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INDUSTRY 4.0 DIGITAL TECHNOLOGIES AS ENABLERS OF SUSTAINABILITY FOR SMALL AND MEDIUM ENTERPRISES

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SALVADOR-BA

ANDRÉ DE MENDONÇA SANTOS

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This thesis has been submitted in fulfilment of the requirements for the Doctor's Degree in Industrial Engineering at the Federal University of Bahia.

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ANDRÉ DE MENDONÇA SANTOS

Tese submetida ao corpo docente do programa de pós-graduação em Engenharia Industrial da Universidade Federal da Bahia como parte dos requisitos necessários para a obtenção do grau de doutor em Engenharia Industrial.

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ABSTRACT

The primary aim of this study is to explore how Industry 4.0 (I4.0) digital technologies can be implemented and applied to achieve sustainability in Small and Medium Enterprises (SMEs) in developing countries. The research followed a two-stage Systematic Literature Review (SLR), analyzing 42 academic articles from the Web of Science and Scopus databases. In the first stage, R® software was used to analyze journal trends, publication countries, and articles' growth over time. The second stage involved a qualitative analysis, identifying 17 sustainability functions that I4.0 contributes to in sustainable manufacturing for SMEs. After the SLR, a quantitative study was conducted to identify which sustainability functions should be prioritized. The Fuzzy DEMATEL method was used, gathering questionnaires from experts to highlight the most prominent and influential functions. Further qualitative research was conducted through semi-structured interviews with SME leaders to identify specific challenges in achieving sustainability and addressing the pillars of Industry 5.0 (I5.0), focusing on sustainability, human-centric, and resilience aspects. Additionally, interviews with technology providers were conducted to evaluate existing solutions available to SMEs. The interview findings were analyzed, and technological solutions were proposed during a focus group session involving four I4.0 experts. A subsequent round of meetings was held to gather feedback from the SMEs. The results demonstrated that digital technologies can indeed support SMEs in achieving sustainability and I5.0 objectives. The study also proposed frameworks for accomplishing these goals, such as creating safer work environments, improving environmental sustainability, and strengthening resilience through increased integration between companies. Moreover, the findings suggest that priority should be given to functions like organizing production processes and employee skill development to reduce the complexity of I4.0 implementation. Lastly, the study highlighted the need for technologies to align with SMEs' requirements, which include ease of implementation, compatibility, and low costs to ensure broader adoption. This paper offers practical guidance to help SME managers in their digitization efforts and contributes to the academic understanding of appropriate digital technologies for SMEs in emerging countries to become more human-centric, sustainable, and resilient.

Keywords: Manufacturing Industry; SME; Entrepreneurship; Sustainable Development; Technology Adoption; MCDM

LIST OF FIGURES

LIST OF TABLES

CONTENTS

1 INTRODUCTION

Technological progress has historically prioritized productivity, performance, and competitiveness, often at the expense of human well-being and environmental considerations (SATYRO *et al.*, 2022). However, with the increasing scarcity of resources, environmental crises, and the demand for improved workplace conditions, stakeholders are now pressuring organizations to adopt sustainable processes (DENICOLAI; ZUCCHELLA; MAGNANI, 2021; KHANZODE *et al.*, 2021). The concept of "sustainable development," was first introduced in the Brundtland (1987) report refers to development that meets current needs without compromising the needs of future generations. This definition has since been refined in the manufacturing context to emphasize high-quality production using fewer natural resources while safeguarding the well-being of employees, consumers, and local communities (MACHADO; WINROTH; DA SILVA, 2020; SHARMA *et al.*, 2021; STOCK; SELIGER, 2016). Thus, companies should aim to balance the three dimensions of sustainability−social, environmental, and economic−known as the Triple Bottom Line (TBL) (ALAYON; SÄFSTEN; JOHANSSON, 2022; BELTRAMI *et al.*, 2021).

To achieve sustainability objectives, emerging digital technologies from Industry 4.0 (I4.0) are proving to be effective solutions for reducing the environmental impact of production processes (EJSMONT; GLADYSZ; KLUCZEK, 2020; EUROPEAN COMMISSION, 2021; GHOBAKHLOO, 2020; IVANOV, 2022). These technologies leverage interconnectivity and enhanced productivity to minimize waste, improve energy efficiency, and promote cleaner production practices overall (NASCIMENTO *et al.*, 2019).

I4.0 integrates cyber-physical systems for data collection and processing to optimize production processes, administrative tasks, and product performance (ABDULAZIZ *et al.*, 2023; FRANK; DALENOGARE; AYALA, 2019). This integration leverages technologies such as the Internet of Things (IoT), cloud computing, big data analytics, and artificial intelligence (AI), enabling data-driven decision-making in management (GHOBAKHLOO, 2020; KAMBLE; GUNASEKARAN; GAWANKAR, 2018; RUBMANN *et al.*, 2015). Although not initially designed for sustainability improvements (INGALDI; ULEWICZ, 2020), I4.0 has shown positive impacts on sustainability across the social, environmental, and economic dimensions (BAI *et al.*, 2020; GHOBAKHLOO, 2020; KAMBLE; GUNASEKARAN; GAWANKAR, 2018; MACHADO; WINROTH; DA SILVA, 2020). Socially, I4.0 supports employee health and safety by minimizing repetitive tasks (BAI *et al.*, 2020; PAPETTI *et al.*, 2020). Environmentally, it reduces water and energy consumption (KUNKEL; MATTHESS, 2020; STOCK; SELIGER, 2016). Economically, I4.0 shortens setup and lead times, increases flexibility, and enhances productivity (FRANK; DALENOGARE; AYALA, 2019; RUBMANN *et al.*, 2015). However, I4.0 has not been explicitly tailored to address the unique challenges faced by small and medium-sized enterprises (SMEs). As a result, these businesses are not fully integrated into the context of I4.0 and sustainability, preventing these approaches from being fully implemented in industrial environments (KHANZODE *et al.*, 2021).

While the SMEs' individual impact may be smaller compared to larger corporations, their aggregated impact on the environment is significant (DENICOLAI; ZUCCHELLA; MAGNANI, 2021). SMEs are responsible for 70% of global industrial pollution and 60% of carbon emissions (EUROPEAN COMMISSION, 2017), they contribute more to environmental degradation and waste production than large corporations (CALOGIROU, CONSTANTINOS, SØRENSEN *et al.*, 2010). Despite their impact, SMEs have largely been overlooked in sustainability research (BROZZI *et al.*, 2020; DEY *et al.*, 2023), especially in developing countries, where greater economic instability and limited infrastructure present additional challenges (NARA *et al.*, 2021). Therefore, targeted strategies are necessary to encourage the adoption of technologies in SMEs in developing countries, with a particular emphasis on sustainable applications (KUMAR; SINGH; DWIVEDI, 2020). In addition to this process, SMEs should actively explore and integrate into the framework of Industry 5.0, which offers a more comprehensive approach by expanding objectives beyond sustainability.

I5.0 was designed with sustainability as a core pillar (MADDIKUNTA *et al.*, 2022; XU *et al.*, 2021), extending to two additional pillars: human-centricity and resilience (IVANOV, 2022). Human-centricity focuses on designing technologies that adapt to human needs, improving ergonomics, well-being, and job satisfaction (ALVES; LIMA; GASPAR, 2023), aligning with the social dimension of sustainability but with a greater emphasis on the integration of operators and technology (LU *et al.*, 2022). The sustainability pillar mandates that industries operate within planetary resource limits (XU *et al.*, 2021), while resilience emphasizes the need for robust production systems that can withstand disruptions and maintain critical infrastructure during crises, such as the COVID-19 pandemic (GHOBAKHLOO *et al.*, 2022a).

The I5.0 is also present within I4.0 digital technologies, making the two revolutions complementary rather than mutually exclusive (EUROPEAN COMMISSION, 2021; MADDIKUNTA *et al.*, 2022). The technological and regulatory advancements in I5.0 redefine the scope of I4.0 technologies, adding value through human-centered, sustainability-focused, and resilient approaches (GHOBAKHLOO *et al.*, 2022a; IVANOV, 2022). I5.0 aims to unlock the full potential of new technologies to drive prosperity, focusing not only on growth but also on respecting planetary limits and placing the well-being of industry workers at the core of production processes (EUROPEAN COMMISSION, 2021). This approach redefines the applications originally envisioned for I4.0 technologies. However, despite being conceived with sustainability as one of its core pillars, Industry 5.0 was not designed with the specific characteristics of SMEs in mind, similar to I4.0. This limitation poses challenges to implementation of concepts and technologies within these enterprises (KHANZODE *et al.*, 2021; MACHADO *et al.*, 2021).

1.1 JUSTIFICATION

SMEs are significant economic drivers for countries, responsible for generating jobs and income (IAKOVETS; BALOG; ŽIDEK, 2023). Globally, SMEs represent 95% of private companies (AYYAGARI; DEMIRGUC-KUNT; MAKSIMOVIC, 2011) and employ over 60% of the workforce (WSF, 2022). These businesses create opportunities for individuals in entry-level positions and those with limited professional training, providing pathways to the labor market for segments that might otherwise face barriers to entry (LOPEZ-NICOLAS *et al.*, 2020). With fewer resources and skilled labor, these companies often overlook their environmental impact, creating a widespread issue that is challenging to address due to their reach and prevalence (ALAYON; SÄFSTEN; JOHANSSON, 2022). Although efforts have been made to connect I4.0 with SMEs (ASCÚA, 2021; CHAVEZ *et al.*, 2022; MITTAL *et al.*, 2018; MOEUF *et al.*, 2020) or SMEs with sustainability (CHEGE; WANG, 2020; CHOWDHURY; SHUMON, 2020; JOURNEAULT; PERRON; VALLIÈRES, 2021; LOPES DE SOUSA JABBOUR; NDUBISI; ROMAN PAIS SELES, 2020), the literature does not yet clarify how I4.0 can facilitate integrating sustainable practices into the operations of these businesses or how these businesses can better prepare organizationally to adopt new technologies (KHIN; HUNG KEE, 2022). This gap is problematic, considering the significant environmental impact of SMEs and the need for solutions tailored to their unique needs (MUKHUTY; UPADHYAY; ROTHWELL, 2022).

While most new technologies are developed with large enterprises in mind, they may not always be suitable for smaller businesses, which face unique requirements and obstacles in their digital transformation efforts (DUTTA *et al.*, 2020; MITTAL *et al.*, 2018). SMEs often lack clarity on where to start implementing new technologies or what to prioritize to reduce effort and complexity in adoption (DEY *et al.*, 2023; NARKHEDE *et al.*, 2023). Many SMEs require low-cost, easy-to-integrate technologies compatible with existing systems (DOSSOU *et al.*, 2022; YANG *et al.*, 2023). Additionally, there is a strong preference for low-complexity initial implementations that can provide insight into the operational benefits of the technology (JAYASHREE *et al.*, 2021a; MASOOD; SONNTAG, 2020). This indicates that effective readiness for new technologies in SMEs should focus on reducing investment risk and ensuring short-term gains (DUTTA *et al.*, 2020). However, existing integration solutions are often complex, centrally managed systems, making adaptation and maintenance prohibitively expensive for SMEs (CHAVEZ *et al.*, 2022; CHOWDHURY; SHUMON, 2020; MITCHELL *et al.*, 2020) Although the literature explores possible applications of I4.0 in SMEs, often lack practical examples that align with the financial and operational constraints of SMEs and deliver sustainable outcomes (JAMWAL; AGRAWAL; SHARMA, 2023; NARKHEDE *et al.*, 2023). Moreover, there is a limited understanding of the factors influencing SMEs' preparedness for I4.0. These factors often encompass organizational, technical, and social dimensions, all of which play a critical role in ensuring readiness for I4.0 implementation (CHONSAWAT; SOPADANG, 2020).

The potential synergies of applying both I4.0 and sustainability have been well-documented (BIRKEL; MÜLLER; MULLER, 2021; BROZZI *et al.*, 2020; EJSMONT; GLADYSZ; KLUCZEK, 2020; GHOBAKHLOO, 2020; KAMBLE; GUNASEKARAN; GAWANKAR, 2018; STOCK; SELIGER, 2016). However, there is limited focus on applicating these concepts in SMEs, with insufficient empirical evidence on the combined impact of digitization and sustainability on SMEs growth. Then, these two aspects are often addressed separately (DENICOLAI; ZUCCHELLA; MAGNANI, 2021).

Furthermore, few studies examine all three pillars of sustainability concurrently or investigate how innovative technologies can enhance sustainable performance (CHEGE; WANG, 2020; NARA *et al.*, 2021). Research at the intersection of SMEs, I4.0, and sustainability often focuses on barriers (KUMAR; SINGH; DWIVEDI, 2020; MACHADO *et al.*, 2021), performance measurement (COSTA MELO *et al.*, 2023a), facilitators for achieving sustainable development (HUNG; CHEN, 2023; JAYASHREE *et al.*, 2021a; KUMAR; REHMAN; PHANDEN, 2022), or single technologies like blockchain (KHAN *et al.*, 2021) and AI (DEY *et al.*, 2023). Studies by Gupta *et al.* (2022) and Jayashree *et al.* (2021b) affirm a positive relationship between the combined use of I4.0 and sustainability in SMEs. However, these works fall short of explaining how technologies can be adapted to help SMEs achieve sustainability functions. Sustainability functions refer to the activities and practices SMEs can implement across various company's areas to achieve sustainability in its three dimensions, which may assist in identifying technologies that best align with organizational goals.

This trend persists in I5.0 studies, where despite sustainability being one of its pillars, the focus lies on large corporations benefiting from technology applications, mainly investigating I5.0 concepts (IVANOV, 2022; LU *et al.*, 2022; NAHAVANDI, 2019; XU *et al.*, 2021). Ghobakhloo *et al.* (2022a) examine how I5.0 can address sustainability, Sindhwani *et al.* (2022) explore enabling technologies for social factors and resilience, and Leng (2022) discusses challenges and enablers for I5.0. Limited research exists on I5.0 implementation in SMEs, usually concentrating on specific topics like maturity models (HEIN-PENSEL *et al.*, 2023; KRAJČÍK, 2021; MADHAVAN; SHARAFUDDIN; WANGTUEAI, 2024), or sustainable practices ((ALI; JOHL, 2023). There remains a lack of guidelines for adopting sustainable manufacturing practices tailored for SMEs (ALAYON; SÄFSTEN; JOHANSSON, 2022). This gap underscores the need to study how digital technologies from I4.0 and I5.0 can assist SMEs in achieving sustainability and addressing I5.0's complementary pillars-human-centric and resilience. This research is even more critical in developing countries, where resources for investments, infrastructure, skilled labor, and training are scarce, leaving SMEs lagging in technology adoption (KUMAR; SINGH; DWIVEDI, 2020; MACHADO *et al.*, 2021; NARA *et al.*, 2021).

The most I4.0 studies are centered in developed countries, while research on this topic in developing economies remains limited (COSTA MELO *et al.*, 2023a; SILTORI *et al.*, 2021). This lack of studies hinders SMEs in developing countries from advancing in sustainable operations (KUMAR; SINGH; DWIVEDI, 2020). Barriers and facilitators often vary significantly depending on the development level of the country in which these SMEs operate, including differences in digital, educational, and economic infrastructure, as well as political stability (ALAYON; SÄFSTEN; JOHANSSON, 2022; JAYASHREE *et al.*, 2021a). In Brazil, challenges are compounded as SMEs face some of the highest interest rates globally, making I4.0 investments challenging (FEIJO, 2024). SMEs in Brazil represent over 70% of jobs and 30% of GDP, yet around 23% of micro and small businesses close within five years, a figure worsened by the COVID-19 pandemic (SEBRAE, 2022). While the literature has addressed digitization and sustainability in Brazil—for example, Machado et al. (2021) analyzed digitalization and sustainability barriers, Ascua (2021) examined I4.0's impact on Latin American SMEs, and Nara et al. (2021) explored the most impactful technologies for sustainability in the Brazilian plastics sector—there is still a need for clear guidance on the pathway that SMEs in a developing country like Brazil should follow to achieve sustainability with I4.0 digital technologies. This guidance is particularly necessary for regions outside central areas in Brazil, which face greater development challenges but need solutions to remain competitive and sustainable.

1.2 OBJECTIVES

The current study focuses on Operations and Technology Management. The primary aim is to explore how I4.0 digital technologies can be implemented and applied to achieve sustainability and I5.0 pillars in SMEs from developing countries. To achieve the general goal of this work, the following specific objectives are proposed:

a) Explore how I4.0 technologies can support SMEs in achieving sustainability;

b) Develop a Multi-Criteria Decision-Making (MCDM) model to prioritize sustainability functions supported by I4.0 technologies in SMEs;

c) Investigate how organizational, technical, and social factors influence the adoption of I4.0 technologies in SMEs;

d) Investigate the potential impact of I4.0 digital technologies on promoting sustainability in SMEs within developing economies such as Brazil;

e) Evaluate the I4.0 technologies and their alignment with the characteristics of Small Firms (SFs) and the three pillars (human-centricity, sustainability, and resilience) of I5.0.

