing (Tavares et al., 2022).

Arguing about the new perspectives I5.0 proposes, a recent report from the European Commission (2024, p. 14) states: “Industry 5.0

provides a transformative vision for the industry as a driver of sustainability, resilience, and human centricity. It supports the shift of industry towards a new paradigm as a powerful lever to help the planet (industry that remains within the planetary boundaries), leaves no one behind and actively contributes to well-being and planetary regeneration.” As a result of this transformative vision, several uncertainties and changes emerge, leading to unknown implications for manufacturing systems, particularly in relation to the human-centric component of I5.0. (Alves et al., 2023; Atif, 2023). Human centricity is a multidimensional framework that prioritizes human needs, characteristics, motivations, and experiences in the design, development, and implementation of technological solutions and organizational practices. Human centricity not only meets functional requirements but also enhances human well-being, capabilities, skills, and working conditions (European Commission, 2024).

In the intensive socio-technical and transformative environment provided by the human-centricity pillar of I5.0, new and unknown

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tensions and challenges arise. According to Smith and Lewis (2011), tensions are one of the necessary elements of paradoxes. Tensions are defined as elements that appear logical when analyzed individually but become inconsistent when juxtaposed. Organizations and individuals often develop responses to navigate such complexities simultaneously. This comprehension implies that if these tensions persist over time during Industry 5.0 implementations in industries, they will become paradoxes. These tensions can become more salient, considering there has been an insufficient understanding of manufacturing management practices from a socio-technical system view (Clausen, 2023). Given the multifaceted nature of the digital transformation of operations, these uncertainties hold significance (Holopainen et al., 2022). An example of these tensions can be found in the digitalization paradox. Gebauer et al. (2020) state that as digitalization investments increase, enterprises face digitalization paradoxes where they may not see corresponding performance improvements. This challenge can arise, for example, when a company (e.g., a small industry) allocates its limited resources between existing processes and I5.0 demands, aiming to deploy the resource-intensive I5.0 technologies effectively. Industrial managers, therefore, must address tensions in time before they amalgamate over time and become paradoxes of more complex resolution.

Additional sources of potential tensions emerging with the I5.0 include the need for new skills and infrastructure, as well as job displacement (Mourtzis, 2024). In this regard, the I5.0 literature also reveals inconclusive findings regarding the tensions arising from the changes required in manufacturing, such as those stemming from the relationship between shop floor workers, machines, and systems. For instance, while replacing manufacturing workers with AI promises efficiency gains and error reduction, it also risks eliminating jobs. This exemplifies a tension where technological advancements simultaneously offer benefits while imposing challenges (Grabowska et al., 2022). Additionally, the advancement of I5.0 towards mass production using machines can challenge workers' efficiency in human-machine collaboration (Tavares et al., 2022). In line with the recent I5.0 literature (Ghobakhloo et al., 2024; Liu et al., 2024; Piccarozzi et al., 2024), the present study argues that a deeper understanding of these and other tensions is lacking in the literature, despite being crucial for advancing the knowledge base on the implementation of I5.0.

The I5.0 realization also introduces some new concepts to manufacturing practices, including human digital twins, human-cyber physical systems, greentelligent manufacturing, and human-robot collaboration. The closer collaboration between shop floor workers and robots aims to replace looped tasks with automation, potentially reducing future job positions (Huang et al., 2022). The problem resides in the fact that existing human factors should not be discarded but rather integrated into an efficient collaboration between human workers and technologies. This paradigm change also highlights the importance of prioritizing up-skilling and re-skilling workers, in particular digital skills, to support the I5.0 realization (Grabowska et al., 2022; Holopainen et al., 2022). Furthermore, it is essential to cultivate internal human capital capable of independently developing new competencies to remain educated on evolving cutting-edge technologies (Grooss et al., 2022). Collectively, these new issues introduce tensions to the interactions between humans and manufacturing systems, necessitating further exploration and reconciliation (Pizoń & Gola, 2023; Tavares et al., 2022; Zizic et al., 2022) as is the focus of this study.

Consequently, we argue that recognizing workers' diverse values and needs is crucial in future technological developments of I5.0 in manufacturing. Hence, manufacturing managers and practitioners aiming to achieve a production paradigm that reconcile mass individualization and personalization must possess a comprehensive understanding of various technologies to facilitate effective human-machine collaboration (Leng et al., 2022). Despite recent research exploring various I5.0 aspects, the salient tensions arising from the transformative vision for manufacturing remain unclear (Clausen, 2023; Diop et al., 2023; Huang et al., 2022). In summary, despite the

significance of these prominent tensions for industries, workers, and society, we lack a coherent understanding of their nature and interrelationships. Therefore, this study addresses the following research question: *RQ. What are the main human-centric tensions in manufacturing arising from the transition to Industry 5.0?* The research operationalized this question through three methodological stages. First, the study conducted a review of academic papers to gain insights into the human-centricity challenges arising from the adoption of I5.0. Second, based on these findings, we develop a theoretical framework that organizes these central human-centricity tensions in the manufacturing context, resulting in a set of identified tensions. The identified tensions were categorized according to the paradox theory (Smith & Lewis, 2011). Third, based on the literature findings, the study develops a novel framework with resolution strategies to address these tensions.

This study establishes theoretical and practical contributions to understanding the I5.0 paradigm in manufacturing. At the theoretical level, this study is one of the pioneering attempts to investigate the human-centric tensions in manufacturing concerning the I5.0 transition and indicate possible resolution strategies to address these tensions. The article contributes to the understanding and classification of these tensions through the introduction of a proposed framework. The article also provides practical contributions by deepening the understanding of these tensions in specific manufacturing areas such as automation, workers' well-being, safety and education, and manufacturing value creation. The article proposes a novel framework for resolution strategies grounded in the theory of tensions in management and organizational studies (Smith & Lewis, 2011). These resolution strategies enhance our comprehension of I5.0, as addressing these tensions can facilitate the implementation of the human-centricity pillar invoked by I5.0. The article provides insights for operations technology management researchers, industrial consultants, and manufacturing companies that are planning or undergoing the transition. It underscores the significance of taking into account the roles of shop floor workers. Finally, this study enriches and supplements I5.0 research by providing new insights into both the literature and manufacturing industries. It examines the emerging phenomenon of I5.0, which remains an emergent and underexplored topic in the literature.

2. Research methodology

2.1. Research design

The methodology adopted in the first phase of the research is the literature review. By examining the main types of review studies according to Grant and Booth (2009), specifically, literature review studies explore recent or current scholarly works and can cover a broad range of subjects with varying levels of completeness and comprehensiveness, potentially including research findings. The scope of the search for relevant studies in literature reviews may or may not be exhaustive, and the quality assessment of those studies can differ. Lastly, the analysis within a literature review may be conceptual, thematic, chronological, or take other forms.

Hence, to address the research question, this study examines the recent Industry 5.0 paradigm and the literature focused on human-centric tensions in manufacturing that arise during the transition to Industry 5.0. The literature review process adopted involved the accumulation, assessment, and synthesis of primary research findings. The study adheres to the PRISMA protocol by Page et al. (2021), chosen for its robust and transparent framework in conducting and reporting literature reviews, as depicted in Fig. 1. The outcomes of this method are derived through the following procedural steps:

First stage - Definition of the research question(s) of the study: The article investigates: *What are the main human-centric tensions in manufacturing arising from the transition to Industry 5.0?*

Second stage - Definition of the research objective of the literature review: The purpose of this study is to identify the main human-centric tensions

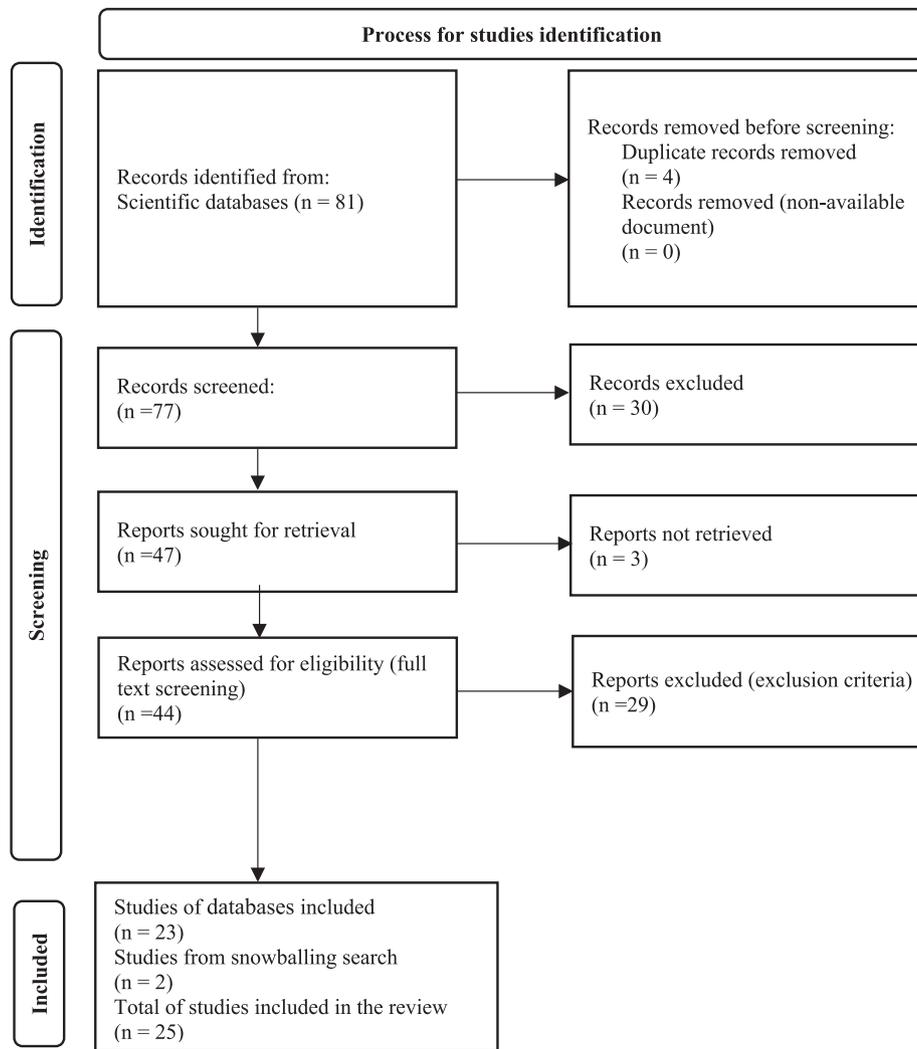


Fig. 1. PRISMA flow diagram of literature review performed. **Source:** Adapted from [Page et al. \(2021\)](#).

in manufacturing arising in the transition to I5.0 and explore resolution strategies to address these tensions.

Third stage - Definition of primary data sources: The database used to collect relevant information was Scopus. Scopus was selected due to the rich array of scientific resources that are combined with advanced search capabilities.

Fourth stage - Definition of keywords: The keywords to respond to the RQ were disclosed to understand the nature of the industrial concepts of I5.0. The keywords were used in combination with each other to give an appropriate result in terms of the literature searched. Those were tightly connected to manufacturing processes, supply chain and value chain operations, human well-being, machine operations and security. From the initial exploration of the literature, we identified the primary search terms: Industry 5.0, human-centric, well-being, human, factors, supply, chain, value, security, risk, management, resilience, sustainability, and resources. Then, the search process related each other in different combinations using Boolean indicators AND/OR to give an appropriate result in terms of literature to answer the RQ and give an understanding of how the topic has been investigated. This combination was necessary because research on human-centric tensions in manufacturing arising from the transition to I5.0 is a nascent and immature area of study. Thus, we decided to employ different combination searches to locate a sufficient amount of relevant articles on the topic of the RQ. Examples of combination queries included: “Resilience” AND “Sustainability” AND “Industry 5.0”; “Human” AND “Centric” AND “Industry 5.0”; “Value”

AND “Supply” AND “Chain” AND “Industry 5.0”; “Human” AND “Factors” AND “Well” AND “Being” AND “Industry 5.0”; “Security” AND “Risk” AND “Management” AND “Resources” AND “Industry 5.0”; “Supply” AND “Value” AND “Chain” AND “Risk” AND “Security” AND “Industry 5.0”.

Fifth stage - Definition of the time interval of the search: The time limitations for this search were between January 2022 and 2024 (August), mainly due to the nature of the recent emergence of I5.0, which is a new concept and there are limited publications that would serve the purpose for which the RQ would be answered.

Sixth stage - Definition of criteria for inclusion and exclusion of studies: The criteria for inclusion in this study were as follows: (i) Empirical and conceptual papers discussing problems of human-centric in manufacturing systems and introduce new concepts for the future implementation of the new I5.0 paradigm; (ii) Recent scientific literature in the area; (iii) Studies discussing that reflect on impact of I5.0 within manufacturing and society, (iv) Technological adoptions within I5.0 and future implementation within human-robot interactions. The exclusion criteria applied were as follows: (i) Papers that superficially touch the subject of human-centric challenges in manufacturing without giving a specific output or opportunities for future research for the relationship with the I5.0; (ii) Studies that do not focus on I5.0 transition or implementation and only generalize the I5.0 aspects; (iii) Unpublished articles and studies that do not give an appropriate output for further research.

Seventh stage – Screening process: The analysis started by inspecting the paper's title and reading through the abstract to establish a connection between the I5.0 concept and frameworks developed by the authors. Papers were excluded based on the information gathered as if they would not serve the purpose of further analysis. The next step was to perform an in-depth analysis of the papers to decide if their content would describe the information to conclude on the possible tensions of I5.0 adaptation within manufacturing. Papers were then grouped to identify the operational tensions and the possible strategies for reconciliation of them. A total of 25 articles were utilized in the study (Fig. 1).

Eighth stage - Methods and tools: Data have been extracted from the papers using a specific criterion for the literature review. The following information was extracted: study objective, methodology, research context, findings, limitations, and principal research opportunities. This data was incorporated into an Excel table for further evaluation.

2.2. Thematic analysis and theoretical lens

This study adopted the typology of tensions according to the paradox theory to investigate the human-centric operational tensions arising during the I5.0 transition. In the context of the study, tensions usually arise from conflicting organizational demands, goals, or forces within the system. This theoretical lens was adopted for two main reasons. First, this theory and the human-centric element of I5.0 are social entities. Second, it is an established theoretical framework for analyzing social-technical systems (Dieste et al., 2022; Gebauer et al., 2020). Human centricity is a multidimensional framework designed to prioritize human needs, characteristics, motivations, and experiences in the development and implementation of technological solutions and organizational practices. This theoretical framework can, therefore, help to understand these tensions, recognizing that integrating human-centric values into technological systems involves balancing competing demands in a coherent and effective manner. It also facilitates a deeper understanding of how seemingly logical and consistent human-centric aspects can become inconsistent when considered together, offering valuable insights for addressing the RQ. The four categories of tensions proposed by the paradox theory utilized to explore the literature are as follows:

(i) *Learning tensions:* learning tensions distinguish themselves within knowledge and future uncertainty. They come from the process of change within the organizational structure and adjusting, renewing, changing, and innovating; (ii) *Belonging tensions:* belonging tensions arise from the conflict between roles, personalities and membership in an organization. It arises between the individual and the organization, as industries promoting certain goals and values and focusing on conformity and assimilation can limit creativity and innovation within the individual in favour of assimilation and conformity with the organization; (iii) *Organizing tensions:* organizing tensions refers to the contradiction between flexibility and structure of an organization. On the one hand, structures in organizations are needed to achieve a sense of coordination and hierarchy, while on the other hand, having flexibility would provide the necessary agility for an organization to respond effectively to change in the environment; (iv) *Performing tensions:* performing tensions refers to having organizations pursuing ambitious goals, high standards and performance targets, emphasis productivity and achievement to gain competitiveness. However, the focus on high performance might lead to longer working hours, cognitive stress and increased pressure on the individual, creating conflict in the management of the company. Those tensions can also interact systemically with each other and create further categorization for potential tensions as follows (Table 1).

A portion of the literature also argues that I5.0 can be viewed as an extension and natural evolution of I4.0 (Adel, 2022; Kemendi et al., 2022). This suggests that analyzing the tensions arising from ongoing I4.0 can provide valuable insights into understanding some of the challenges associated with I5.0 implementation. However, the literature

Table 1
Dynamic interaction among tensions.