1.3 METHODOLOGY

The scientific methodology of research can be classified based on its nature, objectives, approach, and procedures. This work, regarding its nature, falls under applied research, as it is dedicated to generating knowledge for problem-solving, specifically related to the digitization and sustainability of SMEs (NASCIMENTO, 2016; PRODANOV; FREITAS, 2013). Concerning its objectives, it is classified as exploratory research, aiming to provide greater familiarity with the problem to make it explicit or construct hypotheses, achieving clarity through the proposed frameworks (GIL, 2019).

Regarding its approach, this is mixed-method research, as it employs both qualitative and quantitative stages (PRODANOV; FREITAS, 2013). This approach encompasses a comprehensive methodology, including literature review, case studies, interviews, workshops, multi-criteria analysis, and cluster analysis. These combined methods enable an in-depth exploration of various aspects of the topic, enhancing the robustness and reliability of the results. Qualitative studies rely on interpreting observed phenomena and the meaning they carry, or the meaning attributed by the researcher, within the context in which these phenomena exist (NASCIMENTO, 2016). The researcher aims to gather data on the perspectives of local actors (MILES; HUBERMAN; SALDAÑA, 2014). The research involves qualitative procedures such as a literature review through a systematic review and case study, employing semi-structured interviews and focus groups (PATTON, 2014). The case study involves collecting and analyzing information about individuals, families, groups, or communities to explore various aspects of their lives, related to the research topic (PRODANOV; FREITAS, 2013).

Quantitative research requires the use of statistical techniques and allows for the quantification of all collected information, which means translating opinions and information into numbers to classify and analyze them (PRODANOV; FREITAS, 2013). It involves various statistical techniques, such as descriptive analysis, regression analysis, and multivariate analysis. This study employs the quantitative method of Multiple-Criteria Decision-Making (MCDM), specifically fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL), to analyze expert opinions and prioritize variables related to sustainability and I4.0. Additionally, this research employs cluster analysis and Ordinal Logistic Regression to identify significant predictors of I4.0 adoption in Small, Micro and Medium Enterprises (MSMEs). Therefore, this research aims to gain a deep understanding of the analyzed context, exploring the correlation between I4.0, sustainability, and SMEs by studying companies across different sectors.

The methodology of this work is structured in three phases. **Firstly**, it utilizes a Systematic Literature Review (SLR) aligned with best practices in emerging fields related to I4.0, sustainability, and SMEs to understand their correlation. The SLR follows the well-established five-stage methodology proposed by Denyer and Tranfield (2009): (i) formulating questions, (ii) locating studies, (iii) selecting and evaluating studies, (iv) analyzing and consolidating, and (v) reporting results. The search strategy combined the three research themes—I4.0, Sustainability, and SMEs—along with their synonyms. The articles were subjected to multiple filtering stages, resulting in a final selection that included only peer-reviewed studies published in English. This process identified 42 articles deemed highly relevant to the research topic. This approach incorporates statistical analyses aimed at achieving several objectives: tracking the yearly evolution of publications, identifying countries of publication, and evaluating journal significance. The final articles were closely examined to identify sustainability functions that new digital technologies could enhance alongside the quantitative literature analysis.

In the **second phase**, the DEMATEL method was applied to analyze the interrelationships among sustainability functions, identifying the most prominent and influential ones. This method was selected for its capacity to leverage expert knowledge, categorize factors into cause-and-effect groups, and present the results in a structured matrix format (KAZANCOGLU; OZKAN-OZEN, 2018; KUMAR; REHMAN; PHANDEN, 2022). This approach facilitates a systematic and comprehensive understanding of the relationships among the investigation variables. To support the analysis, a carefully designed questionnaire was developed based on prior methodologies (KAZANCOGLU; OZKAN-OZEN, 2018; KUMAR; SINGH; DWIVEDI, 2020). A panel of 15 experts was consulted to correlate the sustainability functions. In constructing a structural model of expert judgments, notable values were assigned to represent the experts' preferences and the importance of factors. However, these values often prove inadequate in real-world contexts due to their inherent ambiguity and the challenges of precise numerical estimation (MACHADO *et al.*, 2021). To address these limitations, fuzzy logic was integrated with the DEMATEL method (VINODH; WANKHEDE, 2020). The model employs fuzzy sets to manage uncertainty and vagueness in expert assessments of the impact levels among factors. These fuzzy values are then converted into crisp values to construct the group's direct influence matrix, which is subsequently analyzed using the classical DEMATEL procedure (SI *et al.*, 2018). Furthermore, sensitivity analysis was conducted to evaluate the robustness of the DEMATEL results (JAMWAL; AGRAWAL; SHARMA, 2023; KUMAR; REHMAN; PHANDEN, 2022).

In the **third study**, also quantitative, a survey method was employed to collect data from 80 companies affiliated with the Brazilian Association of Machinery and Equipment Manufacturers (ABIMAQ-Sul). A questionnaire was designed to evaluate the adoption levels of organizational factors in MSMEs, categorized into strategic, technical, and social dimensions, and to examine the correlation of these dimensions with the level of I4.0 adoption and company size. A two-step cluster analysis was conducted to identify at least two distinct groups for comparing the relationship between organizational factors and technology adoption. After forming the clusters, a demographic analysis was performed to investigate whether the groups exhibited different patterns concerning organizational factors. Data processing and analysis were carried out using R statistical software. Analysis of Variance (ANOVA) was applied to compare the means of organizational factors between clusters (p-value < 0.05) and determine whether the variances were statistically significant (LASSNIG *et al.*, 2018). Lastly, logistic regression was employed to identify which organizational factors as significant predictors of I4.0 adoption in MSMEs.

Finally, we embraced a qualitative case study approach, known for its effectiveness in exploring problems and developing theoretical insights (VOSS; TSIKRIKTSIS; FROHLICH, 2002). This method was instrumental in analyzing the potential uses of digital technologies to assist SMEs in achieving sustainability, human-centricity, and resilience. Our selection of cases followed a theoretical sampling approach, focusing on cases that could illuminate the constructs under investigation (EISENHARDT; GRAEBNER, 2007). Semi-structured interviews served as the primary method for data collection, enabling us to uncover how technologies could enhance productivity and sustainable practices. Our approach aimed to deeply understand the perspectives of local participants, gaining an insider's empathetic viewpoint on the discussed topics (MILES; HUBERMAN; SALDAÑA, 2014). Throughout interviews with SME managers and technology providers, we explored existing technologies, sustainability challenges, and potential integration approaches between digitalization (I4.0 and I5.0), sustainability, and SMEs.

The questionnaire used in the semi-structured interviews underwent review and refinement by four specialists in I4.0 and I5.0 to ensure the construct validity, not involved in the data collection. Additionally, initial interviews with two companies were conducted to fine-tune the instrument. For establishing external validity was conducted multiple case studies, comparing evidence from SMEs that embraced digital technologies to enhance sustainability (VOSS; TSIKRIKTSIS; FROHLICH, 2002). To ensure reliability, we adhered to a case study protocol (MILES; HUBERMAN; SALDAÑA, 2014; PATTON, 2014), and a final report was generated based on transcriptions of the recorded interviews. Regarding data analysis and interpretation, the initial step involved transcribing the recorded interviews, which were subsequently scrutinized to identify potential technology applications for sustainability. Following this, a focus group session engaged four I4.0 and I5.0 experts to analyze the interview outcomes. Finally, we compared the cross-case analysis with the literature and developed proposals for SMEs to achieve sustainability and I5.0 goals through digital technologies.

The articles comprising the thesis were categorized based on their research approach. Article 1 falls under the classification of a literature review. Article 2 employs the quantitative methodology of fuzzy-DEMATEL. Article 3 employs cluster analysis and ordinal logistic regression. Finally, Articles 4 and 5 present qualitative studies based on interviews and focus groups. Therefore, this study consists of five articles, each serving a distinct purpose to fulfill the overall objective, as outlined in Table 1.

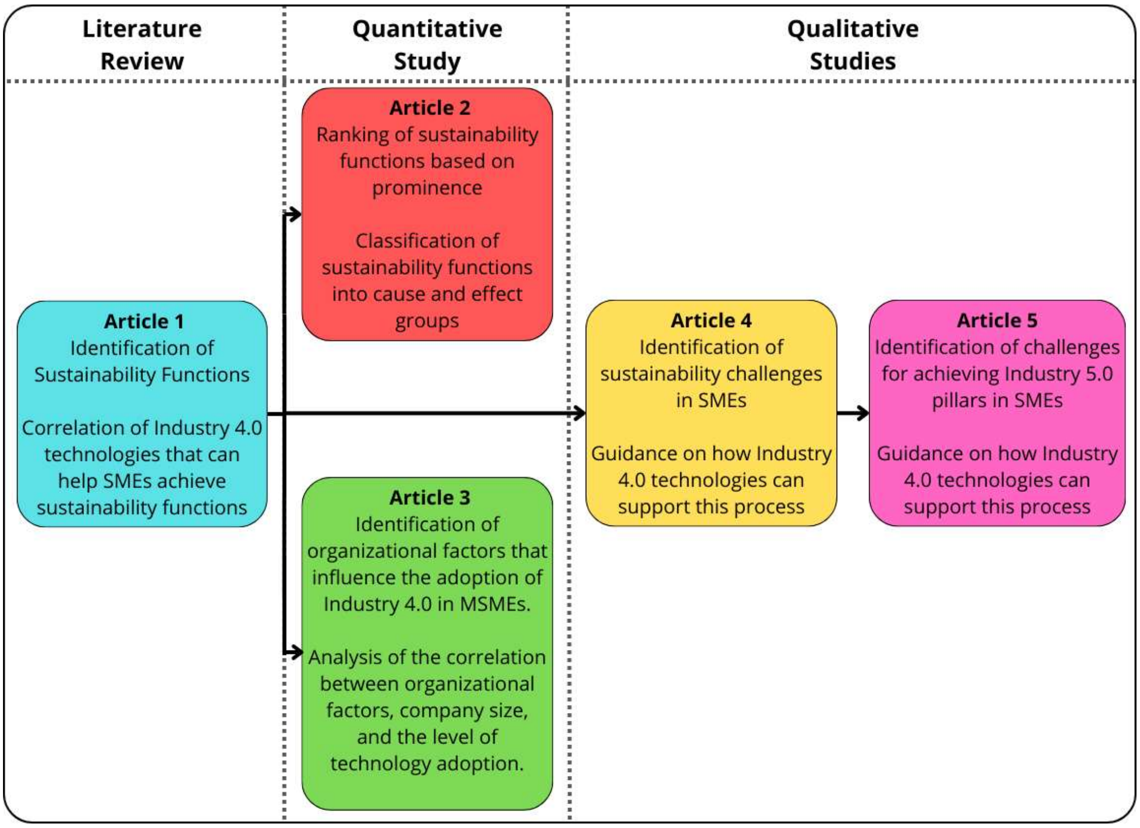
Table 1 - Work structure according to specific objectives

	Research Questions	**Objective**	**Methods**
Article 1	RQ1: How can I4.0 technologies assist SME sustainability? RQ2: What are the potential areas for further research in this context?	Explore how I4.0 technologies can support SMEs in achieving sustainability.	Systematic Literature Review: 1- Quantitative analyses of authors, countries, and research trends; 2- Qualitative analysis; 3 – Proposed framework.

Article 2	Which sustainability functions have the greatest prominence and influence, and should be prioritized for implementation in SMEs?	Develop a Multi-Criteria Decision-Making model to prioritize sustainability functions supported by I4.0 technologies in SMEs	<u>Quantitative research</u>: 1 - Fuzzy-DEMATEL method 2 – Sensitivity Analysis.
Article 3	How do organizational factors influence the adoption of Industry 4.0 technologies in MSMEs?	Investigate how organizational, technical, and social factors influence the adoption of I4.0 technologies in MSMEs	<u>Quantitative research</u>: 1 - A Two-step Cluster Analysis 2 – Ordinal Logistic Regression
Article 4	How can the digital technologies of I4.0 promote sustainability within the context of SMEs in a developing country like Brazil?	Investigate the potential impact of I4.0 digital technologies on promoting sustainability in SMEs within developing economies such as Brazil;	<u>Qualitative research</u>: 1- Semi-structured interviews; 2- Focus group session; 3 – Proposed framework.
Article 5	How can Industry 4.0 digital technologies facilitate the adoption of Industry 5.0 among SFs?	Evaluate Industry 4.0 technologies and their alignment with the characteristics of SFs and the three pillars (human-centricity, sustainability, and resilience) of Industry 5.0	<u>Qualitative research</u>: 1- Semi-structured interviews; 2- Focus group session; 3 – Proposed framework.

Thus, these articles are integrated to achieve the study's objectives (Figure 1). Article 1 begins by identifying the sustainability functions that Industry 4.0 technologies can support in SMEs through a comprehensive literature review. Article 2 prioritizes these functions, highlighting the most prominent and influential ones. Article 3 addresses a gap identified in the literature by Article 1 and identifies the organizational factors that can facilitate the implementation of Industry 4.0 in MSMEs. Article 4 builds on the findings of Articles 1 to identify sustainability challenges faced by SMEs and propose potential technological solutions complemented by organizational changes. Finally, Article 5 expands the focus to I5.0 pillars, building on the viable technological applications for sustainability in SMEs established in the previous articles.

Figure 1 – Relationship between articles



1.4 STUDY DELIMITATIONS

This study was conducted within SMEs. However, it is crucial to note that this term lacks a globally standardized definition. The classification of a company as an SME commonly relies on financial measures and/or the number of employees, which can vary among different countries (COSTA MELO *et al.*, 2023a). The study focused on companies in Brazil, where small companies are defined as having up to 99 employees, while medium-sized companies have up to 500 employees (SEBRAE, 2013). We intentionally selected SMEs from various industry segments to generate diverse results, offering a broader perspective on the phenomenon and facilitating the generalization of our findings. Using this criterion, we engaged with companies participating in an innovation program focused on productivity, a Brazilian service designed to support SMEs.

The rationale for focusing on Brazilian companies is due to the country's status as a developing nation, facing distinct challenges concerning SMEs compared to developed countries (SILTORI *et al.*, 2021). Experts from different regions of the country were consulted to achieve greater generalization in the results of the fuzzy DEMATEL analysis. Hence, this study investigates realities that present more challenging implementations of technology and sustainability, aspects often overlooked in the literature, aiming to fill this knowledge gap (KUMAR; SINGH; DWIVEDI, 2020). It is essential to emphasize that the solutions proposed in this study are primarily focused on strategic and tactical levels rather than operational ones. Given the unique context of each company, the proposed solutions may vary on a case-by-case basis. Nevertheless, they align with the study's objectives by providing a fundamental framework to guide managers in utilizing technologies to address sustainability challenges effectively.

Finally, this study prioritized SMEs in the manufacturing sector, developing frameworks intended to guide managers and technology suppliers in implementing digitalization and sustainability within SMEs. Initially, the model does not encompass applications in the service industry, offering a potential avenue for future exploration.

1.5 CONTRIBUTIONS AND INEDITISM

This work presents several unique contributions and innovations. The first novelty lies in correlating three approaches typically treated separately in the literature: Industry 4.0, Sustainability, and SMEs (DENICOLAI; ZUCCHELLA; MAGNANI, 2021). This study breaks new ground by identifying technologies that can be integrated into the specific context of SMEs, meeting the requirements of low cost and complexity (ASCÚA, 2021; DOSSOU *et al.*, 2022). These results enable SMEs to leverage these technologies to achieve sustainable functions that enhance the quality of work life, resource efficiency, and economic performance (MITTAL *et al.*, 2018; MOEUF *et al.*, 2018).

Secondly, this study prioritizes sustainability functions, highlighting the most prominent and influential ones. It provides valuable insights into key areas SMEs should focus on when implementing sustainable practices, avoiding conflicting efforts that may hinder their progress toward objectives. It can serve as a roadmap, guiding managers toward digitalization and sustainability by allowing them to initially invest in the most impactful functions that influence others. Additionally, the findings highlight the organizational factors that affect I4.0 adoption offering managers insights into the necessary changes in their workflows and identifying key focus areas for action. These contributions can help reduce the complexity of implementing new technologies within these enterprises.