Interaction among the categories of tensions	Definition
<i>Learning – Belonging</i>	Are the tensions that create a conflict between the need to promote improvement by the organization in contrast to generating purpose and a sense of belonging in it.
<i>Learning – Organizing</i>	This tension consists of an organization seeking efficiency and dynamic capabilities while balancing continuous learning principles and appropriate routines.
<i>Learning – Performing</i>	This tension is organized between having a potential foundation for future operations while establishing success in the current.
<i>Belonging – Organizing</i>	The promotion of an individual in the organization is to achieve benefits for the whole, yet having an individual promote his personal strength benefits the organization.
<i>Performing – Belonging</i>	The tension arises from the tension of individual recognition regarding the collective sense of belonging to the environment and company.
<i>Performing – Organizing</i>	The tension of achieving the customer demands while meeting the employee expectations within the environment for high performance.

Source: Adapted from Smith and Lewis (2011).

on I4.0 is still emerging and lacks a specific focus on understanding the tensions resulting from the I4.0 transition. We have identified only one pioneering study with this specific focus (Dieste et al., 2022). Therefore, given that I5.0 is an even more recent paradigm than I4.0, it is reasonable to suggest that there is a significant knowledge gap in understanding the tensions within the I5.0 paradigm.

3. Results

3.1. Industry 5.0: main transition challenges in manufacturing

The results show that, to date, different studies have explored the I5.0 paradigm and the challenges associated with transitioning from current manufacturing practices. According to Piccarozzi et al. (2024), I5.0 places the well-being of industrial workers at the core of the system. While ongoing I4.0 focuses on digitization and enabling technologies, I5.0 is grounded in sustainability and social equity. I5.0 is not merely an industrial revolution; it is also a techno-political phenomenon and represents technological innovation intertwined with policy, as it harnesses the political, regulatory, and governance power of policymakers to drive an industrial transformation rooted in human, social, and environmental values. Liu et al. (2024) identify cost and funding as the most significant challenges affecting the implementation in enterprises of intelligent manufacturing in I5.0. From a broad perspective, the I5.0 transition requires conciliating the challenges between long-term technological impacts on the environment and society, with coordinated collaboration among companies, governments, worker unions, regulators, and tech providers for success (Ghobakhloo et al., 2024). Zizic et al. (2022) scrutinized shifts in the people, organizations, and technology paradigms of I5.0. They underscored the importance of the human aspect and sustainability in the emerging industrial framework. Nevertheless, the research is constrained by specific keyword search criteria, and there is potential for expansion into different subareas. Future exploration can delve into fundamental concepts and key enablers specific to each paradigm, broadening the scope of understanding.

Grabowska et al. (2022) identify issues related to the humanization aspect and the transfer of concepts to the framework of I5.0. They show that employees have a diminished role in previous industrial paradigms (e.g., I4.0) and should be enhanced in the succeeding industrial revolution. It emphasizes the need to retain human factors from existing concepts rather than favoring collaboration between human workers

and technologies. Prioritizing workers' skills development is crucial within the application of the I5.0. However, the study lacks an examination of social, ecological, and economic factors for comprehensive understanding. Future research should understand the appearance of workers in I5.0 and Society 5.0.

Studies have also analyzed the principles of future employment and job transformations within the emerging I5.0 paradigm. [Kolade and Owoseni \(2022\)](#) examine the disruptive impact of the new industrial paradigm on job transformation, offering valuable insights into the human aspect of this transition. The discussion focuses on technology's role in the workplace and its potential effects on the future emphasis on human-centric employment. They reveal diverse perspectives, providing insights into worker skilling and job polarization. It emphasizes the need to address challenges associated with various ideologies when considering the future of workers, skilling, and opportunities. They argue that new research should concentrate on employment and contracting aspects related to worker upskilling employment with a focus on education and support and explore alternative frameworks for policymaking in the context of evolving work structures.

Meanwhile, there is growing research interest in managerial upskilling within supply chains under the new I5.0 paradigm. [Modgil et al. \(2023\)](#) analyzed the essential skills for supply chain experts in the context of I5.0. Employing a multi-criteria decision-making approach, the study focused on human resource professionals. The findings underscored the necessity for advanced skills among individuals in managerial roles to enhance performance and attract high-performing employees. The study suggests the need for a specific skill set in the future to identify these crucial capabilities effectively. The study, however, had limited coverage within various fields of the supply chain industry. To gain a more comprehensive understanding of I5.0 implications, it is necessary to conduct new research across different managerial positions. Already, [Holopainen et al. \(2022\)](#) argue that it is essential to consider an intuitive perspective on digital operations integrated with a technical viewpoint. This implies that industries must strike a balance between intuitive and data-driven decision-making approaches.

Sustainability concerns are also recurrent discussions in the recent I5.0 literature. [Atif \(2023\)](#) scrutinized this context, evaluating the product life cycle and information flow in data platforms within the I5.0 framework. The study claims that I5.0 complements the I4.0 by fostering a transition to human-centric values for enhancement. However, the study's sample size is limited, lacking empirical evidence to substantiate its conclusions. Subsequent research should be conducted to validate socio-economic concepts within the circular economy paradigm. Political and corporate policies need revision to align with the human-centricity of I5.0. Further market research on data dimensions should explore customer expectations, and there is a need for ongoing research on risk management within blockchain technologies. In a similar vein, [Santhi and Muthuswamy \(2023\)](#), through a descriptive review approach, demonstrated that I4.0 prioritizes profit over the environment and society and emphasized the need for human input, particularly on the manufacturing level. The research theorized that the future I5.0 should revolutionize human-robot collaboration and broaden prospects in creative thinking, critical thinking, and sustainability.

The literature also explores potential opportunities and limitations of I5.0. [Adel \(2022\)](#) emphasizes the application of human-centricity within the industrial concept across various domains. The study reveals that while humans need competency skills for effective machine use, the implementation of the I5.0 might incur costs in terms of worker skilling and machinery. The research identifies security concerns within ecosystems as a challenge for countermeasures in data breach incidents. Limitations include the absence of supportive laws for adopting the new framework, emphasizing the need to address human-machine interaction for future work effectiveness. [Adel \(2022\)](#) also suggests that future research should focus on technological advancements in cognitive computing for human-brain-to-machine interactions and gestures for

natural interfacing between humans and machines. [Tavares et al. \(2022\)](#) conducted a systematic literature review analyzing I5.0 challenges in the societal and educational context. Key findings include the need for more than a change in the human-centric approach to societal improvement, the opportunity presented by the COVID-19 pandemic for skillset enhancement in computer-based areas, the necessity for educational institutions to adapt to new societal concepts for integrating technological knowledge, and the importance of further investigation into privacy and security measures for a comprehensive realization of the I5.0 concept. Future studies should concentrate on society-centred activities and assess the impact on the quality of life within different factors in the I5.0.

[Diop et al. \(2023\)](#) conducted a study focusing on risk management within the I5.0 paradigm, particularly analyzing safety hazards emerging from ongoing industrial practices. The authors contend that the current industry practices require a new socio-technical framework for I5.0 to address anticipated disruptive events in value chains effectively. The proposed framework requires validation through case studies and analysis, with future research emphasizing model validation for practical implementation in I5.0. [Boschetti et al. \(2022\)](#) adopted a new methodological approach focusing on a human-centered workspace in the task allocation procedure. Their I5.0 study, grounded in a literature review and a quantitative approach, analyzes dynamic task allocation. The evaluation was conducted through a theoretical case study simulating real-life experiences. Workplace safety emerges as a significant concern in human-machine-related work, emphasizing the need to place operators at the center for effective job process improvement. They propose further investigation into multi-objective task allocation and human safety to prevent potential errors in the future.

[Kemendi et al. \(2022\)](#) investigated the I5.0 paradigm using a literature review and cluster analysis. Analyzing data from European countries, they shed light on standards and preparedness for the transition to I5.0. The findings indicate that I5.0 necessitates elevated standards for workers to perform high-quality work. However, the study suggests that the European Union is not adequately prepared to implement new industry standards due to a shortage of specialists available to manage the shift to I5.0. [Leng et al. \(2022\)](#) explored a tri-dimensional system architecture for the future implementation of I5.0 through a literature review. The study investigated key facilitators, challenges, and the prospective implementation path for practical I5.0 scenarios. The findings emphasized the importance of recognizing diverse worker values and needs, highlighting the initial step towards complete technological worker transformation. The study stressed the necessity of in-depth knowledge of various technologies to support effective human-machine collaboration for the production paradigm of mass individualization and personalization. However, limitations included a scarcity of relevant articles and unclear objectives for constructing the I5.0 architecture concept.

3.2. Main human-centric tensions towards I5.0 transition

Human-centricity is a central theme in the I5.0 transition. [Rannertshauer et al. \(2022\)](#) examined production planning and control systems, exploring a potential connection with human cognitive biases. Their systematic literature review informed the development of a questionnaire assessing human-centric maturity levels in these systems. The findings suggested a link between cognitive biases and the systems, proposing further research to reassess the design of planning and control systems. A limitation of the work is the absence of an approach to assess human-centricity in the maturity levels of these systems. New studies should incorporate factors influencing the design planning of these systems. Similarly, [Pizoń and Gola \(2023\)](#) scrutinized the current state of industrial transformation and the prospective evolution of human-machine relationships. Through a qualitative study, they concentrated on the challenges within the context of I5.0. They found that the new industrial revolution aims to shift the focus from developing technology-

centric solutions tailored specifically for machines. Instead, it prioritizes establishing cooperative interaction between humans and machines. The core emphasis of the I5.0 is to utilize technological advances to integrate the human aspect into production. The new manufacturing paradigm of I5.0 also considers the incorporation of cost-driven technological innovations, such as machinery and equipment, to reduce human labour expenses and significantly influence the production methods of goods. Lastly, research has also indicated that the digital transition will unlock capabilities to meet the growing technological complexity brought by the digitalization of manufacturing.

From a human-centric perspective, this increasing complexity underscores the importance of investigating the specific needs for executing manufacturing digitalization using human-oriented artefacts such as shop floor management visualization boards (Clausen, 2023). According to Lu et al. (2022), the grand social challenges regarding I5.0 human-centric manufacturing are (i) the difficulty of making empathic machines act in a trustworthy manner, (ii) the integration of intelligent machines into the workplace, particularly how they will alter team dynamics in a factory setting. The core issue is determining the extent to which these intelligent machines, referred to as "intelligent atoms", should be allowed to participate in manufacturing and decision-making processes; (iii) the need to adapt technology to human users while simultaneously training people to use these new technologies, since ensuring smooth human-machine interaction and optimal team performance requires continuous training for industrial workers. While the main technical challenges are: (i) the necessity of developing human-centric AI technologies that can embed human-centric values into human-machine collaborations; (ii) the difficulty of ensuring that people can trust machine decisions made by AI systems; (iii) establishing standard performance metrics in human-centric manufacturing across three key aspects: human, machine, and system; (iv) the transition from system-centric to human-centric manufacturing poses significant difficulties for traditional manufacturing systems optimizing human worker wellness while still meeting traditional production scheduling goals. In this regard, the demands of mass personalization make the situation even more challenging to manage effectively. Overall, it is possible to conclude that the research in the area should focus on creating methods and techniques and cultivating best practices to understand the potential inherent in human-machine interactions fully.

Alves et al. (2023) investigated the human-centricity of I5.0 through a systematic literature review of 157 articles. The study assessed whether I5.0 is human-oriented and explored the potential development of human-centricity within new technologies. Findings demonstrated a scarcity of studies proving human-centricity in the I5.0 setting. However, the ideologies and concepts were identified as human-oriented, particularly concerning well-being, safety, and health. Additionally, the study suggested that I4.0 technologies applied to I5.0 could enhance the value of the human factor on the manufacturing floor. Limitations included a lack of real industrial cases demonstrating the human orientation of I5.0, emphasizing the need for further research on human-centricity and methodologies placing the human factor at the center of production. de Assis Dornelles et al. (2022) synthesized eight primary manufacturing activities and eight worker capabilities; the study identified fifteen technologies directly or indirectly influencing manufacturing workers. It explored the positive impacts of technologies on workers and identified usage limits. Notably, the study did not delve into the interfaces between smart manufacturing and small supply chains or address workers' adoption of these technologies. However, future research is recommended to investigate the supportive role of workers in manufacturing processes and assess the benefits of new technologies for workers.

Hein-Pensel et al. (2023) conducted a systematic literature review on I5.0 maturity models, explicitly focusing on human-centric aspects and their application to small and medium enterprises (SMEs). They concluded that existing maturity models lack a human-centric focus and fail to adequately assess the readiness of SMEs for I5.0. The study

revealed a deficiency in models addressing the transformation processes with a human-centric approach. However, limitations include a scarcity of models reflecting genuine human-centricity and the absence of practical application in corporate or manufacturing environments. Future research should evaluate and develop maturity models tailored to SMEs. Chourasia et al. (2023) explore the role of I5.0 in the medical sector, emphasizing human-robot collaboration. They anticipate I5.0 benefits in digitizing patient data for efficient access and interconnection, with automation easing surgical burdens on doctors. However, integration demands skilled workers in IoT services and software development, incurring high costs with uncertain outcomes. The study recommends further discussions on the collaboration between intelligent machines and skilled workers within the I5.0 framework. Ivanov (2023) introduces a logical-organizational framework for I5.0, emphasizing value creation and sustainability. The literature review reveals the concept's underexplored aspects in supply chain and operations value addition. The study suggests I5.0's flexibility for reconfiguration to maximize value and dynamics across networks and chains. Future research should explore human-centricity, sustainability, and value creation as integral components of the business model before implementing the I5.0 in real-life conditions.

Huang et al. (2022) explore the coexistence of I5.0 and Society 5.0, introducing concepts like human digital twins, human-cyber-physical systems, greentelligent manufacturing, and human-robot collaboration. The study envisions replacing repetitive tasks with automation, potentially reducing future job numbers. To accelerate development and societal benefits, further research is recommended on the foundational aspects of both concepts. Battini et al. (2022) introduced a multi-objective job rotation scheduling model for I5.0, aiming to optimize job assignments and individual rest-break plans based on human factors. The study prioritizes worker-centric principles within the I5.0 context, emphasizing the importance of human involvement in the production process. Their work suggests future research to explore various solutions for the proposed model, considering different worker profiles and learning curves in training environments.

3.3. I5.0 human-centric tensions in manufacturing: a paradox theory view

By adopting the paradox theory as a theoretical lens, the literature examined can be categorized as follows:

3.3.1. Learning tensions

Several I5.0 studies highlight a crucial lack of necessary skills for workers to operate machinery effectively in the workplace (Kolade & Owoseni, 2022). Essential education is imperative for the future generation of smart workers to leverage machinery, emphasizing the human-centricity of manufacturing. Additionally, managerial upskilling is essential for enhanced performance and attracting high-performing employees (Modgil et al., 2023). This emphasis on advanced skills, education, and upskilling creates a gap in the transition to I5.0, as current manufacturing practices lean towards automation, potentially sidelining human involvement. Moreover, security and privacy are prevalent concerns during the transition to the new I5.0 paradigm. Ensuring the security of workplace ecosystems is a significant challenge when implementing countermeasures against data breaches (Adel, 2022). This underscores the necessity for highly skilled workers capable of addressing such issues and integrating new technological knowledge into the evolving industrial framework (Tavares et al., 2022). There is a need for further investigation into privacy and security measures, coupled with the education of workers, to establish enhanced frameworks in this regard.

Belonging tensions. The role of humans in the future I5.0 depends on resilience, human-centricity and sustainability of supply and value chains (Ivanov, 2023). Nevertheless, the further repercussions of I5.0 remain unexplored within the aspect of value creation and business

ecosystems. This landscape can potentially create tensions regarding where humans should stand within the new I5.0 paradigm and how much value they will provide to an organization upon successful implementation.

3.3.2. Organizing tensions

The importance of workers in the new I5.0 paradigm is being addressed within the production systems and information exchange between humans and machines (Lu et al., 2022; Zizic et al., 2022). Organizations should investigate giving humans a more significant role in the manufacturing context instead of replacing it with automatization (Grabowska et al., 2022). Human factors are essential for collaboration between robots and should be researched further to avoid possible tensions. The economics of the current digitalization practices in industry is one of the topics that is being addressed regarding the future I5.0 concept. Reducing waste and continuous improvement can contribute to human-centricity values in I5.0 (Atif, 2023). On the other hand, I4.0 is more focused on maximizing profits and eliminating the human factor, which might prove contradictory while converting to new industrial standards associated with I5.0 (Santhi & Muthuswamy, 2023). The consequence is that the revision of human factors within I5.0 should be taken into consideration to limit the possible tensions that might arise within the economic and social perspectives.