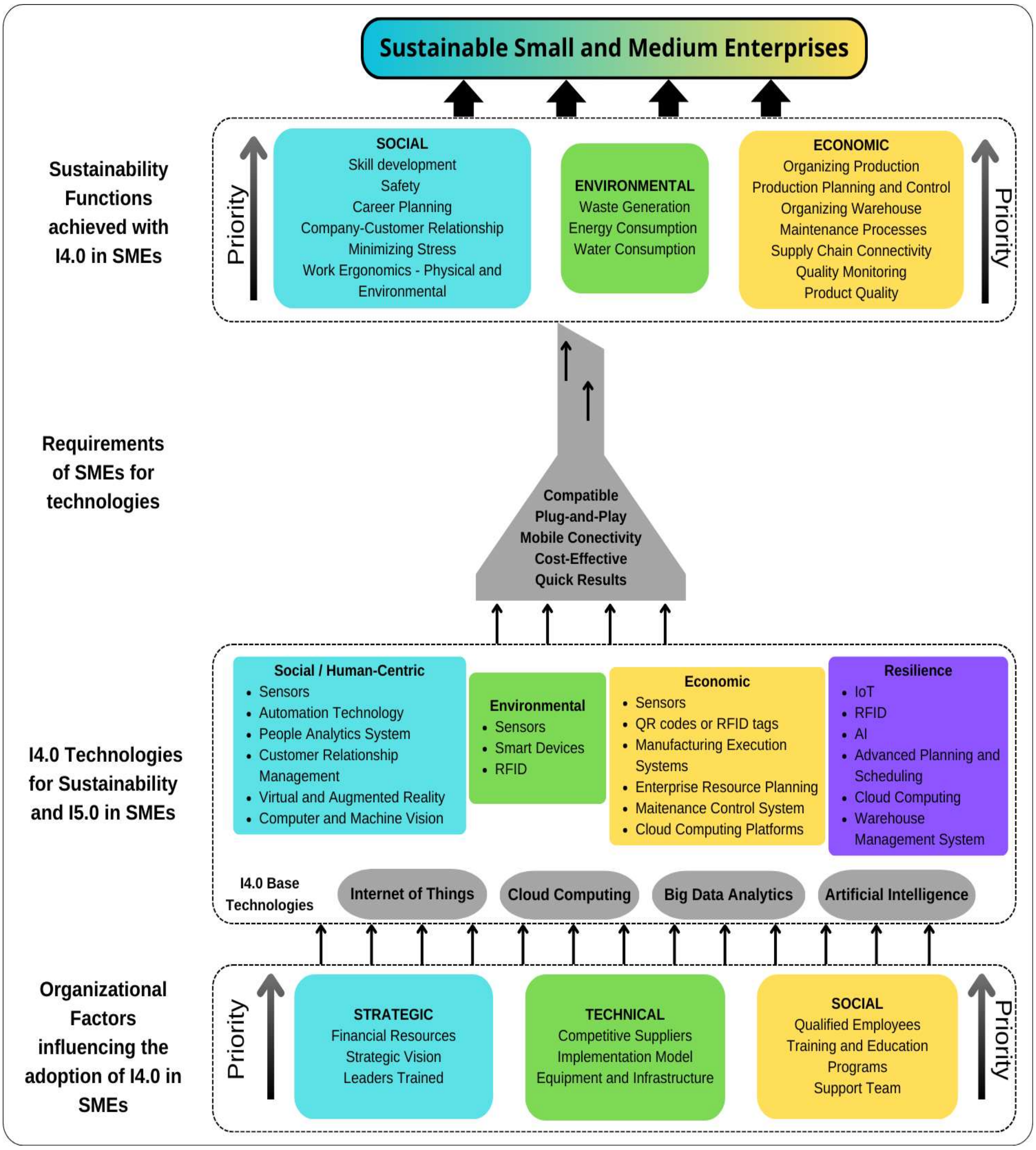
Thirdly, the inclusion of Industry 5.0 in the study represents a unique contribution to literature, exploring its applicability to SFs. The findings indicate opportunities for implementing new technologies to achieve human-centricity, sustainability, and resilience pillars (SINDHWANI *et al.*, 2022; XU *et al.*, 2021). This approach brings these advanced concepts closer to the reality of SFs, demonstrating practical feasibility where such integration previously seemed out of reach.

Fourthly, this study is pioneering in investigating the implementation of digital technologies in developing countries like Brazil, where research in this field remains limited (COSTA MELO *et al.*, 2023b; JAYASHREE *et al.*, 2021b). The results reveal adaptable solutions tailored to the reality of companies in these regions, expanding the potential impact of new technologies.

The final contribution of this work lies in presenting its findings as frameworks developed through methodological analyses. These frameworks can guide both managers and academics in applying digital technologies to achieve sustainability in SMEs. The results offer a roadmap for implementation, enabling managers to maximize the impact of sustainable practices while avoiding the allocation of financial and time resources to low-return activities (MITTAL *et al.*, 2018). Figure 2 consolidates the frameworks from the five articles in this study, illustrating how the I4.0 digital technologies can support SMEs in achieving sustainability and I5.0 pillars, aligned with the sustainability functions identified in Article 1. The sustainability functions were ranked, as shown in the results of Article 2, indicating an order of priority for investments and efforts. Furthermore, the organizational factors influencing the adoption of I4.0 are identified as support mechanisms for the implementation process (Article 3).

It suggests that the specific applications of digital technologies to achieve sustainability and the pillars of I5.0 should be based on IoT, cloud computing, big data analytics, and AI, as indicated by the analysis in Articles 4 and 5. Additionally, it outlines the requirements that technologies must meet for successful implementation in the context of SMEs in developing countries, also derived from Articles 4 and 5. The social dimension of I4.0 and the human-centric pillar of I5.0 are integrated into the framework (Fig. 2), because they converge on the same theme: valuing employees and the need to adapt technologies to their use. Since the study focuses on SMEs, which require simple and tangible applications, the social aspect has been centered on the employee, as does the human-centric approach, without delving into external aspects such as benefits for the neighboring community using technologies.

Figure 2 - Framework consolidating the findings of the five articles in the study



1.6 SCIENTIFIC PRODUCTION

The development of this thesis enabled the production of five scientific articles. Each of the articles listed below is associated with a specific objective of this work, collectively supporting the overall goal and forming the basis for the proposed framework shown in Figure 2:

Article 1: Santos, A.M.; Sant'Anna, A.M.O. *Industry 4.0 Technologies for Sustainable Small-Medium Enterprises: A Systematic Literature Review and Future Directions*. ***Journal of Cleaner Production*** (Impact Factor: 9.7; Qualis Capes: A1). https://doi.org/10.1016/j.jclepro.2024.143023

Article 2: Santos, A.M.; Sant'Anna, A.M.O.; Barbosa, A.S.; Becker, A.M.; Ayala, N.F. *Multi-criteria decision-making model for sustainability functions integrated Industry 4.0 technologies within Small and Medium Enterprises in Emerging countries*. ***International Journal of Productivity and Performance Management*** (Impacto Factor: 5.9; Qualis Capes: A1). https://doi.org/10.1108/IJPPM-10-2023-0557

Article 3: Santos, A.M.; Fettermann, D.C.; Ayala, N.F.; Sant'Anna, A.M.O. *How organizational factors influence the Industry 4.0 adoption in Micro, Small, and Medium Enterprises*. Submitted to: ***Management Decision*** (Impact Factor: 4.10; Qualis Capes: A1). MD-10-2024-2210. Review submitted on 01/10/2024

Article 4: Santos, A.M.; Becker, A.M.; Ayala, N.F.; Sant'Anna, A.M.O. *Industry 4.0 as an enabler of sustainability for Small and Medium Enterprises*. ***Academia Revista Latinoamericana de Administracion*** (Impact Factor: 1.3; Qualis Capes: A3). https://doi.org/10.1108/ARLA-07-2023-0118

Article 5: Santos, A. M.; Becker, A.M.; Ayala, N.F.; Sant'Anna, A.M.O; Mendes, G. H. S. *Driving Small Firms towards Industry 5.0 in emerging countries: the essential role of Industry 4.0 technologies*. Submitted to: ***Technovation*** (Impact Factor: 11.1; Qualis Capes: A1). TECHNOVATION-D-24-00461. Review submitted on 20/10/2024.

1.7 STRUCTURE OF THE THESIS

This thesis is structured into seven chapters, as depicted in Figure 3. Chapter 1 provides a contextualized introduction to the topic, encompassing: problem contextualization and rationale for the work execution; the general and specific objectives of this study; the chosen methodology; study limitations; scientific productions resulting from the thesis; and the structure of the study itself. The subsequent chapters aim to achieve the specific objectives.

Chapter 2 presents the findings of the literature review, examining how existing literature perceives the correlation between I4.0, Sustainability, and SMEs.

Chapter 3 is dedicated to prioritizing sustainability functions supported by I4.0, identifying what should be prioritized for investment by SME managers.

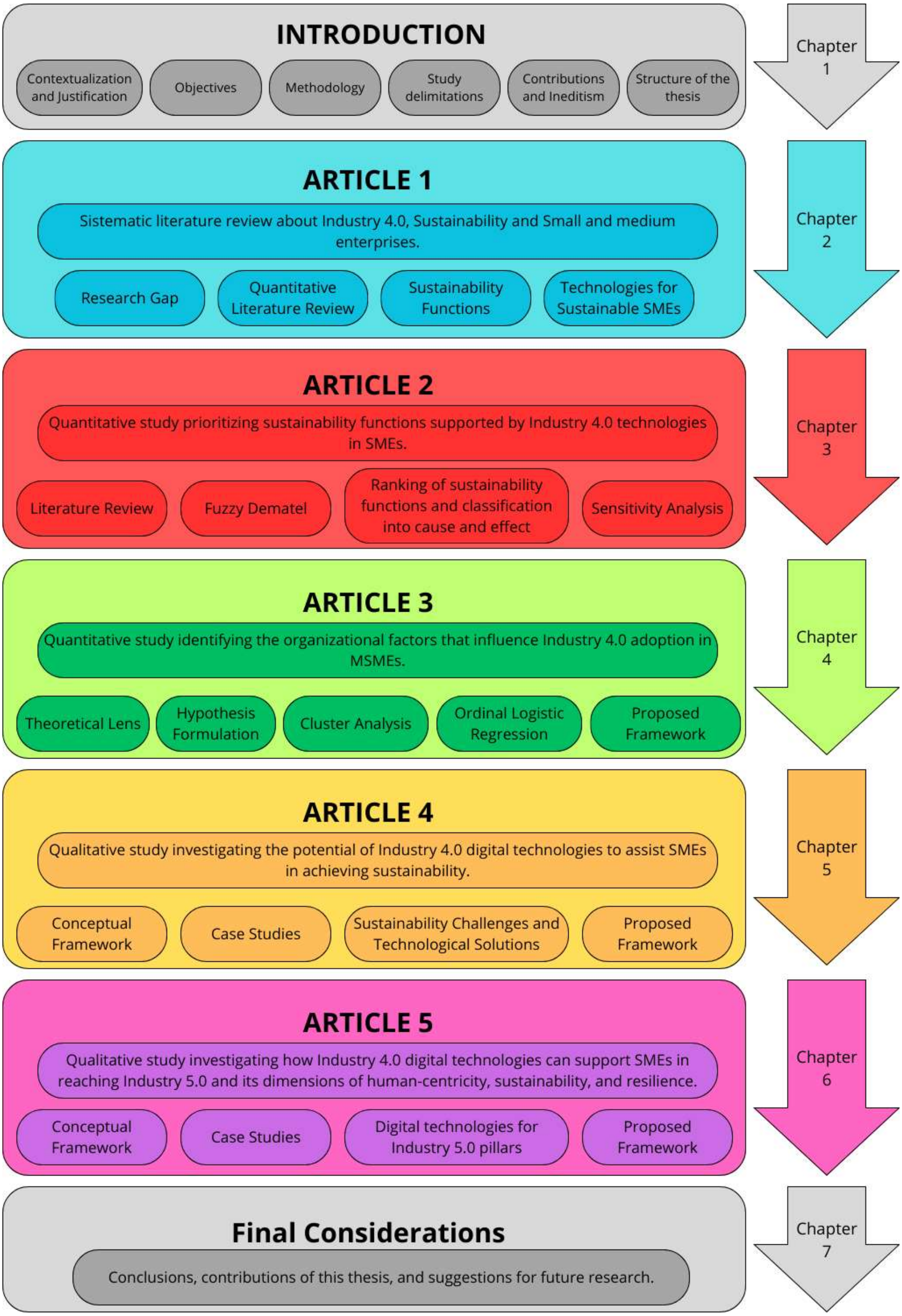
Chapter 4 correlates organizational factors with company size and the level of I4.0 adoption in MSMEs.

Chapter 5 delves into the potential of I4.0 digital technologies to assist SMEs in achieving sustainability.

Chapter 6 discusses how I4.0 digital technologies can support SMEs in reaching I5.0 pillars, as human-centricity, sustainability, and resilience.

Finally, Chapter 7 is dedicated to the concluding remarks, contributions of this thesis, and suggestions for future research based on the findings of this study.

Figure 3 - Flowchart of the thesis' structure developed



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Review

2 INDUSTRY 4.0 TECHNOLOGIES FOR SUSTAINABLE SMALL-MEDIUM ENTERPRISES: A SYSTEMATIC LITERATURE REVIEW AND FUTURE DIRECTIONS

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Abstract

Industry 4.0 (I4.0) has revolutionized manufacturing, necessitating an examination of its sustainability implications, particularly for Small and Medium Enterprises (SMEs). Consequently, this study aims to investigate how I4.0 technologies can assist SMEs in achieving sustainability. A systematic literature review (SLR) was conducted to achieve this goal, utilizing articles from the Web of Science and Scopus databases. Following a structured methodology, 42 articles were selected based on predefined criteria. In the first stage of the SLR, R® software was utilized to analyze journals, countries, and article growth. Subsequently, with the assistance of Mendeley®, the selected articles were analyzed to identify correlations among I4.0, sustainability, and SMEs. This process identified 17 sustainability functions supported by I4.0 in SMEs, including Employee skill development, Controlling Waste Generation, and Organizing Production Processes. Furthermore, the results demonstrate how I4.0 technologies can assist SMEs in achieving each sustainability function. The most suggested technologies include the Internet of Things (IoT), Cloud Computing, Big Data Analytics, and Artificial Intelligence, serving as the foundation for specific applications across the three dimensions of sustainability. This article contributes to theory by synthesizing previous knowledge of three approaches that had not been studied before and identifying research gaps for future work, such as the correlation between I4.0 and sustainability in service-oriented SMEs and studying the implementation of Industry 5.0 in SMEs. Finally, this research will guide manufacturers, industrialists, and technology suppliers in designing and implementing technologies to facilitate I4.0 for sustainable development in SMEs.

Keywords: Sustainability; SME; Smart Industry; Advanced Manufacturing; Industry 4.0.

2.1 INTRODUCTION

Industry 4.0 (I4.0) represents a significant advancement in decision-making processes by integrating technological devices, enhancing connectivity, and facilitating information exchange (FRANK; DALENOGARE; AYALA, 2019; JENA; MISHRA; MOHARANA, 2020). This integration converges products, stakeholders, and manufacturing equipment. It enables seamless data sharing across various stages of the product life cycle, thereby enhancing efficiency, production output, and operational profits (STOCK; SELIGER, 2016). To achieve this integration, I4.0 technologies such as the Internet of Things (IoT), Cloud Computing (CCO), Big Data Analytics (BDA), and Artificial Intelligence (AI) are utilized for data collection and analysis. These technologies cover a wide range of aspects, including product location, waste generation quantities, workplace conditions, and other specific applications (KAGERMANN; WAHLSTER; HELBIG, 2013; KUMAR; SINGH; DWIVEDI, 2020; LOPES DE SOUSA JABBOUR *et al.*, 2018).

Initially, I4.0 primarily prioritized economic factors, emphasizing productivity and efficiency enhancements. However, there is a growing societal expectation and government regulations for organizations to demonstrate sustainable performance (JAYASHREE *et al.*, 2021b; PANDYA; KUMAR, 2023). Sustainability aims to integrate processes and systems capable of producing high-quality products and services using fewer natural resources, all while ensuring the safety of employees, consumers, and surrounding communities (MACHADO; WINROTH; DA SILVA, 2020; STOCK; SELIGER, 2016). This concept is commonly framed around the Triple Bottom Line (TBL), encompassing social, environmental, and economic dimensions (BEIER *et al.*, 2017; DOSSOU *et al.*, 2022). These dimensions are interrelated, offering opportunities for synergies to bolster sustainability efforts (BROZZI *et al.*, 2020; JAYASHREE *et al.*, 2021a). Therefore, exploring how I4.0 technologies can be effectively integrated into this sustainable framework is imperative.

Historically, conventional manufacturing systems have often neglected environmental and social considerations, resulting in economic disparities, health concerns, and environmental pollution (BAI *et al.*, 2020). In contrast, I4.0 presents an opportunity to integrate sustainability-focused technologies (NARA *et al.*, 2021; STOCK; SELIGER, 2016). Socially, I4.0 enhances workplace conditions, supporting employee well-being and safety (BAI *et al.*, 2020; BROZZI *et al.*, 2020). Environmentally, it promotes resource efficiency and energy conservation (INGALDI; ULEWICZ, 2020; NASCIMENTO *et al.*, 2019). Economically, it facilitates precise planning, reducing lead times, and enabling product customization (FRANK; DALENOGARE; AYALA, 2019; WANG *et al.*, 2017). However, for these advancements to have a substantial impact, they must extend beyond large corporations to include Small and Medium Enterprises (SMEs), which often exhibit slower adoption rates (BHATIA; DIAZ-ELSAYED, 2023; DEY *et al.*, 2023).