3.3.3. Performing tensions

The performance of workers in the manufacturing context has been recently investigated within the standards of the European Union (Kemendi et al., 2022). In order to provide a better quality of work, the current manufacturing standards should be revised and updated for the future industrial framework required by I5.0, as there is a shortage of highly skilled workers. In regard to that, the study was conducted on new system architecture for I5.0 execution (Leng et al., 2022). Workers have different values and needs and should be approached individually to achieve the best results within the workplace. As a result, tensions might arise if the values of the employees are not met within the organizational setting.

3.4. Dynamic interactions among human-centric tensions

The current literature analysis reveals a learning-organizing tension concerning the dynamic interplay between safe collaboration among machines and workers. This tension emerges due to a deficiency in systems supporting collaboration between workers and machines during the I5.0 transition (Boschetti et al., 2022). Notably, motion controls and real-life position tracking systems are inadequately developed to ensure the safety of human-machine collaboration in the workplace.

An illustration of the performing-organizing tension is the exchange of information between humans and machines, which arises from the inadequacy of effective methods for data exchange (Adel, 2022). Current capabilities for data exchange, particularly between the human brain and machine cognitive computing algorithms, are not sufficiently advanced for practical utilization in shop floor jobs within the I5.0. Already, the occurrence of risks and hazards within production systems during disruptions creates a learning-organizing tension (Diop et al., 2023). The absence of practical risk assessment and decision-making frameworks for disruptive and extreme events suggests that companies and organizations are unprepared to manage high-risk disruptive events, such as the COVID-19 pandemic, without proper guidance or frameworks.

The advent of the new industrial revolution of I5.0 may impact worker skills and education, creating a learning-belonging tension (Kolade & Owoseni, 2022). This tension arises due to the lack of proper standards for worker education and skilling amid the shift towards automation in companies. Factors such as the rising cost of education, the prevalence of open online courses, dynamic shifts in worker competencies, and the impact of automation shaped the future design of

employee skill sets and abilities required for a competitive advantage in the workplace and desired worker efficiency by shop floor employers.

Customization and mass production within manufacturing systems give rise to belonging-performing tension (Tavares et al., 2022). This tension stems from the challenge of adapting to customer needs while balancing them with mass production, a common occurrence in the new industrial concept of I5.0. I5.0 places a significant emphasis on mass customization for customers and mass production within the workplace, necessitating human-machine collaboration to enhance efficiency.

The shift from the removal of workers in the current digitalization practices in industry (e.g., I4.0) to their elevation in I5.0 creates a learning-belonging tension (Grabowska et al., 2022). While these practices focuses heavily on automation and the gradual elimination of the human factor from the manufacturing floor, I5.0 necessitates human-robot collaboration for enhanced performance. Implementation of human-robot collaboration is intended to reduce errors and improve work quality in various fields for better results and accuracy, leading to the establishment of a belonging-performing tension (Chourasia et al., 2023). This tension is a common challenge discussed in the I5.0 as it strives to enhance work quality by implementing human-robot collaboration in manufacturing.

The pursuit of waste reduction and balanced production through improved collaboration between humans and machines gives rise to a performing-belonging tension (Adel, 2022). While current manufacturing practices of digitalization aim to minimize waste through automation and streamlined production, I5.0 seeks to reintegrate humans into manufacturing alongside machines to reduce waste further and achieve balanced production through enhanced data accessibility. This intricate dynamic establishes tensions between the presence of human workers and the performance of machines.

The automation of work, coupled with the creativity demanded in the workplace, along with task repetition and problem-solving capabilities, forms a performing-belonging tension (Adel, 2022). The human-robot collaboration of I5.0 aims to eliminate repetitive tasks in manufacturing, replacing them with machine-controlled operations to foster more creative thinking. This introduces a distinct tension between having humans closely involved with machines to enhance creativity-driven capabilities. The examination of the literature also reveals studies investigating work safety in human-robot operations. Workers safety and tension during machine utilization create a belonging-organizing tension (Boschetti et al., 2022). While I5.0 technologies offer improved insights into worker health, real-time feedback, and guidance for improvement, in practice, these machines can malfunction, posing risks and potential harm to workers in the process.

Cognitive biases related to human-centricity in I5.0 create a learning-organizing tension (Rannertshausen et al., 2022). Given that I5.0 is data-driven, information availability and decision-making can significantly impact production planning. The vast amount of information gathered must be carefully screened to prevent cognitive biases from influencing decision-making, potentially affecting shop floor workers in highly customizable production setups. Digitalization underscores the importance of data-driven decision-making and analytics skills, necessitating the development of human capital at both operational and managerial levels (Grooss et al., 2022).

Researchers have also explored the replacement of the human workforce with AI-driven operators, establishing a performing-belonging tension (Grabowska et al., 2022). While I5.0 is purportedly centred on a human-centric approach, there is a growing interest in purely replacing humans with AI-driven machines to reduce errors and costs and optimize manufacturing and production processes on the shop floor. This creates a tension between maximizing workplace performance and uplifting humans into the I5.0 to maintain a human-centric focus.

Prioritizing efficiency over human-related activities creates a performing-belonging tension (Atif, 2023). This tension emerges when the current emphasis on automation is applied in I5.0 to minimize

Table 2
Categorization of the human-centric tensions in manufacturing arising in the transition to I5.0.

Human-centric I5.0 tensions in manufacturing		
Learning – Belonging (LB):	Learning (L):	Learning – Organizing (LO):
<ul style="list-style-type: none"> • Lack of proper standards for worker education and skilling following the automatization shift within companies (LB1). (Kolade & Owoseni, 2022). • Uplifting workers for the I5.0 paradigm while simultaneously reducing human factors in the current practices of industry (LB2). (Grabowska et al., 2022; Lu et al., 2022). 	<ul style="list-style-type: none"> • Lack of essential digital skills and digital education for workers and managers (L1). (Kolade & Owoseni, 2022). • Security measures and data privacy in manufacturing systems are of concern due to the lack of skilled workers (L2). (Adel, 2022; Tavares et al., 2022). 	<ul style="list-style-type: none"> • Lack of safety systems supporting work collaboration between workers and machines can affect their safety (LO1). (Boschetti et al., 2022). • Deficiency in effective risk assessment and decision-making frameworks tailored for manufacturing handling disruptive, rare, and extreme events. Consequently, they are ill-prepared to address highly disruptive events and associated risks. (LO2). (Diop et al., 2023). • Availability of information can impact production planning and decision-making within the manufacturing (LO3). (Rannertshausser et al., 2022)
Belonging (B):	Belonging-Organizing (BO):	Organizing (O):
<ul style="list-style-type: none"> • Value creation by humans is not efficiently explored within industries and business ecosystems (B1). (Ivanov, 2023). 	<ul style="list-style-type: none"> • Small businesses swiftly adapted to pandemic disruptions, yielding positive outcomes. However, this adaptation came at the expense of 14.0 costs associated with automation and digitalization, potentially sidelining human-centric values (BO1). (Madhavan et al., 2022). 	<ul style="list-style-type: none"> • Worker's importance is questioned in accordance with automatization progression (O1). (Madhavan et al., 2022; Zizic et al., 2022; Tavares et al., 2022). • Efficiency improvements and waste reduction are being questioned with a greater focus on incorporating human factors (O2). (Adel, 2022; Atif, 2023).
Performing-Belonging (PB):	Performing (P):	Performing-Organizing (PO):
<ul style="list-style-type: none"> • The progression of I5.0 towards mass production using machines may pose challenges to workers' efficiency in human-machine collaboration (PB1). (Leng et al., 2022; Lu et al., 2022; Tavares et al., 2022). • Implementation of machinery within accuracy and work quality in regard to human-robot coordination (PB2). (Chourasia et al., 2023). • The reduction of waste through machine utilization and increased efficiency are achieved by eliminating the human factor and human participation in manufacturing (PB3). (Adel, 2022; Atif, 2023). • Although I5.0 aims to replace repetitive tasks with machine-controlled operations to foster creativity, tensions arise from balancing human involvement with machines to enhance creativity-driven capabilities in manufacturing (PB4). (Adel, 2022). • The integration of intelligent machines into the workplace, particularly how they will alter team dynamics in a factory setting. The core issue is determining the extent to which these intelligent machines should be allowed to participate in manufacturing and decision-making processes (PB5). (Lu et al., 2022). • Replacing manufacturing workers with AI promises efficiency gains and error reduction in manufacturing, but it also carries the risk of eliminating the human element (PB6). (Grabowska et al., 2022). • Some sustainable approaches, such as Circular Economy focuses on machinery efficiency to reduce waste rather than the incorporation of human-machine cooperation (PB7). (Atif, 2023). 	<ul style="list-style-type: none"> • Concurrence of different manufacturing performance measures and needs impacting the workers' quality of job and efficiency (P1). (Boschetti et al., 2022). • New standards of living for manufacturing workers should be revised to maintain further workers' efficiency within the I5.0 (P2). (Kemendi et al., 2022; Santhi & Muthuswamy, 2023). • Establishing standard performance metrics in human-centric manufacturing across three key aspects: human, machine, and system (P3). (Lu et al., 2022). 	<ul style="list-style-type: none"> • The exchange of data, in the form of inputs and outputs, between the human brain and machine cognitive computing algorithms is not sufficiently advanced to be applied in manufacturing jobs (PO1). (Adel, 2022).

Source: Authors own elaboration.

human interaction, costs, and waste through the use of machines. This is particularly relevant in the Circular Economy, which emphasizes resource efficiency and waste reduction, similar to I5.0, utilizing a circular approach and recycling of used products and resources. However, this approach primarily focuses on machine usage for efficiency, sidelining human-machine collaboration.

In the context of post-pandemic knowledge and I5.0 adaptation for future disruptive events, a belonging-organizing tension emerges (Madhavan et al., 2022). This tension manifests within disruptions and adaptations in the manufacturing setting concerning human interactions. The recent COVID-19 pandemic demonstrated that rapid adaptation in small-medium businesses had a positive impact. The main

tensions identified are organized in Table 2 for a more structured categorization. These findings address the RQ postulated in this article.

4. Discussion

4.1. Navigating human-centric tensions towards Industry 5.0: implications for industries and practitioners

This study aimed to understand the primary human-centric tensions associated with I5.0. The research findings highlight several significant human-centric implications, particularly for manufacturing industries and systems. The results indicate that the reduction or elimination of job

positions in the current digitalization paradigms (i.e., I3.5, I4.0) through intensive automation of production systems raises employment concerns in contemporary society (Grabowska et al., 2022). The increasing prevalence of the highest level of automation, which sidelines humans from manufacturing workplaces, warrants attention. In light of the new I5.0 paradigm, which advocates for intensive human-machine collaborations, efforts should be directed towards reintegrating workers into the manufacturing systems. The article findings also indicate that safety factors remain a concern, given that the scope and complexity of the new systems required by the I5.0 are not yet fully understood (Boschetti et al., 2022; Lu et al., 2022).

The study also shows that, in order to balance competing demands while transitioning to I5.0, one of the primary focuses for industries should be ensuring the well-being of manufacturing workers. The research highlights a deficiency in the proper skilling of workers, particularly in machinery operations (Kolade & Owoseni, 2022). This deficiency may have implications for the future skill set of workers in manufacturing, potentially leading to shortages, particularly for highly skilled workers who are currently in high demand and equipped to handle the new technologies introduced in the I5.0 (Kemendi et al., 2022).

The research also reveals that the human-centric emphasis of I5.0 can exert a more prominent influence on customer satisfaction. Given that customer satisfaction involves a trade-off between customization and mass production, achieving it will require a high level of human-machine collaboration to maintain and/or enhance operational efficiency (Tavares et al., 2022). This dynamic introduces challenges in production balancing and generates unknown tensions between the organization and the market (consumers), specifically regarding the conflict between pursuing mass production and offering personalized products. Consequently, developing ultra-flexible manufacturing automation for personalized products becomes essential in the context of I5.0 (Lu et al., 2022).

Another finding that stands out from the results reported earlier refers to the relationship between the value of shop floor workers and the need for new work design approaches under the I5.0. The findings indicate that, given the human-centric tensions associated with Industry 5.0, the value of each shop floor worker is increasingly questioned. This is due to their diverse needs, which call for more individualized approaches (Leng et al., 2022). These findings raise questions about work design adjustments needed to address the new requirements required by I5.0. Organizations that fail to meet individual needs may face reduced operational efficiency and experience increased tensions related to employee well-being.

The current investigation identified emerging human-centric tensions that can impact industrial managers. The findings indicate that implementing upskilling programs for these managers is crucial for attracting top-performing employees (Modgil et al., 2023). However, it potentially creates a gap within the current education models in terms of human-centric demands. These findings reinforce the idea that an intense focus on manufacturing automation may exacerbate deficiencies in critical managerial skills. This underscores the importance of a socio-technical manufacturing system aligned with I5.0, which should integrate human-centric skills across systems, human interactions, and organizational aspects, among other factors.

Overall, the present study provides the first assessment of operational tension resulting from the I5.0 transition in manufacturing, addressing the knowledge gap investigated. This gap builds upon two main aspects. First, the human-centricity pillar of I5.0 introduces new and unknown tensions within its transformative socio-technical environment. Second, existing I5.0 research shows inconclusive results about the tensions emerging from changes in manufacturing, particularly concerning the dynamics between shop floor workers, machines, and systems. The categorization of the tensions identified (see Table 2) contributes to advancing the knowledge of the subject and addresses the RQ examined in this article.

In summary, the study shows that I5.0 raises implications for workers within employment and safety in the workplace, with automation being one of the main drivers for worker removal and the importance of proper skilling of workers that can either raise or decrease their value. Companies evaluate the human factor in terms of the economy and human-centricity, in contrast to automation and disruptive events. This implies that industrial managers' capabilities should be changed according to the changing organizational environment. Moreover, the results showed that governmental policies should be updated in terms of the I5.0 understanding and implementations to minimize organizational barriers.

4.2. Social and policy implications

The study adds new insights to enhance our understanding of the upcoming Industrial Revolution by revealing emerging human-centric tensions within manufacturing. This contribution is particularly valuable from both social and policy-making perspectives. The article contributes by demonstrating that economic factors represent only one aspect of the discussion on how they can contribute to human-centricity in the industrial context (Atif, 2023). The article results provide support for the premise that, in the context of I5.0, the value of human workers for an organization can be modified if there is no tangible evidence of their contribution. While it is acknowledged that industries at the strategic level prioritize profits, other decision-makers (i.e., middle and lower management) assess the value of human factor by considering different criteria (Santhi & Muthuswamy, 2023).

The study also contributes to expanding the social debate on the education of newly employed workers and future employees in the I5.0 context, encompassing research challenges related to the transformation of society and current educational institutions. The integrative analysis of the findings allows us to infer that a proposed solution involves incorporating education not only for work-related activities but also for the cultural aspect of society driven by consumerism (Tavares et al., 2022). This solution emphasizes the need for specialists in various fields, advocating for the upskilling of workers in technical skills such as system engineering and computing programming, as well as soft skills like creativity and communication.

However, an important social issue that emerges from the findings is that if humans (e.g., blue-collar workers) eventually fail to prove their value to the manufacturing system, automation might dominate within manufacturing systems, potentially leaving humans' role in secondary relevance. The article also contributes emphasizing the implications of risks and hazards in complex environments, such as manufacturing systems under I5.0, particularly when facing external social disruptions (Diop et al., 2023). For instance, the COVID-19 pandemic demonstrated that many companies are inadequately prepared to manage highly disruptive events. Social disruptions affecting supply chains and production systems can significantly impact an organization's operations and productivity. Our findings broadly suggest that, within this spectrum, small to medium-sized companies can potentially manage to more quickly adapt to disruptive events (Madhavan et al., 2022), albeit at the cost of human-centricity being questioned, particularly in deciding whether full automation should take precedence.