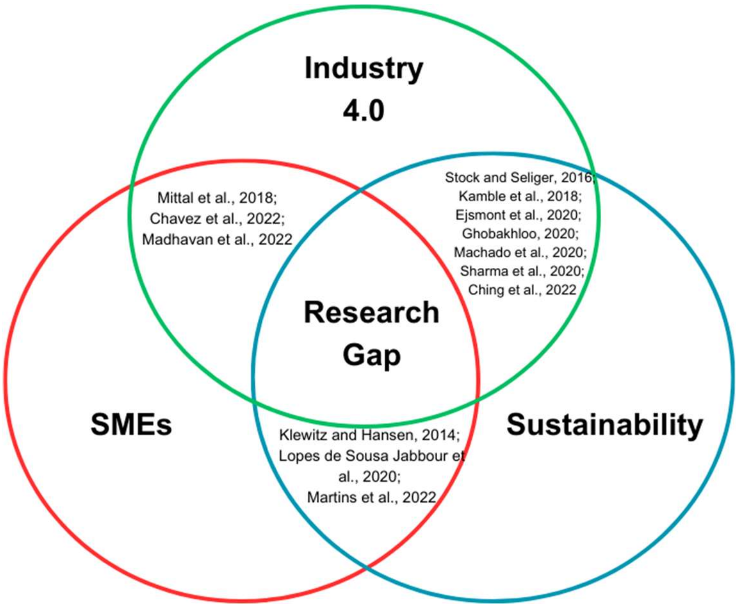
The economic progress of a nation depends on its ability to develop SMEs due to its significance in job creation and income generation (IAKOVETS; BALOG; ŽIDEK, 2023). With SMEs representing 90% of all businesses worldwide, their sheer abundance significantly contributes to environmental pollution (WORLD BANK, 2019). Furthermore, they have a considerable social impact, employing 50% of the workforce and constituting the majority of female employment (LOPEZ-NICOLAS *et al.*, 2020). These statistics underscore the importance of SMEs and their role in promoting sustainability. However, the existing literature lacks adaptations of technologies and sustainable practices tailored to these companies, resulting in delays in the implementation process since managers are uncertain about how to proceed (SHARMA *et al.*, 2023). SMEs possess unique characteristics such as limited investment capacity, a shortage of skilled labor, infrastructure constraints, a lack of technological expertise, and a single owner who must oversee various areas of the company (KHANZODE *et al.*, 2021). These challenges are exacerbated in the post-COVID-19 pandemic period, during which SMEs encountered difficulties in managing their operations (BHATIA; DIAZ-ELSAYED, 2023). This underscores the importance of providing I4.0 technologies tailored to the specific context of SMEs and minimizing barriers to implementation, thereby fostering higher adoption rates and advancing sustainability goals. Unfortunately, such integrated approaches are lacking in the literature (INGALDI; ULEWICZ, 2020; MOEUF *et al.*, 2020).

2.1.1 Research Gap

The viability of I4.0 relies on the ability of SMEs to embrace and deploy these technologies towards sustainable objectives, given their social, environmental, and economic significance (IAKOVETS; BALOG; ŽIDEK, 2023). However, current research predominantly focuses on large enterprises, neglecting the distinctive management characteristics of SMEs when proposing technological solutions (MACHADO *et al.*, 2021). Some of the SMEs' needs involve low-cost technologies compatible with existing systems (DOSSOU *et al.*, 2022; YANG *et al.*, 2023). Additionally, there is significant interest in low-complexity initial implementations that provide visibility into how the technology will function (JAYASHREE *et al.*, 2021a; MASOOD; SONNTAG, 2020). This implies that the readiness for new technologies in SMEs should address issues such as reducing investment insecurity and ensuring short-term benefits (DUTTA *et al.*, 2020). However, existing integration solutions often represent complex and centrally organized systems, making their adaptation and maintenance costly for SMEs (CHAVEZ *et al.*, 2022). Consequently, technologies and sustainable practices tailored for large corporations may not be applicable or effective for SMEs. This underscores the need to investigate how I4.0 and sustainability can be effectively integrated within the SME context.

To address this gap, this article employs a Systematic Literature Review (SLR), utilizing both quantitative and qualitative analyses, to enrich comprehension of research and practical dimensions. This methodology enables the consolidation of findings from eligible papers through a structured and systematic approach (TOTH-PETER *et al.*, 2023). The principal objective is to investigate how I4.0 technologies can support SMEs in achieving sustainability while considering the specific characteristics of these companies. This synthesis integrates the pivotal triad of I4.0, Sustainability, and SMEs, as depicted in Figure 4. The study stands out from previous literature reviews by comprehensively addressing all three interconnected topics, bridging a gap where prior reviews (Fig. 4) predominantly focus on interactions between only two of these elements. This endeavor aims to provide a holistic perspective and deeper insights into the correlations among I4.0 technologies, sustainability practices, and the challenges and opportunities SMEs encounter. Doing so contributes to a more thorough understanding of this field and suggests potential practical applications.

Figure 4 - Research gap in Literature Reviews



The decision to conduct this additional literature review stems from the need for a more comprehensive exploration of the relationship between I4.0 and Sustainability within the context of SMEs. This area has been inadequately addressed in the literature reviews outlined in Table 2. These review articles were selected based on their significance in intersecting areas of approaches and their high citation counts, and none of them encompass all three approaches investigated in this study.

Some prior review studies have indeed examined all three topics simultaneously. For example, Costa Melo's literature review focuses on analyzing both external and internal variables to assess the digital and sustainable performance of SMEs (COSTA MELO *et al.*, 2023a). Lopes et al. (2022) conducted a quantitative review but did not extensively explore the potential of technologies in promoting sustainability among SMEs. Isensee et al. (2020) delved into the relationship between SMEs' organizational culture, environmental sustainability strategies, and digitization strategies. Thus, none of these mentioned works specifically explored how I4.0 technologies can support sustainability in SMEs while considering their unique characteristics, supported by practical examples. Conversely, Narkhede et al. (2023) reported some practical examples; however, they did not address how to meet the specific needs of SMEs. Furthermore, the authors conducted an analysis based on key management areas rather than sustainability aspects. Therefore, there is a pressing need for SMEs to comprehend the potential applications of technologies tailored to their context, as they encounter challenges in selecting technologies that are cost-effective, easy to implement, and have clear return objectives (SILTORI *et al.*, 2021).

There is a noticeable absence of empirical evidence exploring the collective influence of I4.0 and sustainability on SME growth, primarily due to their isolated treatment in existing studies (DENICOLAI; ZUCCHELLA; MAGNANI, 2021). When considering the three approaches, the works focus on challenges (JAMWAL; AGRAWAL; SHARMA, 2023; KUMAR *et al.*, 2023) and facilitators (HARIASTUTI *et al.*, 2022; MACHADO *et al.*, 2021), without indicating potential applications for SMEs. Additionally, few articles examine all three dimensions (COSTA MELO *et al.*, 2023a; LOPES DE SOUSA JABBOUR *et al.*, 2018). Consequently, each existing work has specific scopes that do not offer detailed insights into the research gap. Thus, synthesizing current findings becomes imperative to drive progress in sustainability within SMEs. To accomplish this, the following research questions (RQs) will be used as a guide:

- ***RQ1: How can I4.0 technologies assist SME sustainability?***
- ***RQ2: What are the potential areas for further research in this context?***

Table 2 - Literature reviews papers about the connection between Industry 4.0, Sustainability, and Small and Medium Enterprises

Paper	Dimension			Description of the content of the literature reviews
	I4.0	Sust*	SME	
(KLEWITZ; HANSEN, 2014)		X	X	Explore the sustainable product, process, and organizational innovation practices within SMEs.
(STOCK; SELIGER, 2016)	X	X		Integrate sustainable manufacturing principles with Industry 4.0 requirements.
(KAMBLE; GUNASEKARAN; GAWANKAR, 2018)	X	X		Propose a sustainable framework for Industry 4.0.
(MITTAL *et al.*, 2018)	X		X	Review maturity models for Industry 4.0 and their relevance to SMEs.
(EJSMONT; GLADYSZ; KLUCZEK, 2020)	X	X		Establish the correlation between Industry 4.0 and sustainability across diverse sectors.
(GHOBAKHLOO, 2020)	X	X		Examine the societal and environmental sustainability perspectives within the context of Industry 4.0.
(LOPES DE SOUSA JABBOUR; NDUBISI; ROMAN PAIS SELES, 2020)		X	X	Investigate factors affecting the environmental, social, and financial performance of SMEs in Asia.
(MACHADO; WINROTH; DA SILVA, 2020)	X	X		Emphasize the interplay between sustainable manufacturing concepts and emerging technologies.
(SHARMA; JABBOUR; LOPES DE SOUSA JABBOUR, 2020)	X	X		Conduct a bibliometric analysis of sustainability and Industry 4.0, identifying research areas and gaps.
(CHING *et al.*, 2022)	X	X		Identify potential contributions of Industry 4.0 to sustainable manufacturing.
(MARTINS *et al.*, 2022)		X	X	Categorize research themes in sustainability within SMEs into four distinct clusters.

(CHAVEZ *et al.*, 2022)	X		X	Assess the level of digitization in applications supporting deviation management for SMEs.
(MADHAVAN *et al.*, 2022)	X		X	Synthesize academic research on Industry 4.0 and Industry 5.0 in the context of SMEs.
This work	X	X	X	Industry 4.0 technologies for sustainability within small and medium enterprises

*Sust: Sustainability

Consequently, this research delves into how these technologies can foster sustainability, building upon existing knowledge in the literature and indicating practical and viable applications for the context of SMEs. Moreover, it presents these contributions in the form of sustainability functions that can be enhanced through I4.0 technology in SMEs, such as enhancing skill development in the social dimension, monitoring energy consumption and waste in the environmental dimension, and optimizing production processes in the economic dimension. The viable technologies for SMEs in each sustainability function are also identified. In this manner, this study contributes by integrating findings from I4.0, sustainability, and SMEs, providing insights for both managers and academics, and outlining potential future research based on the identified gaps in the existing literature.

The remainder of this article is structured as follows: Section 2 outlines the research methodology employed for the SLR. In Section 3, quantitative and qualitative analyses of the identified articles are presented, exploring the potential impacts of I4.0 on the three dimensions of sustainability. In Section 4, sustainability functions were integrated with I4.0 technologies. Finally, in Section 5, the article concludes by summarizing the research findings, presenting future research avenues, and discussing the study's limitations.

2.2 LITERATURE REVIEW

This study employs a SLR following best practices in emerging fields, serving a dual purpose. Firstly, it examines authors, countries, and research growth. Secondly, it identifies specific sustainability functions and I4.0 technologies relevant to SMEs. The use of SLR methodology is employed to study specific aspects of a phenomenon that are not yet fully understood (TOTH-PETER *et al.*, 2023). The choice of SLR in this study is supported by its ability to identify, systematically select, and critically assess existing research to address formulated questions with methodological rigor, thereby facilitating the identification of research gaps (GHOBAKHLOO *et al.*, 2021; ROUSSEAU; MANNING; DENYER, 2008). Upholding principles of transparency and inclusivity, SLR promotes replicability and offers an objective perspective on research outcomes (DENYER; TRANFIELD, 2009). The use of this methodology can be observed in studies by Ghobakhloo (2020), Birkel et al. (2021), Ghobakhloo et al. (2021), Ching et al. (2022) and Toth-Peter et al. (2023).

The two researchers collaborated in formulating and validating the systematic review protocol, guiding all stages from initial search to article selection, and resolving discrepancies through regular meetings. Emphasizing transparency at each step ensured scientific rigor, reliability, and reproducibility in the SLR process (ROUSSEAU; MANNING; DENYER, 2008). To meet these standards, this article adheres to the well-established five-stage methodology proposed by Denyer and Tranfield (2009) (depicted in Figure 5), a widely endorsed approach in the literature (BIRKEL; MÜLLER; MULLER, 2021; COSTA MELO *et al.*, 2023a; JAMWAL *et al.*, 2021).

Figure 5 - Methodology of a systematic literature review (adapted from Denyer and Tranfield (2009))

For a clearer delineation of the review's objective, the first step of the study involves formulating the RQs (ROUSSEAU; MANNING; DENYER, 2008). These questions, along with justifications and research gaps, were presented in the introduction to guide the purpose of the research precisely. As a result, this study focuses on the convergence of research topics (refer to Fig. 4) to synthesize existing findings and propel knowledge advancement.

The second stage involves locating studies that meet the review's objective by conducting searches within databases (DENYER; TRANFIELD, 2009). The chosen databases for this research were Scopus and Web of Science (WoS), both widely used in bibliographic research (COSTA MELO *et al.*, 2023a; EJSMONT; GLADYSZ; KLUCZEK, 2020; GHOBAKHLOO *et al.*, 2021; MACHADO *et al.*, 2021). Renowned for their meticulously curated content and regular updates, Scopus and WoS ensure high-quality indexed documents (POWELL; PETERSON, 2017).

A search string was crafted using predefined keywords and Boolean connectors, as outlined in Table 3. These strings were tailored to encompass specific keywords related to the research questions, identified after an initial review. Notably, "Industry 4.0" is predominantly termed in Europe, whereas in the Americas and Asia, it is referred to more commonly as advanced manufacturing or smart industry (EJSMONT; GLADYSZ; KLUCZEK, 2020). This choice reflects the strategies of national governments to enhance manufacturing competitiveness and broaden the search scope. Additionally, terms such as Smart Manufacturing and Fourth Industrial Revolution were added, as they are noted synonyms of I4.0 (GUPTA *et al.*, 2022). After conducting trials to ensure accuracy, the final search sequences were defined. Furthermore, the search was limited to scientific research published after 2011, which marked the introduction of the term "Industry 4.0" (KAGERMANN; WAHLSTER; HELBIG, 2013).

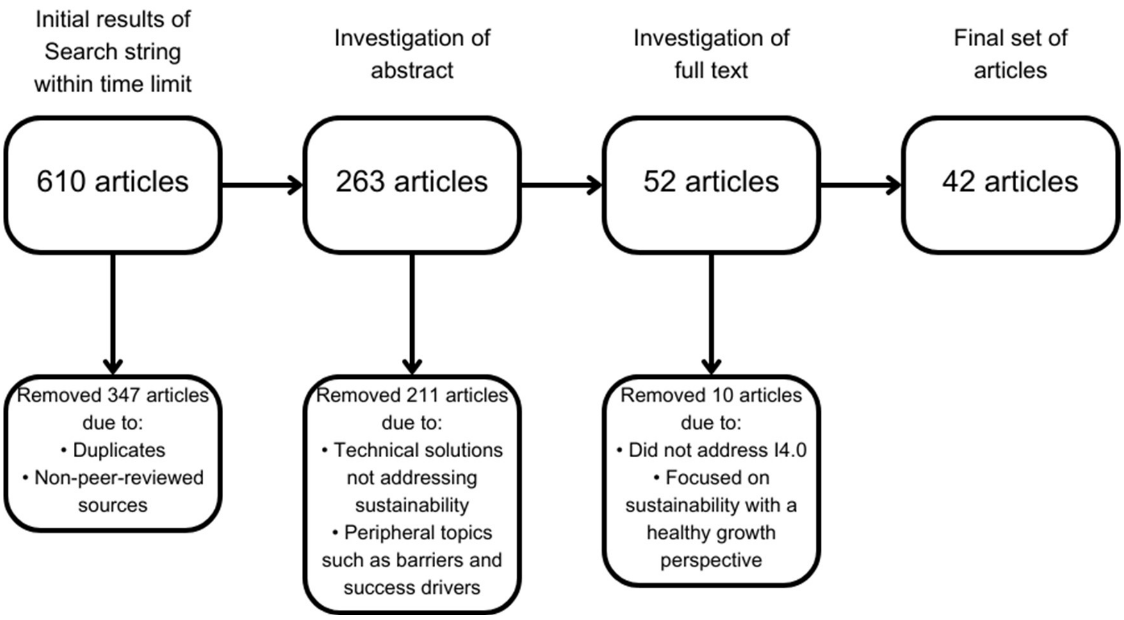
Table 3 - Research protocol for WoS and Scopus databases

Search String	("Industry 4.0" OR "Smart Industry" OR "Advanced Manufacturing" OR “Smart Manufacturing” OR “Fourth Industrial Revolution”) AND ("sustainability" OR "sustainable" OR “TBL” OR “Green” OR “eco”) AND ("Small and Medium" OR " Small & Medium" OR SME*)
Time Horizon	January 2011 – December 2023
Publication Type	Peer-reviewed journal articles in English

For discussion, it is crucial to acknowledge that there is no globally standardized definition for SMEs. These companies are independent entities, and their classification as SMEs typically relies on financial metrics and/or employee count, which can vary significantly among different countries due to local laws. For instance, countries like Brazil and the United States classify SMEs as having up to 500 employees, while in Chile, it is up to 200, and in Japan, temporary employees are also considered (COSTA MELO *et al.*, 2023b). Therefore, articles using the term SMEs may encompass different quantities of employees or company revenue. The TBL was included when researching sustainability, corresponding to the three sustainability dimensions. Lastly, green and eco were also considered to identify works focusing on the environmental dimension.

Following the definition of search criteria, specific inclusion and exclusion parameters are applied. The articles located were assessed, and those not directly relevant for addressing the RQs are excluded from the study (DENYER; TRANFIELD, 2009). The search was conducted in March 2023 and repeated in June 2023 and March 2024. As illustrated in Figure 6, considering the time horizon limitation, the search yielded 610 articles. The selection and evaluation steps included three filtering stages, with two independent reviewers analyzing the results of each filter and working together to reach a consensus. Initially, the selection was restricted to articles from peer-reviewed academic journals written in English (refer to Table 3) in the first filter. To ensure academic rigor, materials such as book chapters, books, conference papers, doctoral theses, editorial notes, etc., were excluded (KAMBLE; GUNASEKARAN; GAWANKAR, 2018). Additionally, duplicate articles between the databases were removed, resulting in a final set of 263 publications.