According to the research findings, it is possible to infer that policymakers need to embrace the emerging I5.0 standard by thoroughly examining and updating existing digitalization policies, which sometimes give strong emphasis to new technologies and digitalization in a pure technocratic manner. In this regard, policymakers can face several challenges, including the need to develop coherent policies that regulate digitalization levels in alignment with the distinct economic conditions of different regions worldwide.

The requirements of I5.0 in highly industrialized nations, such as the USA, China, and Germany, are likely to differ significantly from those in less industrialized regions like Africa and South America. This implies, for example, that the European Union, as a key international stakeholder in developing industrial policies, should critically assess and adapt

current standards to ensure a higher quality of work within companies (Kemendi et al., 2022). In terms of social contributions, the study and its results can enrich the debate on the social repercussions of I5.0 by indicating that if these challenges are not addressed, future workers may struggle to maintain a work-life balance, face overwork, and ultimately underperform within industries.

4.3. Theoretical implications: navigating contradictions and strategies for tensions resolution

This paper contributes to the I5.0 literature by strengthening the argument that digitalization and automation in this emerging paradigm prioritize human-centricity and foster collaboration between humans and machines. To enhance the well-being and safety of shop floor workers in the context of I5.0, existing knowledge from previous digitalization paradigms (e.g., I3.5, I4.0) can be leveraged to develop solutions that are specifically tailored to employee needs, thereby prioritizing the human factor (Alves et al., 2023). One issue arising from this observation is that the adoption of technologies tailored to organizational needs can directly or indirectly influence workers' activities and constraints, ultimately enhancing operational performance and effectiveness.

This article advances existing knowledge by enhancing the understanding of how various theoretical models influence human-centricity within organizations. In this context, our findings suggest that examining the development of maturity models of I5.0 implementation in firms can provide valuable insights into transformation processes that align with a human-centric approach (Hein-Pensel et al., 2023). Additionally, this paper contributes to the research by arguing that diverse industrial environments should be studied across different workplaces to evaluate their I5.0 initiatives' effectiveness and their impact on human efficiency (Chourasia et al., 2023). For example, the healthcare industry represents a crucial manufacturing environment where achieving high efficiency and work quality is essential to ensuring the safety of users, including health professionals and patients.

The findings presented in this paper provide new insights into the tensions that can hinder value creation in manufacturing systems. The study has found that optimizing value creation in manufacturing under I5.0 involves utilizing diverse frameworks in the organizational context (Ivanov, 2023). According to the findings, we can infer that the flexibility of the I5.0 should prioritize sustainability, value creation, and adaptation to varying environments in the future industrial revolution. An implication of this is the need to explore novel I5.0-oriented roadmaps and implementation models to optimize manufacturing systems. Developing models that enhance worker effectiveness and reduce fatigue offers organizations an opportunity to transition into a more human-centric setting (Battini et al., 2022). Finally, creating environments that mimic human activity may eliminate repetitive tasks through automation, providing workers with more meaningful responsibilities (Huang et al., 2022).

The research findings theoretically contribute by indicating that effective collaboration between machines and humans necessitates the choice and integrated implementation of different technologies to enhance work performance and facilitate information exchange. Recognizing the need for optimal collaboration in manufacturing, this proposed integration of technologies should evaluate digital tools from a future-oriented perspective, emphasizing their potential impact on workers' health, well-being, and performance (de Assis Dornelles et al., 2022). This underscores the importance of viewing technologies not solely as drivers of process efficiency but as tools supporting workers in their daily tasks. In the same vein, the article contributes to the I5.0 literature by highlighting the critical role of data gathering and processing for companies in meeting market demands, customizing products, reducing waste in the production process, and improving overall efficiency. As a recommended strategy, companies should fully transition to the new technologies promoted to gain a comprehensive

understanding of data within smart machines and devices in manufacturing, fostering improved information flow among them (Atif, 2023).

This work contributes to existing knowledge of manufacturing practices affected by digitalization. Traditional manufacturing practices involved repetitive tasks within a closed loop, leading to standardized production processes that historically constrained product customization and often failed to address specific customer needs. The article results provide further support for the hypothesis that an alternative strategy to address this issue in I5.0 initiatives is the early-stage implementation of mass customization for products (Pizoń & Gola, 2023). This approach seeks to reduce the repetitive tasks performed by humans and enables customers to exert greater control over product variability. The adoption of mass customization is anticipated to bring about substantial improvements in future production methods, ultimately enhancing the overall quality of manufactured goods.

Finally, the article contributes theoretically by demonstrating that, amidst the ongoing wave of digitalization, humans have been gradually replaced by elements of automation, diminishing their perceived importance within the manufacturing landscape. The rapid adaptation of technology posed challenges, leaving individuals with insufficient time to develop the necessary skills and creative thinking for effective utilization. A proposed I5.0-oriented solution involves the development or adaptation of new tools and technologies to assist workers in their daily tasks, including networked sensors, AR/VR systems, digital twins, and artificial intelligence (Zizic et al., 2022). These technologies must be able to facilitate information exchange between the virtual and physical worlds, enhance job responsibilities for workers, and align with customer demands for innovative products.

4.4. Addressing human-centric tensions in the implementation of I5.0 in manufacturing

Based on the literature analysis, this study contributes to enhancing research and practice related to managing human-centric tensions in the implementation of I5.0 in manufacturing. Drawing on the paradox theory, Table 3 organizes a set of possible resolution strategies. Each resolution strategy has been assigned a corresponding tension (as outlined in Table 2).

This resolution framework contributes to advancing knowledge in the theme of I5.0 and benefits industry professionals. The study showed that scientific knowledge about machinery from previous waves of industrialization (e.g., I3.5, I4.0) could be beneficial in adjusting the workplace to the workers' needs and promoting the human factor (Alves et al., 2023). The integration of this knowledge can facilitate the application of new technologies within manufacturing to improve workers' tasks and address the tension of automation and well-being. Providing workers with different tools and shaping technology around them can further impact their well-being and health while also increasing performance (de Assis Dornelles et al., 2022).

The article further contributes, indicating that a decrease in the amount of work can be facilitated through mass customization in the I5.0 paradigm (Pizoń & Gola, 2023). Eliminating pointless loops in employees' work can benefit both the workers and the market (i.e., customers) within future production methods based on I5.0. The study also suggests that mirroring the environment within the workplace is a possible solution for identifying and eliminating repetitive tasks (Huang et al., 2022). This can be achieved by introducing automation in their place and providing workers with more meaningful tasks in manufacturing. The article shows that information exchange between humans and machines can be improved by developing appropriate tools in the context of I5.0 (Zizic et al., 2022). These tools will improve communication between humans and machines, promoting the meeting of customer demands for new products in the process. This implies that upskilling workers in different fields will be necessary for the effective I5.0 transition, especially within new emerging fields of system

Table 3
A framework for resolving tensions in the implementation of I5.0 in manufacturing.

Resolution strategies	Learning tension influenced	Organizing tension influenced	Belonging tension influenced	Performing tension influenced	Interlinked tensions influenced
<i>Intelligent automatization of manufacturing systems (e.g., co-robots), reducing repetitive tasks of workers</i>		O1, O2			LO1, PB2, PB3, PB4, PB5, PB6
<i>Application of I5.0 maturity models to promote human-centricity systems</i>		O1		P2	B01, LB2
<i>Adoption of customized I5.0 frameworks according to different manufacturing settings</i>		O1, O2			LO2
<i>Incorporating decision models for performance-fatigue balance in manufacturing</i>		O2		P1, P3	LB2
<i>Developing new technologies to aid workers in the workplace</i>		O1			PO1, LO1
<i>Full transformation to digital landscapes to improve manufacturing efficiency, information flow and reduce waste</i>		O2			LO2, LO3, PB7
<i>Intelligent shifting to a mass customization approach of the products</i>		O1			PB1
<i>New tools to aid workers at the workplace within digital space</i>		O1			
<i>Upskilling of manufacturing workers in terms of soft skills and higher education</i>	L1, L2	O1			LB1, LB2
<i>Developing new decision models, approaches, concepts and frameworks that will improve human-centric value creation in manufacturing</i>		O1	B1	P2	LB2

Source: Authors own elaboration.

engineering and programming, as well as soft skills like creativity and communication (Tavares et al., 2022). Further skilling of workers in fields that promote human-machine collaboration will be beneficial in regard to mass customization and creativity in the workplace.

Overall, the article contributes to the recent discussion concerning the I5.0 transition by suggesting that manufacturing companies should incorporate maturity models into their current manufacturing practices to consider and enhance the human-centric and socio-technical perspective of future I5.0 transformation (Hein-Pensel et al., 2023). The article shows that industries can benefit from incorporating contingency models tailored to the specific industrial segment. These models can also be explored within different workplaces to analyze how they might affect human efficiency (Chourasia et al., 2023). The paper also indicates that value creation within companies can be optimized using different I5.0 frameworks (Ivanov, 2023). These frameworks should be flexible within sustainability and value creation for quick adaptation to any setting.

Taken together, the findings of this paper offer valuable insights into strategies for reconciling emerging I5.0 tensions in manufacturing. The categorization of resolution strategies (Table 3) contributes to advancing knowledge in proposing solutions. Some of the suggested solutions involve adapting workers through the use of advanced machinery and technology tailored to worker needs, reducing potential workload via mass customization, eliminating repetitive tasks through automation, and upskilling employees, providing tools to enhance productivity and creativity. We also recommend that industries and technological practitioners incorporate socio-technical maturity models emphasizing a human-focused perspective, evaluate their performance in different environments, and utilize adaptable frameworks for optimized value creation and sustainability.

5. Conclusions and research agenda

In this study, the objective was to investigate the human-centric tensions that may impact the implementation of I5.0 and propose resolution strategies to address these tensions. To achieve this objective, we employed a literature review to gather, assess, and synthesize primary research findings. The research findings contribute to the existing knowledge by identifying and classifying the tensions that may arise during the transition to I5.0, particularly concerning human-centric factors in manufacturing. Unlike current industry practices that prioritize technological advancements and reduce human participation through automation, the future I5.0 paradigm aims to reintegrate humans into the workplace. It offers distinct resolutions across various

facets of the organizational framework.

Specifically, regarding the implications of I5.0, the article found that the I5.0 transition raises contemporary employment concerns. The categorization of human-centric tensions identified (Table 2) contributes to advancing scientific knowledge on the possible I5.0 implications. The study found that I5.0 prioritizes human-robot collaboration, necessitating efforts for shopfloor workers' reintegration. Persistent safety concerns stem from underdeveloped human-machine collaboration systems. In terms of manufacturing workers' well-being, the study found that ensuring shop floor workers' well-being is vital. This challenge can be addressed by addressing the current skill deficiencies of manufacturing workers. Research insights also show that balancing customer satisfaction involves trade-offs, generating tensions within organizations, especially in manufacturing. The study further enhances industrial knowledge by demonstrating the critical importance of upskilling managers for effective adaptation while also emphasizing the need for policymakers to update standards to align with the I5.0 paradigm.

In this study, a set of resolution strategies has been proposed to help reconcile these human-centric tensions of I5.0. The resolution framework for human-centric tensions in manufacturing (Table 3) contributes to advancing the theoretical and practical knowledge in the field. The study showed that scientific knowledge accumulated before the I5.0 could be beneficial in adjusting the workplace to the manufacturing workers' needs and promoting the human factor. It will be possible to apply new technologies within manufacturing to improve workers' tasks and address the tension between automation and well-being. Providing workers with different tools and shaping technology around them can further impact their well-being and health while also increasing performance.

Although this study offers unique insights and findings on human-centric I5.0 tensions in manufacturing, it is not without limitations. The primary limitation lies in the scarcity of empirical research and case studies on I5.0 implementation, leading to a restricted understanding of emerging tensions. Furthermore, the article is limited by the lack of relevant or seminal works that directly address the research question under investigation, hindering the development of a more robust research framework in the first phase of research. Given that I5.0 is a relatively recent theme under exploration, the availability of articles on the subject is limited, and the chosen keywords may have constrained the pool of available literature.

For future research, the topic of human-centric I5.0 tensions in manufacturing adaptation presents a promising avenue for empirical and field-based studies. Building on our findings, future research questions aimed at deepening the understanding of human-technology integration may include:

- How can existing human factors be effectively integrated into the collaboration between humans and cutting-edge technologies in I5.0? What are the best intervention models and roadmaps to make this transformation happen in practice?
- What are the primary challenges faced by industries in incorporating human-centric elements into the new I5.0 paradigm while simultaneously maintaining their ongoing industrial and digital initiatives (Industry 3.5, Industry 4.0) in their manufacturing systems?

Moving forward, future research on challenges in worker skill development is required to understand:

- What strategies can be employed to integrate existing human factors while prioritizing worker skill development in I5.0?
- What specific challenges and tensions in human-technology collaboration need to be addressed as a priority in incorporating humanization into I5.0?

Research to advance the knowledge of the impact on human value in industries is required to understand:

- In what ways does the diminished role of employees in ongoing waves of digitalization of manufacturing necessitate improvement in the next wave of industrial transformations?
- What technologies are necessary to support effective human-machine collaboration in the context of I5.0?
- How can a comprehensive understanding of cutting-edge technologies contribute to the successful integration of mass individualization

and personalization in production paradigms during the transition towards I5.0?

Regarding tensions in work design transformation, promising future research questions include:

- What are the specific tensions between humans and production systems arising from the work design transformation in I5.0?
- How can these tensions be explored, understood, and reconciled to facilitate a smoother transition towards a working design 5.0?

CRediT authorship contribution statement

Diego A. de J. Pacheco: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Bartosz Iwaszczenko:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Appendix

Table A1

List of papers included in the literature review.

Author (s) (Publication year)	Publication title
Adel (2022)	Future of industry 5.0 in society: human-centric solutions, challenges and prospective research areas
Alves et al. (2023)	Is Industry 5.0 a Human-Centred Approach? A Systematic Review
Atif (2023)	Analyzing the alignment between circular economy and industry 4.0 nexus with industry 5.0 era: An integrative systematic literature review
Battini et al. (2022)	Towards Industry 5.0: A multi-objective job rotation model for an inclusive workforce
Boschetti et al. (2022)	Human-Centered Design for Productivity and Safety in Collaborative Robots Cells: A New Methodological Approach
Chourasia et al. (2023)	A Critical Review on Industry 5.0 and Its Medical Applications
Diop et al. (2023)	Asset and Risk Management Approach in the Context of Complexity in Industry 4.0/5.0 Systems
Ghobakhloo et al. (2024)	Beyond Industry 4.0: a systematic review of Industry 5.0 technologies and implications for social, environmental and economic sustainability
Grabowska et al. (2022)	Industry 5.0: improving humanization and sustainability of Industry 4.0.
Hein-Pensel et al. (2023)	Maturity assessment for Industry 5.0: A review of existing maturity models.
Huang et al. (2022)	Industry 5.0 and Society 5.0— Comparison, complementation and co-evolution.
Ivanov (2023)	The Industry 5.0 framework: Viability-based integration of the resilience, sustainability, and human-centricity perspectives
Kemendi et al. (2022)	Industry 4.0 and 5.0– organizational and competency challenges of enterprises
Kolade and Owoseni (2022)	Employment 5.0: The work of the future and the future of work
Leng et al. (2022)	Industry 5.0: Prospect and retrospect
Liu et al. (2024)	Towards Industry 5.0: Challenges and enablers of intelligent manufacturing technology implementation from a sustainability perspective
Lu et al. (2022)	Outlook on Human-Centric Manufacturing towards Industry 5.0
Modgil et al. (2023)	Developing human capabilities for supply chains: an industry 5.0 perspective.
Piccarozzi et al. (2024)	Roadmap to Industry 5.0: Enabling technologies, challenges, and opportunities towards a holistic definition in management studies.
Pizoń and Gola (2023)	Human–Machine Relationship: Perspective and Future Roadmap for Industry 5.0 Solutions
Santhi and Muthuswamy (2023)	Industry 5.0 or Industry 4.0? Introduction to Industry 4.0 and a peek into the prospective Industry 5.0 technologies
Rannertshausser et al. (2022)	Human-centricity in the design of production planning and control systems: A first approach towards Industry 5.0
Tavares et al. (2022)	The Challenges and Opportunities of Era 5.0 for a More Humanistic and Sustainable Society—A Literature Review
Zizic et al. (2022)	From Industry 4.0 towards Industry 5.0: A review and analysis of paradigm shift for the people, organization and technology.

Source: Authors own elaboration.

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