Figure 6 - Article selection strategy, adapted from Birkel *et al*. (2021)



In the second filtering stage, articles were assessed based on their titles and abstracts, focusing on thematic relevance regarding I4.0 and sustainability, particularly in the context of SMEs. Close attention was paid to articles mentioning I4.0 in their keywords but lacking direct implications for sustainability dimensions and SMEs. Articles discussing barriers and roadmaps without consideration for SMEs and articles that considered the term "SME" as "SMED – Single Minute Exchange of Die" were removed. This filter also excluded articles that merely mentioned sustainability as a potential future research area or used the term sustainability in a different context (e.g., related to the financial sector). This additional filter aimed to ensure that the retained articles in the first stage were directly relevant to the area of interest (COSTA MELO *et al.*, 2023a). Any articles found irrelevant after reviewing their titles and abstracts were excluded, and the reasons were documented in the Mendeley software. This iterative selection process ensured consistent classification of the literature (BIRKEL; MÜLLER; MULLER, 2021).

In the third filtering stage, the remaining 52 documents underwent a thorough review of their full texts, excluding 10 articles that marginally addressed the intersection of I4.0, sustainability, and SMEs, contributing minimally to the study. Emphasis was placed on articles that did not use sustainability as a concept of the TBL dimensions but rather as an indication of healthy business growth. The final selection consists of a total of 42 articles, which were utilized for the present study. The fourth stage of the SLR methodology involves analyzing and consolidating the results, which are approached both qualitatively and quantitatively.

2.2.1 Quantitative analysis

Bibliometric analysis was conducted to offer quantitative insights into the progression of research. These analyses, utilizing statistics-based methods, aimed to achieve multiple objectives: tracking the yearly publication evolution, identifying publication countries, and assessing the significance of journals. The bibliometric analysis was executed using R software, specifically leveraging the Bibliometrix package tailored for science mapping (SHARMA; JABBOUR; LOPES DE SOUSA JABBOUR, 2020). This open-source software tool allows bibliometric analysis, which was performed on the final sample of 42 articles from the research.

2.2.2 Qualitative Analysis

A detailed examination of the articles was conducted following the quantitative analysis to address the RQs. During this phase, the 42 papers were manually profiled using Mendeley software and organized in an Excel spreadsheet according to Summarization guidelines (DENYER; TRANFIELD, 2009). Each article was thoroughly reviewed to extract its objectives, methodology, main results, and contributions. Utilizing the three dimensions of sustainability as categories, feasible sustainability functions for implementation by SMEs were identified and grouped. Sustainability functions were considered activities and practices SMEs can perform in different company areas to achieve sustainability in its three dimensions.

Subsequently, I4.0 technologies that emerged as potential enablers of sustainability and meet SMEs' requirements, such as low cost and simplicity of implementation, were linked to their respective sustainability functions. Through this content-centric review, the research team identified 17 sustainability functions facilitated by I4.0 for SMEs. Finally, a table was elaborated to present these sustainability functions alongside the most recurrent I4.0 technologies.

2.3 RESULTS

Table 4 presents the 42 articles used in this study. Quantitative and qualitative analysis of the articles are carried out in the following sections.

Table 4 - Final articles from the literature review process and their main contributions

Nº	Authors	Main results
1	(DAWAL *et al.*, 2015)	Analyzed the effects of advanced manufacturing and sustainability on the manufacturing capabilities of SMEs.
2	(MÜLLER *et al.*, 2018)	Explored the economic, ecological, and social advantages and challenges posed by the IoT within SMEs
3	(LI; FAST-BERGLUND; PAULIN, 2019)	Studied the dynamics of information and knowledge sharing within a human-centric Industry 4.0 framework among Swedish SMEs.
4	(BROZZI *et al.*, 2020)	Explored the perceived benefits of Industry 4.0 for businesses across various company sizes.
5	(KUMAR; SINGH; DWIVEDI, 2020)	Investigated potential challenges in adopting Industry 4.0 technologies in the context of the Circular Economy in SMEs.
6	(OJSTERSEK; BUCHMEISTER; HERZOG, 2020)	Presented the utilization of simulation cameras for evaluating manual workstations.
7	(PAPETTI *et al.*, 2020)	Developed a methodology for assessing workplace ergonomics utilizing IoT devices in SMEs.
8	(BIRKEL; MÜLLER; MULLER, 2021)	Investigated the potential of Industry 4.0 concerning Triple Bottom Line.
9	(DENICOLAI; ZUCCHELLA; MAGNANI, 2021)	Studied the correlation between internationalization, sustainability, and digitalization in SMEs.
10	(JAYASHREE *et al.*, 2021a)	Explored how Industry 4.0 can assist SMEs in managing economic, environmental, and social assets.
11	(JAYASHREE *et al.*, 2021b)	Examined how Industry 4.0 determinants affect manufacturing SMEs in achieving sustainability.
12	(KHAN *et al.*, 2021)	Highlighted how blockchain can contribute to sustainable practices in SMEs.
13	(KHANZODE *et al.*, 2021)	Modeled barriers of Industry 4.0 for sustainable production in SMEs.
14	(MACHADO *et al.*, 2021)	Identified key barriers and facilitators for integrating Industry 4.0 and sustainability in SMEs supply chains.
15	(GUPTA *et al.*, 2022)	Verified that Industry 4.0 and sustainable operations can facilitate achieving operational excellence in SMEs.
16	(DOSSOU *et al.*, 2022)	Presented a sustainable digital transformation methodology for SMEs.
17	(HARIASTUTI *et al.*, 2022)	Identified the drivers of technological innovation in metallurgical SMEs.
18	(JAYASHREE *et al.*, 2022)	Explored success factors for adopting Industry 4.0 and sustainable practices in SMEs.
19	(KHAN; PIPRANI; YU, 2022)	Demonstrated the significant and positive impact of technological innovations on Circular Economy practices in SMEs.
20	(KUMAR; REHMAN; PHANDEN, 2022)	Explored facilitators strengthening the social performance of Indian SMEs in the digital era.

21	(LOPES, 2022)	Studied the relevant factors related to the introduction of new technologies associated with Industry 4.0 in SMEs.
22	(RAUTENBACH; DE KOCK; GROBLER, 2022)	Explored challenges, readiness, and opportunities associated with data science implementation in SMEs.
23	(RIOSVELASCO-MONROY *et al.*, 2022)	Applied the COHRV model to help SMEs implement Industry 4.0 for sustainability.
24	(RONAGHI; MOSAKHANI, 2022)	Highlighted the contributions of blockchain technology to corporate social responsibility in SMEs.
25	(TICK *et al.*, 2022)	Identified appropriate strategic directions for SMEs in digitalization and sustainability.
26	(VOZA; SZEWIECZEK; GRABARA, 2022)	Explored how Serbian and Polish SMEs perceive the impact of digitalization on sustainability.
27	(ABDULAZIZ *et al.*, 2023)	Proposed a framework for evaluating IoT readiness among Malaysian SMEs.
28	(BETTIOL *et al.*, 2023)	Examine the labor productivity gains of Industry 4.0 technology adoption in SMEs.
29	(BHATIA; DIAZ-ELSAYED, 2023)	Developed a framework for selecting key criteria for SMEs when choosing technology.
30	(DEY *et al.*, 2023)	Demonstrated how AI adoption can foster sustainability and resilience in supply chains within the Vietnamese SME ecosystem.
31	(COSTA MELO *et al.*, 2023b)	Proposed a framework for measuring the sustainable performance of SMEs.
32	(COSTA MELO *et al.*, 2023a)	Introduced variables for assessing the technological and sustainable performance of SMEs.
33	(FINDIK; TIRGIL; ÖZBUĞDAY, 2023)	Investigated correlations between the influence of Industry 4.0 on the Circular Economy, drawing evidence from European SMEs.
34	(HUNG; CHEN, 2023)	Explored the impact of Industry 4.0 on Sustainable Development Goals within Taiwanese SMEs.
35	(IAKOVETS; BALOG; ŽIDEK, 2023)	Examined the implementation of a mobile application for sustainable effects in SMEs.
36	(JAMWAL; AGRAWAL; SHARMA, 2023)	Identified challenges for SMEs in adopting Industry 4.0 to achieve sustainability.
37	(KUMAR *et al.*, 2023)	Identified barriers to sustainability and Industry 4.0 adoption in SMEs.
38	(NARKHEDE *et al.*, 2023)	Examined the applicability and potential benefits of Industry 4.0 technologies in critical functional areas of SMEs.
39	(PANDYA; KUMAR, 2023)	Assessed the most preferred Industry 4.0 technologies for enhancing sustainability in service-based SMEs.
40	(PEROTTI *et al.*, 2023)	Evaluated circular economy capabilities for SMEs with the assistance of digital technologies.
41	(SHARMA *et al.*, 2023)	Identified and ranked barriers and facilitators to the digitization of manufacturing operations in SMEs.
42	(YANG *et al.*, 2023)	Hierarchized key criteria for adopting Industry 4.0 in SMEs.

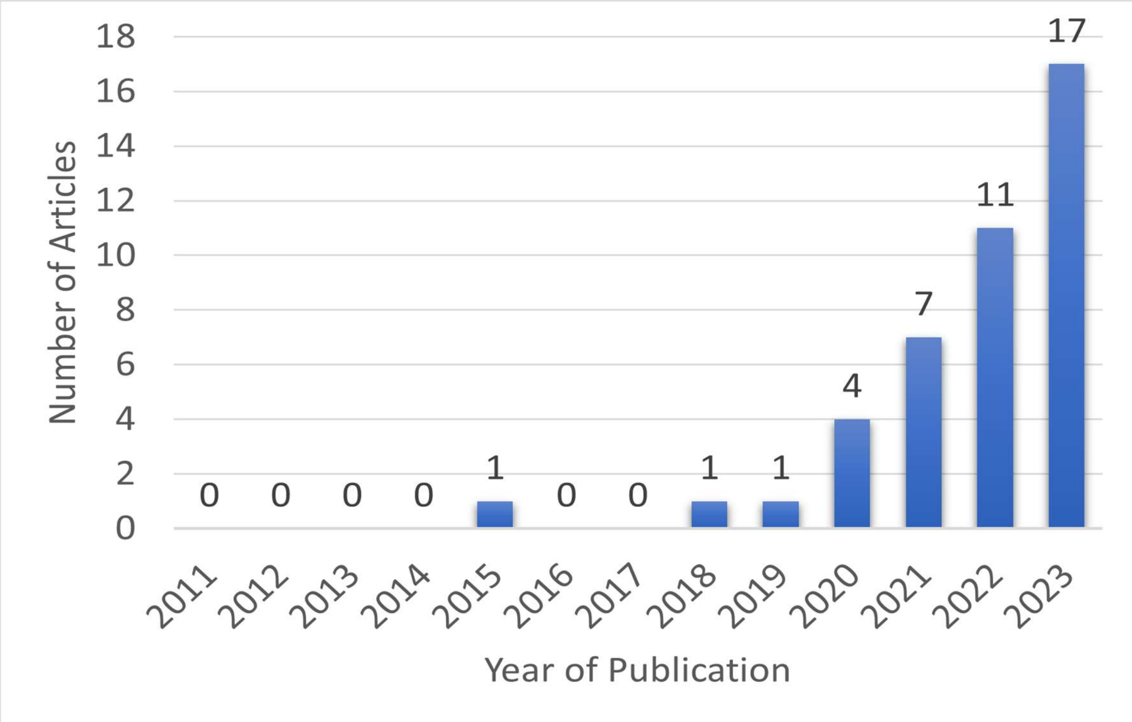
2.3.1 Analysis

This section examined the quantitative bibliometric characteristics of all 42 papers, aiming to reveal the status and evolution of knowledge related to I4.0, sustainability, and SMEs.

2.3.1.1 Number of papers published per year

Figure 7 illustrates the number of yearly publications. A consistent growth in the number of published papers was observed, indicating an evolutionary trend compatible with a new research field. Notably, there was a significant growth in publication rates after 2019, which may be attributed to the dissemination of the COVID-19 pandemic. COVID-19 accelerated the adoption of more advanced and mature technologies, with automation paving the way for connectivity through IoT systems to sustain revenue during the pandemic (BHATIA; DIAZ-ELSAYED, 2023; COSTA MELO *et al.*, 2023a).

Figure 7 - Papers published between 2012 and 2023

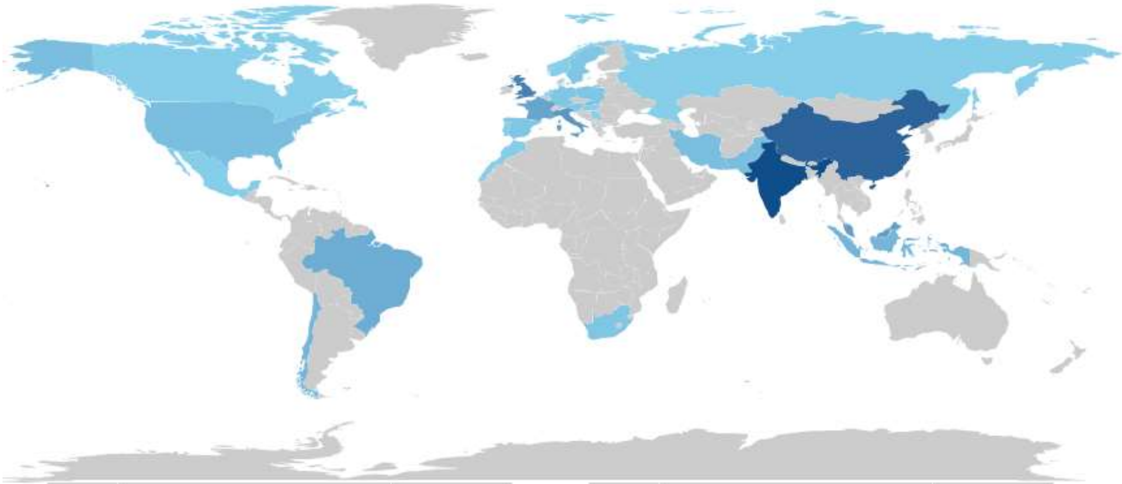


Despite the emergence of the term "Industry 4.0" in 2011 (KAGERMANN; WAHLSTER; HELBIG, 2013), Figure 7 indicates that its correlation with sustainability began later. This could be attributed to the development of national government digitization programs, where sustainability was integrated later (MACHADO; WINROTH; DA SILVA, 2020). Furthermore, it is worth noting that I4.0 was initially not conceived with SMEs in mind, as the initial focus was on implementing it in large corporations (MACHADO *et al.*, 2021). This fact may justify the recent growth of research in the area. Ejsmont et al. (2020) and Jamwal et al. (2021) also observed similar period of research growth in these areas. This result underscores the need for a literature review capable of consolidating articles and their findings

2.3.1.2 Origin of publications

Figure 8 illustrates the primary regions where studies were conducted and highlights their distribution across continents. In this analysis, each publication was attributed to the country represented by the institution of its first author. A total of 29 countries with publications were identified, with 13 having three or more publications. Notably, China and India stand out as research leaders based on the number of publications, indicating the growing interest of developing countries in reducing their environmental impacts and strengthening their SMEs, which are crucial for the operation of these nations (DUTTA *et al.*, 2020; GHOBAKHLOO *et al.*, 2021; JAMWAL; AGRAWAL; SHARMA, 2023).

Figure 8 - Place of application of the studies



Rank	Country	Frequence
1°	INDIA	18
2°	CHINA	15
3°	UK	11
4°	ITALY	8
5°	MALAYSIA	7

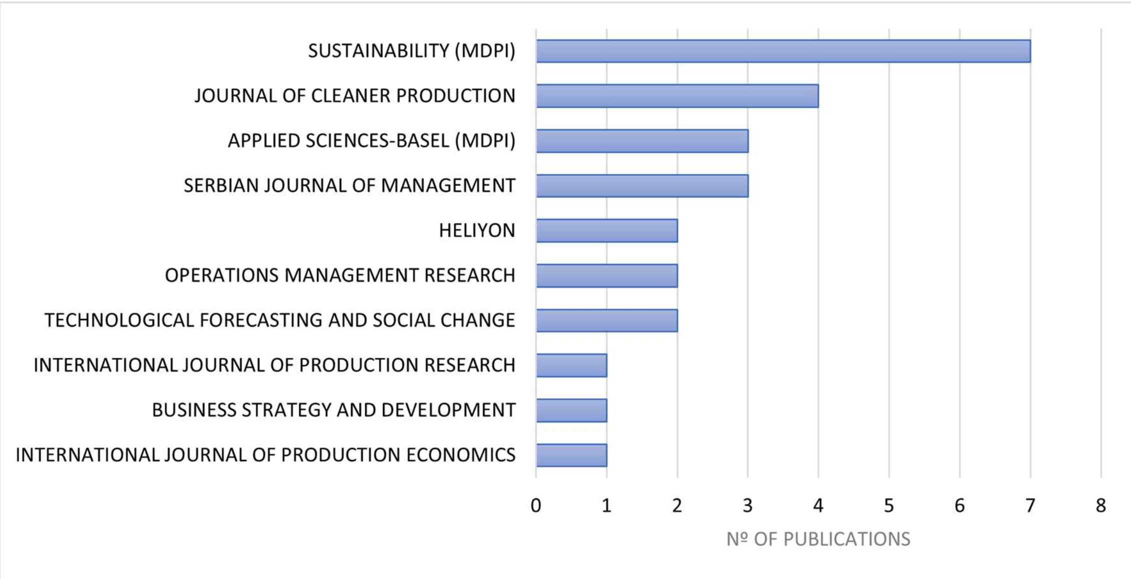
Rank	Country	Frequence
6°	FRANCE	6
7°	BRAZIL	5
8°	CHILE	4
9°	INDONESIA	4
10°	IRAN	3

This observation contrasts with previous studies that did not focus solely on SMEs, as the results of the review works indicate a higher concentration of articles in developed countries (KAMBLE; GUNASEKARAN; GAWANKAR, 2018; SHARMA; JABBOUR; LOPES DE SOUSA JABBOUR, 2020). It suggests that solutions for sustainable and I4.0-oriented SMEs are relevant for developing countries, considering the economic importance and the need for SMEs to remain competitive (IAKOVETS; BALOG; ŽIDEK, 2023). Additionally, it indicates that this theme should be further explored in future literature to address the specificities of different developing countries (MACHADO *et al.*, 2021)

2.3.1.3 Publication source

The list of journals included in the sample can be found in Figure 9. The analyzed articles are divided among 26 different journals. Additionally, four of these journals publish 40% of the total papers. Conducting this research allowed the identification of key journals, which can be regarded as authoritative references in the convergence of I4.0, sustainability, and SMEs.

Figure 9 - Publication sources



Most articles have been published in the "Sustainability" journal (MDPI). This open-access journal has an impact factor of 3.9 (2022) and has been committed to publishing scientific research for over a decade. This popularity can be attributed to the journal's thematic focus, with one of its primary areas of interest being the enhancement of sustainability through I 4.0 (EJSMONT; GLADYSZ; KLUCZEK, 2020). The second most prominent journal is the "Journal of Cleaner Production", with an impact factor of 11.1 (2022), which centers on Cleaner Production, Environmental, and Sustainability research and practice. Although the number of papers in other journals is smaller, they all share a common focus on sustainable operations, products, and manufacturing. This emphasizes the interdisciplinary interest in the field (TOTH-PETER *et al.*, 2023). Finally, the listed journals can offer valuable resources for researchers to make informed decisions regarding publications at the intersection of I4.0, sustainability, and SMEs (MACHADO; WINROTH; DA SILVA, 2020).

2.4 SUSTAINABILITY FUNCTIONS FOR SMALL AND MEDIUM ENTERPRISES

In this section, sustainability functions were identified and categorized into primary information areas corresponding to the dimensions of sustainability. These functions were recognized as opportunities for SMEs to attain sustainability with the support of I4.0 technologies. Existing literature review alternatives primarily target large companies' context (CHING *et al.*, 2022; SHARMA; JABBOUR; LOPES DE SOUSA JABBOUR, 2020). Therefore, technologies customized for the realities of SMEs were aligned with sustainable practices across all three dimensions, leading to the presentation of sustainability functions in the subsequent subsections.

2.4.1 Social

The first dimension of sustainability is social. It encompasses aspects such as the workplace environment, occupational health and safety, human-centered job design, and skill development (PAPETTI *et al.*, 2020). This dimension holds even more significance for SMEs, which generate numerous jobs with modest wages and play a pivotal role in industrializing underdeveloped regions and mitigating regional disparities (KUMAR; REHMAN; PHANDEN, 2022; LI; FAST-BERGLUND; PAULIN, 2019). Research suggests that the integration of I4.0 technologies in SMEs leads to an average increase in labor productivity of about 7.4% among adopters (BETTIOL *et al.*, 2023). The functions identified in the literature through which I4.0 technologies can contribute to SMEs in the social dimension are presented as follows:

Employee skill development

The primary function of social sustainability revolves around developing employees' skills. According to the existing literature, mobile applications emerge as potential solutions as they enable real-time updates and the transmission of work instructions to smartphones and tablets. This, in turn, reduces errors and shortens training durations (IAKOVETS; BALOG; ŽIDEK, 2023). These applications typically allow for real-time updating and sending of work instructions, ideal for SMEs that require flexibility in the production line (OJSTERSEK; BUCHMEISTER; HERZOG, 2020). Their widespread acceptance among various age groups and educational levels is facilitated because smartphones are integral to employees' daily routines (JAYASHREE *et al.*, 2021a).

Another solution highlighted in the literature is Virtual and Augmented Reality. These technologies can potentially improve employee ideation, creativity, and critical thinking through gamification tools and personalized learning paths (KUMAR; SINGH; DWIVEDI, 2020; YANG *et al.*, 2023). The utilization of Augmented Reality to support classroom training is beneficial for managing digital data and reducing human efforts (JAMWAL *et al.*, 2021).

Recruitment, Selection, and Career Planning

The second function identified in the literature review pertains to recruitment, selection, and career planning. In this context, the literature suggests that software based on CCO, BDA, and AI has the potential to assist SMEs. These technologies analyze the historical data of specific positions, aiding in identifying the most suitable candidates with the requisite skills (RONAGHI; MOSAKHANI, 2022; STRAZZULLO; MORO; CRICELLI, 2023). This function can minimize the need for specialists in the area, something uncommon in the reality of SMEs.

Another possibility is using AI and data analysis as the foundation for Human Resource Management (HRM), allowing SME managers to extract significant patterns from employee data and offer personalized schemes for professional development (STRAZZULLO; MORO; CRICELLI, 2023). This improves the effectiveness of learning programs and talent retention while assisting managers in medical record management, salary adjustments, and vacation scheduling (MÜLLER *et al.*, 2018). These software programs allow SME managers to conduct people analytics, studying technical and socio-behavioral competencies using dynamic dashboards with multiple graphics and a complete team view.

Improving Work Ergonomics - Posture, Movements, Physical Effort

The third function involves enhancing work ergonomics to optimize employees' posture, movements, and physical effort. The literature suggests leveraging IoT devices and Computer Vision technologies to assist SMEs in this regard. For instance, Papetti et al. (2020) reported using wearable devices such as chest straps, sensor-equipped glasses, and EMG bracelets to facilitate cognitive analyses. These cost-effective tools enable the analysis of parameters such as heart rate, respiratory frequency, back posture, and eye movement.

Similarly, Ojstersek et al. (2020) examined a manual assembly workstation, employing an accessible spherical camera to collect real-world manufacturing system data. Using computer vision, body movements can be tracked, postures can be corrected, displacement patterns can be adopted, and time for non-value-adding activity can be minimized. This methodology involves the analysis of physical effort, ergonomics, and the rate of preventable workplace accidents, thereby mitigating the need for dedicated process analysts. Significantly, this approach does not require users to possess research expertise or extensive programming knowledge, a resource often scarce in SMEs.

Improving Work Ergonomics - Environmental Analysis

Apart from evaluating posture and actions, ergonomic analysis necessitates an examination of the employee's working environment. For instance, in noise control, the literature suggests using a conventional sound level meter equipped with a digital display to measure and display real-time decibel levels in the workspace (DOSSOU *et al.*, 2022). IoT sensors can capture real-time data related to temperature, relative humidity, and lighting conditions. These solutions can be integrated with the company's software or smartphones, sending information periodically and issuing alerts in case of non-compliance (ABDULAZIZ *et al.*, 2023).

Minimizing Effort, Stress, and Monotony

Another function in which technologies can significantly assist SMEs is minimizing the effort, stress, and monotony of workstations, thereby decreasing errors and injuries (BEIER *et al.*, 2017; BIRKEL; MÜLLER; MULLER, 2021). According to the literature, this goal can be achieved by automating primarily manual tasks; however, it is crucial to embrace a collaborative approach that involves both machines and operators to reduce resistance to I4.0 (BETTIOL *et al.*, 2023; LI; FAST-BERGLUND; PAULIN, 2019; OJSTERSEK; BUCHMEISTER; HERZOG, 2020). The automation of basic functions, along with the use of intelligent systems, supports employees in performing monotonous and repetitive tasks, resulting in greater satisfaction and motivation (BROZZI *et al.*, 2020). Additionally, technology facilitates the integration and adaptability of work for individuals with disabilities and older employees, whose proportion is increasing due to changing age demographics (MARK *et al.*, 2019).

Moreover, administrative tasks can also benefit from automation (LI; FAST-BERGLUND; PAULIN, 2019). This approach typically employs rule-based logic to automate business processes, reducing or eliminating time-consuming tasks (IAKOVETS; BALOG; ŽIDEK, 2023). For this function, integrative process management software and even automated spreadsheets can be utilized, given the need for technologies with low complexity in SMEs. These alternatives allow for the reduction of time-consuming tasks, minimizing human errors, and enabling the team to focus on high-value tasks (BIRKEL; MÜLLER; MULLER, 2021; IAKOVETS; BALOG; ŽIDEK, 2023).

Enhancing Workplace Safety

I4.0 technologies can also assist SMEs in enhancing workplace safety levels. Specifically, tools such as smart cameras, intelligent sensors, smart safety wearables, and AI-based location recognition systems can identify and report any human or machine behavior that might give rise to safety concerns (GHOBAKHLOO, 2020; KAMBLE; GUNASEKARAN; GAWANKAR, 2018). The safety control solution thoroughly analyzes patterns using computer vision and AI, leveraging historical data, to constantly monitor the production areas of industrial plants. It generates alerts for violations, sending them to managers' mobile devices for instant correction (CHING *et al.*, 2022).

Improving Company-Customer Relationship

The final function of social sustainability is enhancing SMEs' connections with external stakeholders, particularly their consumers (LI; FAST-BERGLUND; PAULIN, 2019; RONAGHI; MOSAKHANI, 2022; WANG *et al.*, 2017). The existing literature emphasizes that a deeper understanding of customers can be achieved through software bolstered with CCO and BDA, which predict behaviors and understand preferences, and habits, facilitating more informed decision-making (RAUTENBACH; DE KOCK; GROBLER, 2022). Solutions like Cloud-based Customer Relationship Management (CRM) enable tracking sales results, managing customer relationships, and integrating with email for targeted marketing campaigns. Additionally, they offer mobile and communication app integration, simplifying adoption by SMEs. These systems, hosted in the cloud, also utilize AI to obtain insights through data analysis, optimizing the relationship with consumers, which not only reduces response time but also builds trust (DENICOLAI; ZUCCHELLA; MAGNANI, 2021; SHARMA *et al.*, 2023).

2.4.2 Environmental

The second dimension of sustainability is primarily focused on environmental sustainability, which involves preserving the ecological and environmental balance of the planet. This dimension encompasses maintaining a delicate equilibrium between consumption and renewal (GHOBAKHLOO, 2020). Therefore, SMEs should integrate these concerns into their manufacturing processes (KHANZODE *et al.*, 2021). The functions identified in the literature through which I4.0 technologies can contribute to SMEs in the environmental dimension are presented as follows:

Reducing Energy Consumption and Waste

The first function of environmental sustainability pertains to sustainable energy consumption (NASCIMENTO *et al.*, 2019). Nowadays, energy costs directly impact product prices, and the increasing stringency of government regulations underscores the importance of managing energy consumption (BEIER *et al.*, 2017; DOSSOU *et al.*, 2022). The literature review reveals that the application of IoT devices enables the monitoring of energy consumption and the detection of potential waste (MÜLLER *et al.*, 2018; RIOSVELASCO-MONROY *et al.*, 2022). The integration of real-time consumption data serves to mitigate the risk of companies surpassing contracted energy limits, while also providing insights into resource efficiency within production activities (BAI *et al.*, 2020). Additionally, integrating variable speed drives with AI allows for the examination of operational points, thus suggesting optimal configuration choices and enhancing energy efficiency (DENICOLAI; ZUCCHELLA; MAGNANI, 2021; DOSSOU *et al.*, 2022; FINDIK; TIRGIL; ÖZBUĞDAY, 2023). These devices are renowned for their user-friendly installation and rapid delivery of results, advantages that prove beneficial for SMEs (KUMAR *et al.*, 2023).

Reducing Water Consumption and Waste

The second function involves the potential utilization of I4.0 technologies to regulate water consumption and mitigate waste in SMEs. It is widely acknowledged that the advancement of modern technologies often correlates with an increase in the consumption of natural resources (VOZA; SZEWIECZEK; GRABARA, 2022). In this context, IoT technology facilitates the real-time monitoring of water consumption, minimizing unnecessary resource utilization (FINDIK; TIRGIL; ÖZBUĞDAY, 2023; JENA; MISHRA; MOHARANA, 2020). The core of this approach relies on sensors that capture flow and pressure data every second. In case of irregularities, alerts are swiftly sent directly to smartphones or computers. This method minimizes the risk of environmental harm, as unnoticed leaks could result in delayed detection.

Controlling Waste Generation

Controlling waste resulting from production processes is a crucial aspect of environmental sustainability, and I4.0 technologies can support this regard (BAG; PRETORIUS, 2022). The objective is to provide managers with a clear view of the production process parameters, empowering them to devise solutions for waste reduction. The literature suggests employing technologies such as IoT for pollution control (BAI *et al.*, 2020; JAYASHREE *et al.*, 2022). By leveraging IoT sensors, waste management systems can gather real-time data on current production waste, enabling efficient recycling practices and offering precise information to managers (FINDIK; TIRGIL; ÖZBUĞDAY, 2023). This information allows for monitoring of production process efficiency, with intelligent synchronization minimizing manufacturing waste (SHARMA *et al.*, 2023). Incorporating IoT devices and AI offers insights into productivity enhancement and cost reduction, identifying optimization opportunities, thus reducing the need for process experts in SMEs (ABDULAZIZ *et al.*, 2023; KUMAR *et al.*, 2023; MACHADO *et al.*, 2021).

The literature presents a more comprehensive solution by adopting Green Information Systems (GIS) bolstered by IoT, CCO, AI, and blockchain (RONAGHI; MOSAKHANI, 2022). This system consolidates an organization's ecological practices, making sustainability data easily accessible, preventing equipment failures, and suggesting sets of production and process parameters that enhance efficiency and reliability (BAG; PRETORIUS, 2022; KHAN *et al.*, 2021).

2.4.3 Economic

The third and final dimension is the economy. The applicability of technologies in this dimension involves factory floor automation, process monitoring, and supply chain visibility, resulting in enhanced reliability, reduced machine downtime, optimized inventory, and increased employee engagement (CHING *et al.*, 2022). The functions identified in the literature through which I4.0 technologies can contribute to SMEs in the economic dimension are presented as follows:

Organizing Production Processes

The literature review reveals that one of the functions of economic sustainability that technologies in SMEs can support is the organization of production processes. To fulfill this objective, cloud-based management systems like Manufacturing Execution Systems (MES) are recommended. MES proves to be particularly suitable for small-scale manufacturing as it facilitates the control and monitoring of production processes through direct data collection from the production floor via IoT devices or mobile devices (JAMWAL *et al.*, 2021). The monitored data encompasses various processes within the company, including manufacturing, assembly, inventory, service calls, OEE, and traceability. Its modular structure makes it a viable option for SMEs, enabling phased implementation (DEY *et al.*, 2023).

At a more advanced level of integration, Enterprise Resource Planning (ERP) emerges as a means to leverage data derived from MES and complement other facets of the company, such as finance, human resources, sales, and procurement (GHOBAKHLOO, 2020; MÜLLER *et al.*, 2018). Despite already being established in the market, these systems can be enhanced with CCO and BDA in new versions, thereby organizing processes and ensuring greater precision in final product costing and production order tracking. Typically, such implementations are supported by the technology provider, which includes training in tool utilization, facilitating the decision-making process for SMEs (JAYASHREE *et al.*, 2022)

Organizing Warehouse

The literature review delineates the second function of economic sustainability, focusing on inventory organization. I4.0 technologies offer SMEs a pathway through Cloud-based Warehouse Management Systems (WMS), which enhance material and information flows within warehouses (SHARMA *et al.*, 2023). This technology facilitates the storage of comprehensive information, including the precise positioning of each item, ensuring complete control over all stored objects. To address this need, the literature emphasizes integration with RFID chips or QR codes, which streamline wireless identification and location tracking of all materials (NARKHEDE *et al.*, 2023; STOCK; SELIGER, 2016). This identification process provides enhanced visibility into attributes such as batch information, receipt dates, and storage dates accessible on mobile devices.

These systems, typically user-friendly, guide employees to the appropriate placement for items, preventing potential location errors or incorrect product storage.

Simplifying Production Planning and Control

As an extension of the second, the third function is distinctly presented to ensure clarity. This function revolves around the simplification of production planning and control for SMEs. For this purpose, the literature indicates the adoption of Advanced Planning and Scheduling (APS), which can meticulously process information from diverse sources to manage uncertainties and fluctuations in demand proactively (DEY *et al.*, 2023). In doing so, they optimize resource utilization, refine material procurement processes, and promote demand-driven operational strategies (NARKHEDE *et al.*, 2023; SHARMA *et al.*, 2023). This approach further enhances the supply chain by minimizing redundant storage and the potential for shortages (KHAN; PIPRANI; YU, 2022). Furthermore, it can alert SME managers on their mobile devices about delays and material shortages, facilitating the planning of inputs and manufacturing orders.

Optimizing Supply Chain Connectivity

The fourth function of economic sustainability focuses on optimizing integration and connectivity within the supply chain (SC) (BETTIOL *et al.*, 2023; KAGERMANN; WAHLSTER; HELBIG, 2013). The strategic deployment of IoT devices, BDA, and AI substantially enhances the transparency of logistical operations, ensuring seamless process alignment and more effective data exchange (KHAN *et al.*, 2021; PEROTTI *et al.*, 2023; RIOSVELASCO-MONROY *et al.*, 2022). With the establishment of IoT beyond the company's boundaries, logistical operations can be aligned with processes more effectively, and agile supply chains can respond to customer requests more flexibly (ABDULAZIZ *et al.*, 2023; BIRKEL; MÜLLER; MULLER, 2021; MOEUF *et al.*, 2018). Some AI-driven systems based on sensor data can generate performance metrics that can be remotely tracked while storing historical production data with CCO to enhance SC management. Meanwhile, some software vigilantly monitors produced components by utilizing control towers across SC members and promptly identifies supplies at risk (RIOSVELASCO-MONROY *et al.*, 2022). In this manner, SMEs can meticulously plan to fulfill the requirements of their business partners, thereby facilitating horizontal integration, enhancing SC transparency, and promptly identifying potential disruptions (MÜLLER *et al.*, 2018).

Optimization of Maintenance Processes

The fifth function of economic sustainability revolves around optimizing maintenance processes. The integration of I4.0 technologies can enhance the maintenance of machinery and production equipment, thereby extending their lifespan and preventing unplanned shutdowns (HARIASTUTI *et al.*, 2022; JAMWAL; AGRAWAL; SHARMA, 2023). The literature review reveals that sensor-based real-time data collection can send alerts to SME managers in case of inconsistencies (HARIASTUTI *et al.*, 2022). This approach facilitates the identification of overpowered motors and machines operating below optimal efficiency. With the support of BDA and AI, maintenance management software assists in planning and scheduling maintenance activities to prevent machine downtime (DEY *et al.*, 2023). Based on historical analysis of failures and downtime, work orders are automatically generated according to the configured period for preventive maintenance of the resource or tool (BAG; PRETORIUS, 2022). These work orders provide the service executor with a task list on their mobile device, simplifying the work.

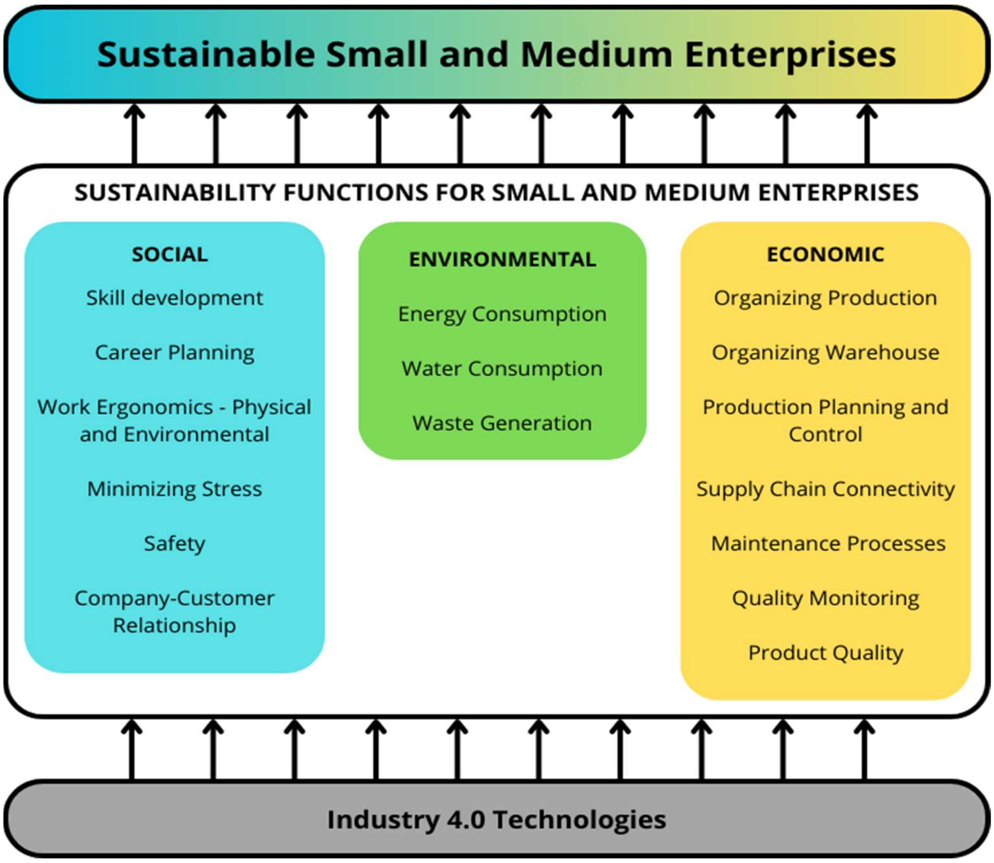
Improve Quality Monitoring

Technology plays a pivotal role in the sixth aspect of economic sustainability, which is improving quality control—a task demanding a high level of attention from employees and one that can harm companies in case of undetected defective products (LOPES DE SOUSA JABBOUR *et al.*, 2018). In this context, industrial automation reduces the need for extensive human intervention, resulting in fewer errors (RAUTENBACH; DE KOCK; GROBLER, 2022). The literature underscores that AI-based technologies provide the skill set and opportunities necessary for defect-free manufacturing (JAMWAL *et al.*, 2021; NARKHEDE *et al.*, 2023; PEROTTI *et al.*, 2023). This solution identifies defects through comparisons with pre-classified images, employing Computer Vision for increased agility and precision in the quality inspection process.

Enhancing Product Quality

The final function of economic sustainability that can benefit from the use of I4.0 technologies in SMEs is product development. However, this function is better suited for SMEs that manufacture technological products. According to the literature, IoT, CCO, and BDA are recommended because they monitor product performance across its entire lifecycle, track instabilities and defects, and remotely diagnose faults (NASCIMENTO *et* *al.*, 2019; PEROTTI *et al.*, 2023; ROSA *et al.*, 2020). Products equipped with intelligent devices are capable of communicating with the customer and the manufacturer, providing information on the product's usage status, and identifying defects (KUMAR; SINGH; DWIVEDI, 2020). Examples of this approach are closely tied to the circular economy, such as battery exchange processes, a problem often unnoticed by consumers (FINDIK; TIRGIL; ÖZBUĞDAY, 2023; ROSA *et al.*, 2020). Furthermore, the data collected by devices integrated into products serve as inputs for refining new product versions.

Figure 10 - Framework for Small and Medium Sustainable Enterprises Supported by Industry 4.0 Technologies



The previous discussion was summarized in the framework depicted in Figure 10. It illustrates how I4.0 technologies form the foundation enabling SMEs to achieve sustainability functions across three dimensions: social, environmental, and economic. In this manner, SMEs can achieve the status of Sustainable Small and Medium Enterprises, fostering improved employee well-being, optimized use of natural resources, and increased economic competitiveness.

2.5 INDUSTRY 4.0 TECHNOLOGIES INTEGRATED WITH SUSTAINABILITY FUNCTIONS FOR SMALL AND MEDIUM ENTERPRISES

The literature indicates that the primary expected benefits for SMEs when adopting I4.0 include cost savings, increased productivity, and reduced waste, with a focus on the economic aspect of sustainability (TICK *et al.*, 2022). Additionally, Bai et al. (2020) suggested that significant sustainable practices could be achieved if I4.0 technologies were evaluated and implemented across all dimensions of sustainability. Studies by Dawal (2015) and Gupta (2022) show that adopting I4.0 technologies can improve environmental sustainability, ultimately enhancing operational excellence. However, there is a need for clearer definitions of technologies and applications for this purpose. Despite SMEs' commitment to sustainability, they lack knowledge on how to develop green decision-making capabilities (DEY *et al.*, 2023). To address these issues, the findings of this literature review are consolidated in Table 5.

This literature review underscores the importance of specific technologies for SMEs to achieve sustainability across all three dimensions. Particularly, I4.0 technologies such as IoT, CCO, BDA, and AI are highly recommended due to their simplicity and broad applicability, making them the most recurrent choices, as shown in Table 5 (FRANK; DALENOGARE; AYALA, 2019). These technologies serve as foundational elements for various applications and emerge as preferred choices for meeting sustainability objectives (MOEUF *et al.*, 2020; PANDYA; KUMAR, 2023). The implementation of these technologies enables SMEs to enhance production efficiency and product quality, continuously monitor energy consumption, foster a safe working environment, and reduce workloads, thereby promoting job satisfaction (JAYASHREE *et al.*, 2021b). Additionally, mobile applications emerge as another notable technology in Table 5, complementing the primary technologies by offering enhanced connectivity and integration (IAKOVETS; BALOG; ŽIDEK, 2023; KHANZODE *et al.*, 2021; PANDYA; KUMAR, 2023). Mobile devices facilitate employee mobility throughout the workday, aiding in the material study, report generation, process analysis, monitoring, and communication (BIRKEL; MÜLLER; MULLER, 2021; IAKOVETS; BALOG; ŽIDEK, 2023).

Table 5 also presents several technologies, such as HRM, CRM, GIS, MES, ERP, APS, with specific applications for managing different sustainability functions of SMEs, such as personnel, planning, processes, and warehouse. These technologies may not initially be identified as I4.0 technologies. However, they utilize integrated information bases, bolstered by IoT sensors and RFID for data collection, as well as CCO, BDA, and AI for calculations, statistics, and analysis, thereby enhancing the quality of work and decision-making (IAKOVETS; BALOG; ŽIDEK, 2023). Thus, I4.0 builds upon the foundations of previous industrial revolutions, leveraging existing and/or new technologies, however with a renewed focus and a more interconnected and intelligent approach (XU; XU; LI, 2018). This integration of complex systems into simpler and more routine software for SME managers can facilitate the implementation of technologies with a sustainable focus (JAYASHREE *et al.*, 2021a).

The technologies proposed to support sustainability functions took into account the needs of SMEs. Initially, simple and cost-effective technologies were suggested, as financial constraints are one of the major obstacles to implementing I4.0 in SMEs (SHARMA *et al.*, 2023). Technologies capable of integrating with existing systems of SMEs, ensuring compatibility, were prioritized. If smart technology is compatible with the organization's system, it will be more readily accepted. Conversely, if the SME has to make various adjustments, such as software integration, they will be more reluctant to adopt new technologies (JAYASHREE *et al.*, 2021a). Another aspect considered in the suggested technologies is the ease of implementation. Excessive complexity or lengthy implementation times can confuse users and negatively impact adoption decisions (ABDULAZIZ *et al.*, 2023). In this way, the suggested technologies meet the requirements of SMEs, enabling these companies to achieve sustainability functions (BAI *et al.*, 2020; JAYASHREE *et al.*, 2021b).

Table 5 - Sustainability functions integrated with Industry 4.0 technologies

Dimension	**Sustainability Function**	**Industry 4.0 Technology**																
		MOB	RFID	**IOT**	AUT	**CCO**	**BDA**	**AI**	BCH	VAR	HRM	CV	CRM	GIS	MES	ERP	WMS	APS
Social	Employee skill development	X								X								
	Recruitment, Selection, and Career Planning					**X**	**X**	**X**			X							
	Improving Work Ergonomics - Posture, Movements, Physical Effort			**X**								X						
	Improving Work Ergonomics - Environmental Analysis	X		**X**														
	Minimizing Effort, Stress, and Monotony				X													
	Enhancing Workplace Safety			**X**	X			**X**				X						
	Improving Company-Customer Relationship					**X**	**X**						X					
Environmental	Reducing Energy Consumption and Waste			**X**				**X**										
	Reducing Water Consumption and Waste			**X**														
	Controlling Waste Generation			**X**		**X**		**X**	X					X				
Economic	Organizing Production Processes	X		**X**		**X**	**X**								X	X		
	Organizing Warehouse	X	X			**X**											X	
	Simplifying Production Planning and Control	X																X
	Optimizing Supply Chain Connectivity			**X**		**X**	**X**	**X**										
	Optimization of Maintenance Processes	X		**X**			**X**	**X**										
	Improve Quality Monitoring							**X**				X						
	Enhancing Product Quality			**X**		**X**	**X**											
Total		**6**	**1**	**10**	**2**	**7**	**6**	**7**	**1**	**1**	**1**	**3**	**1**	**1**	**1**	**1**	**1**	**1**

*MOB=Mobile Applications; RFID=Radio Frequency Identification; IoT=Internet of Things; AUT=Automation; CCO=Cloud Computing; BDA=Big Data Analytics; AI=Artificial Intelligence; BCH=Blockchain; VAR=Virtual and Augmented Reality; HRM=Human Resource Management; CV=Computer Vision; CRM=Customer Relationship Management; GIS=Green Information Systems; MES=Manufacturing Execution Systems; ERP=Enterprise Resource Planning; WMS=Warehouse Management System; APS=Advanced Planning and Scheduling

2.6 CONCLUSIONS CONTRIBUTIONS AND LIMITATIONS

This study aimed to explore how I4.0 technologies can help SMEs achieve sustainability, considering the specific characteristics of these companies. To achieve this, a SLR was conducted from 2011 to 2023. The search encompassed the extensive WoS and Scopus scientific databases, and after applying pre-established criteria, 42 relevant papers were identified. The analysis unfolded in two key phases. Firstly, a quantitative analysis indicated the growth in the number of research studies, the representation of investigations in developing countries, and journals to guide research in the area. Then, in the qualitative phase, 17 sustainability functions divided into social, environmental, and economic dimensions were identified, including Employee skill development, Controlling Waste Generation, and Organizing Production Processes. These functions can be supported by I4.0 technologies to promote sustainability in SMEs. For each sustainability function, technologies capable of assisting SMEs in achieving objectives were identified. IoT, CCO, BDA, and AI stood out as the technologies that most assist SMEs, serving as a basis for various specific sustainable applications. Finally, the results were analyzed to identify potential blind spots in current research and determine promising subjects for future research. Thus, no equivalent SLR consolidates the possibilities of I4.0 technologies in assisting sustainability in SMEs, merging these approaches that have not been investigated together (DENICOLAI; ZUCCHELLA; MAGNANI, 2021; MÜLLER *et al.*, 2018).

2.6.1 Theoretical implications and suggestions for future research

The article systematically reviews the existing scientific literature, focusing on integrating I4.0, sustainability, and SMEs. This study expands the perspective of previous SLRs that focused on analyzing the intersection of only two of the three approaches. It correlates all three approaches, enabling SMEs to become more sustainable with the assistance of I4.0 technologies. The findings indicate that I4.0 technologies adapted to the realities of SMEs contribute to sustainable manufacturing through 17 sustainability functions, divided into the TBL. As a result, the study sheds light on the potential utilization of I4.0 technologies in SMEs, extending its scope beyond economic aspects to include social and environmental factors (DEY *et al.*, 2023; STRAZZULLO; MORO; CRICELLI, 2023).

The results diverge from studies conducted on large companies by indicating that sustainability functions operate more at the level of practical application rather than visionary concepts, which is appealing to SME managers (MASOOD; SONNTAG, 2020). Ghobakhloo (2020) identified functions such as Business Model Novelty and Innovation, Economic Development for the country, Environmental Responsibility Development, Social Welfare Enhancement, and Job Creation in areas of informatics, mechatronics, and processes, which have broader implications and encompass activities beyond the scope of SME managers. Similarly, Ching et al. (2022) pointed out some technologies and functions, such as Cyber-Physical Systems and Intelligent Robots for Harmful Emission Reduction, Digital Twin technology for Sustainable Product Development, and Smart Grids for Energy Sustainability. According to Moeuf et al. (2020), more robust cyber-physical systems, machine-to-machine connectivity, and autonomous robots are not considered key items for SMEs due to the implementation and maintenance costs. Lastly, Birkel et al. (2021) did not specify which technologies can contribute to specific functions in their study. Therefore, the technologies proposed in these reviews do not align with the cost constraints or implementation complexity required by SMEs. Conversely, the functions proposed in this study predominantly depend on readily accessible technologies tailored for SMEs with well-defined objectives.

This SLR conducted in this research indicates that a body of academic articles already addresses the relationship among the three approaches. However, some research gaps not addressed in the literature indicate that further investigations should be conducted in the future.

Firstly, the literature underscores the significance of government involvement in fostering knowledge and practices related to I4.0 among SMEs (ABDULAZIZ *et al.*, 2023; KHAN *et al.*, 2021). If the government aims to employ I4.0 technologies to bolster sustainability, they should infuse production technologies with a sustainability-oriented vision, particularly for SMEs, which require more targeted governmental support (COSTA MELO *et al.*, 2023b; HUNG; CHEN, 2023). Nevertheless, the literature offers limited insight into the concrete efforts undertaken and the potential measures governments can implement to attain the desired objective of digitized, sustainable, and competitive SMEs (KUMAR; SINGH; DWIVEDI, 2020). The inadequacy of regulations and governmental absence emerge as key barriers to I4.0 adoption in SMEs, often stemming from a lack of guidance in appropriate actions (KHANZODE *et al.*, 2021). Therefore, it is fundamental to identify which actions governments can develop to drive sustainability and I4.0 in SMEs.

Secondly, current literature indicates a shift in competition dynamics from individual companies to supply chains (BROZZI *et al.*, 2020; MÜLLER *et al.*, 2018). Consequently, SMEs must be integrated into the processes of sustainability and I4.0 throughout the entire SC, bolstering resilience while minimizing environmental waste. This study identified that integrating SMEs with their SC business partners is an economic sustainability function that can be supported by I4.0 technologies. However, despite literature suggesting that large companies can assist SMEs in sustainability and I4.0 processes, specific actions are not delineated (BIRKEL; MÜLLER; MULLER, 2021; YANG *et al.*, 2023). Therefore, future research may outline a pathway to guide large companies on promoting sustainability and I4.0 throughout their supply chains, thereby strengthening the entire ecosystem.

Thirdly, a lack of guidance for SMEs on where to begin their adoption process of I4.0 technologies has been identified (MITTAL *et al.*, 2018). The results of this SLR identifying I4.0 technologies to achieve sustainability functions emphasizing the need for gradual implementation to mitigate cost barriers. However, the results do not indicate where companies can begin. Thus, there is a need for roadmaps that guide SME managers on initiating the implementation process of technology and sustainable practices. Furthermore, they need to determine the required readiness level in their operational and organizational processes, encompassing human resources and infrastructure, to kickstart the adoption of sustainable-focused I4.0 (ABDULAZIZ *et al.*, 2023; BAG; PRETORIUS, 2022). Therefore, pathways for implementing technologies and accompanying programs specifically designed for SMEs should be developed, as SMEs cannot be overlooked on the path to I4.0 and sustainability (MÜLLER *et al.*, 2018).

Fourthly, the literature lacks a clear definition of actions that SME managers should take to ensure the proper implementation of I4.0 technologies and sustainable practices. One of the key characteristics of SMEs is that they typically have a single owner who performs various managerial functions, including process management, personnel management, and procurement (LOPES DE SOUSA JABBOUR; NDUBISI; ROMAN PAIS SELES, 2020). These managers often find themselves overwhelmed with the demanding nature of SME operations, potentially leading to the neglect of innovations, I4.0, and sustainability initiatives (KUMAR; REHMAN; PHANDEN, 2022). The findings underscore the importance of support and awareness from top leadership as facilitators for the adoption of I4.0 technologies (MOEUF *et al.*, 2020). However, the literature lacks an analysis of the behaviors and attitudes managers should exhibit to facilitate the integration of I4.0 and sustainability in SMEs. It is essential to delineate how this managerial support can be implemented in the company's routine to facilitate employee acceptance and minimize the risks of frustration due to unattained results (BETTIOL *et al.*, 2023).

Fifthly, the research examined the correlation between I4.0, sustainability, and manufacturing SMEs. While existing literature has laid a foundation for investigating I4.0 technologies in manufacturing SMEs, there is still a need for research in service-oriented SMEs. Pandya and Kumar (2023) delved into the impact of I4.0 technologies on social sustainability in service SMEs, citing examples such as pilot training, workload reduction in the healthcare sector, and enhanced customer satisfaction. However, the literature lacks research on how I4.0 technologies can contribute to sustainability in service-oriented SMEs. This gap presents an opportunity for future studies to explore environmental and economic dimensions.

Sixthly, while the research primarily focused on utilizing I4.0 technologies, the literature is already advancing into the realm of I5.0 and its pillars of sustainability, human-centricity, and resilience. I5.0 builds upon the concepts and technologies of I4.0, broadening the focus beyond mere technological advancements to encompass the socio-environmental impacts of this industrial evolution (EUROPEAN COMMISSION, 2021). Additionally, it expands the scope of sustainability considered in this study, emphasizing human-centricity and resilience as pivotal in the new industrial era. Consequently, investigating the interrelation between I5.0 and its pillars with the specific characteristics of SMEs emerges as a promising field of inquiry.

Seventhly, this study highlights the positive potential of technology utilization as a means for SMEs to attain sustainability. Nevertheless, the literature suggests that technological adoption can also have adverse effects on the social and environmental dimensions of sustainability (NARKHEDE *et al.*, 2023). For instance, the increasing energy demands to support a growing array of devices and machinery (LOPES DE SOUSA JABBOUR *et al.*, 2018), shorter product life cycles (NASCIMENTO *et al.*, 2019), and potential impacts on low-skilled or unskilled labor (DUTTA *et al.*, 2020) are notable concerns. Consequently, future research endeavors could delve into identifying these potential adverse impacts of technology adoption on sustainability in SMEs, elucidating their root causes, and proposing strategies to mitigate them, thereby bolstering the positive outcomes.

Lastly, with regard to methodology and sample selection in research articles, there is a notable gap in exploring the adoption of I4.0 across different countries, where approaches to

I4.0 and sustainability may vary (JAYASHREE *et al.*, 2021b). This is particularly pertinent for comparisons between developed and developing nations, as the roles of SMEs within these contexts can differ (RONAGHI; MOSAKHANI, 2022). Moreover, the issue of environmental and social sustainability in emerging economies has not been adequately addressed by researchers and requires further exploration (RONAGHI; MOSAKHANI, 2022). Therefore, studying the realities of SMEs in different countries to achieve sustainability and I4.0 is a possibility for future research.

2.6.2 Practical Implications

From a managerial standpoint, this article offers an overview of the potential advantages of I4.0 as a catalyst for enhancing sustainability practices within SMEs. The findings underscore specific technologies and their applications across dimensions of sustainability. It is essential to recognize that environmental and social considerations go beyond mere byproducts of economic gains (BIRKEL; MÜLLER; MULLER, 2021).

For SME managers, this study provides specific applications of I4.0 technologies so that SMEs can achieve sustainability. Managers can use the results to identify sustainability functions suitable for each company's organizational reality and objectives. Therefore, management must formulate and execute strategies, investing in improvements for employees, the environment, and economic returns. The possibility of creating a clear and viable objective can help SME transformation and mitigate employee resistance (KUMAR *et al.*, 2023).

Furthermore, it was observed that due to SMEs' limited resources, beginning with IoT applications can help them realize incremental benefits in their journey towards I4.0 (PANDYA; KUMAR, 2023). Additionally, CCO, BDA, and AI can support this process since they serve as foundational technologies for specific applications such as CRM, ERP, and APS (FRANK; DALENOGARE; AYALA, 2019). In this context, SMEs demand and prefer technologies with low implementation complexity. If the implementation time and integration challenges with the organization's systems exceed expectations, there may be resistance to technology adoption (JAYASHREE *et al.*, 2021a). This emphasizes the need for technology providers to create and offer simpler solutions specifically designed for SMEs, with cost estimates to prevent overlooking expenses during implementation (BETTIOL *et al.*, 2023). Additionally, they should invest in technical support services to address the shortage of technical skills, a significant barrier to adopting I4.0 within SMEs (JAYASHREE *et al.*, 2022).

2.6.3 Limitations

The literature review followed a systematic, transparent, and reproducible process already consolidated in the literature (DENYER; TRANFIELD, 2009); however, it still has certain limitations. Firstly, the databases used may constrain the number of articles found. While WoS and Scopus are comprehensive and reputable, they cover only a fraction of scientific publications, so some works may not have been included in the review process. Nevertheless, recent publications in high-level operations management journals, such as Business Strategy and Environment and the International Journal of Production Research, also include review articles whose data collection was obtained from these two databases (BAG; PRETORIUS, 2022; GHOBAKHLOO, 2020). Future work may expand the analysis to a greater number of databases.

Secondly, some works may not have been found despite the search string encompassing the names of the three main approaches of interest and their synonyms. For example, articles involving unique technologies that did not explicitly use "Industry 4.0" as a keyword or research focused on micro-enterprises without specifically mentioning "SMEs" in the keywords might be missing from this analysis. Additionally, the absence of a globally defined SME may have excluded articles from companies that would fit this definition (COSTA MELO *et al.*, 2023b). Future work may expand the search strings.

Thirdly, the research was limited to peer-reviewed journal articles, ensuring high quality. However, it omitted, for instance, conference papers, book chapters, and articles in other languages, which could also contain valuable information (BIRKEL; MÜLLER; MULLER, 2021; EJSMONT; GLADYSZ; KLUCZEK, 2020). As ongoing research and related themes continue to evolve, articles published in non-academic sources but with potentially significant results were not included in this SRL. Future work may expand this scope by including conference papers and other languages in the results.

Fourthly, despite the literature analysis identifying sustainability functions, the study did not indicate a priority order for implementation. SMEs lack pathways guiding how they should implement new technologies and sustainable practices (DENICOLAI; ZUCCHELLA; MAGNANI, 2021; MITTAL *et al.*, 2018; YANG *et al.*, 2023). Thus, future work can address this limitation of the study. Additionally, the benefits of these functions should not be considered guaranteed, as they depend on the context and circumstances in which SMEs operate (CHING *et al.*, 2022). Future research can offer more insights by empirically examining and exploring each function. Finally, this study prioritized sustainability functions that were considered more feasible given the constraints of SMEs. However, other sustainability functions may be relevant beyond those identified in this work and can be explored in future studies.

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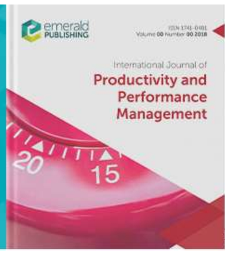

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3 MULTI-CRITERIA DECISION-MAKING MODEL FOR SUSTAINABILITY FUNCTIONS INTEGRATED INDUSTRY 4.0 TECHNOLOGIES WITHIN SMALL AND MEDIUM ENTERPRISES IN EMERGING COUNTRIES

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Abstract

Purpose: In the Industry 4.0 (I4.0) era, small and medium enterprises (SMEs) face significant pressure to make their manufacturing operations more sustainable. However, SMEs often lack the knowledge and information needed to leverage I4.0 technologies for achieving sustainability. This paper aims to develop a Multi-Criteria Decision-Making (MCDM) model to prioritize sustainability functions supported by I4.0 technologies in SMEs.

Methodology: The Fuzzy-DEMATEL method was developed to classify sustainability functions based on their prominence and influence, categorizing them into cause-and-effect groups. Experts in I4.0 technologies, sustainability, and SMEs from Brazil were consulted during the data collection phase. Sensitivity analysis was also performed to validate the results obtained through the DEMATEL method.

Findings: The results indicate that the most prominent and influential sustainability functions include Organizing Production Processes, Employee Skill Development, and Simplifying Production Planning and Control. Therefore, investing in I4.0 technologies to support these functions can enable SMEs to amplify the impact of their sustainability initiatives and improve operational efficiency. The authors also observed that Improving Quality Monitoring is the primary function within the effect group.

Originality: This study ranks key sustainability functions as actions and practices that SMEs can implement using I4.0 technologies to achieve sustainability. It also identifies the most prominent and influential functions managers should prioritize when investing in I4.0 technologies.

Practical Implications: This paper serves as a roadmap for SME managers seeking to enhance the effectiveness of their sustainability practices using I4.0 technologies, thereby maximizing impact while minimizing the complexity of implementation.

Keywords: Sustainable Development; Sustainable Operations Management; SME; Smart Manufacturing; Fuzzy-Dematel; Technology Adoption.

3.1 INTRODUCTION

Industries are increasingly investing in sustainable production processes in response to the growing occurrence of environmental disasters and rising global temperatures (DENICOLAI; ZUCCHELLA; MAGNANI, 2021). The focus is primarily on reducing resource consumption, minimizing waste generation, and enhancing working conditions, all while maintaining economic competitiveness (DOSSOU *et al.*, 2022; SHARMA *et al.*, 2021). However, companies face considerable challenges in achieving these goals, particularly due to uncertainty about how to effectively implement sustainability practices (CHEGE; WANG, 2020; LOPES DE SOUSA JABBOUR; NDUBISI; ROMAN PAIS SELES, 2020). Small and medium-sized enterprises (SMEs), particularly, require guidance on where to begin and which practices and technologies should be prioritized to achieve sustainability (JOURNEAULT; PERRON; VALLIÈRES, 2021).

SMEs are defined by their relatively lower revenue and smaller workforce, although these criteria vary across countries (CHEGE; WANG, 2020). Despite these variations, SMEs often face less pressure than larger corporations, as their environmental impact is sometimes underestimated due to their size (BROZZI *et al.*, 2020). However, research indicates that SMEs contribute to over 70% of global industrial pollution (EUROPEAN COMMISSION, 2017), surpassing the combined environmental impact of large companies (CALOGIROU, CONSTANTINOS, SØRENSEN *et al.*, 2010). This highlights the critical need to explore alternatives, such as Industry 4.0 (I4.0) technologies, to support adopting sustainable practices in SMEs (DEY *et al.*, 2023).

I4.0 technologies have the potential to significantly enhance sustainability in manufacturing companies (BIRKEL; MÜLLER; MULLER, 2021; EJSMONT; GLADYSZ; KLUCZEK, 2020; GHOBAKHLOO, 2020; KAMBLE; GUNASEKARAN; GAWANKAR, 2018; STOCK; SELIGER, 2016). However, the wide array of available technologies, combined with uncertainty regarding their implementation and benefits, poses substantial challenges for the digitalization of SMEs (MACHADO *et al.*, 2021). This often hinders the establishment of clear, viable objectives, leading to frustration (BETTIOL *et al.*, 2023). It is essential to identify which sustainability functions should be prioritized in order to avoid fragmented efforts and resource misallocation. These functions encompass actions and practices that SMEs can develop using I4.0 technologies to achieve goals across the three dimensions of sustainability: social, environmental, and economic, as identified in the work of Santos and Sant'Anna (2024).

Consequently, this study's research question (RQ) is: ***Which sustainability functions have the greatest prominence and influence, and should be prioritized for implementation in SMEs?***

This paper aims to develop a Multi-Criteria Decision-Making (MCDM) model to prioritize sustainability functions supported by I4.0 technologies in SMEs. The methodology applies an MCDM approach, specifically employing the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method, which is particularly suited for analyzing the influence of one sustainability function on another (SI *et al.*, 2018). Questionnaires were distributed to experts in I4.0, sustainability, and SMEs in Brazil, a developing country, who used their expertise to identify the most prominent and influential functions. To account for uncertainties in expert opinions, fuzzy set theory was integrated with DEMATEL (PERÇIN, 2018). The Fuzzy-DEMATEL method was then applied to evaluate the causal relationships between sustainability functions, leveraging the insights provided by the experts.

This study contributes to the literature by establishing correlations between I4.0, sustainability, and SMEs—topics that are often explored in isolation (DENICOLAI; ZUCCHELLA; MAGNANI, 2021). Additionally, it prioritizes the sustainability functions enabled by I4.0 technologies, allowing SMEs to enhance their operational and administrative sustainability by identifying the most influential and prominent functions. Furthermore, this study draws on the expertise of specialists from a developing country, such as Brazil, where challenges related to investment, labor, and infrastructure are particularly pronounced (ASCÚA, 2021; SANTOS *et al.*, 2024).

The remainder of the paper is organized as follows: Section 2 reviews the literature and discusses sustainability functions. Section 3 details the methodological process for prioritizing functions using the fuzzy-DEMATEL method. Section 4 presents the results of the analysis and includes a discussion. Finally, Section 5 offers concluding remarks, highlights the contributions of the research and addresses its limitations.

3.2 LITERATURE REVIEW

The advent of I4.0 technologies offers opportunities for companies to achieve their sustainability goals across the Triple Bottom Line (TBL) (BEIER *et al.*, 2020; GHOBAKHLOO, 2020). Socially, I4.0 has been associated with improved safety and working conditions (IAKOVETS; BALOG; ŽIDEK, 2023; OJSTERSEK; BUCHMEISTER; HERZOG, 2020). Environmentally, it enhances energy efficiency, reduces waste generation, and optimizes resource allocation (DENICOLAI; ZUCCHELLA; MAGNANI, 2021; FINDIK; TIRGIL;

ÖZBUĞDAY, 2023). Economically, it assists in inventory management and organizing production processes (DEY *et al.*, 2023; NARKHEDE *et al.*, 2023). However, these benefits are primarily observed in large enterprises within developed countries, highlighting a gap in the literature regarding the impact of I4.0 and sustainability on SMEs in developing nations (SANTOS *et al.*, 2024; SHARMA; JABBOUR; LOPES DE SOUSA JABBOUR, 2020).

SMEs are crucial for driving industrial growth in developing countries, necessitating effective strategies to promote technology adoption and enhance sustainability (LOPES DE SOUSA JABBOUR; NDUBISI; ROMAN PAIS SELES, 2020). However, current approaches often remain superficial, and SMEs face significant barriers to implementing sustainable manufacturing practices, such as high investment costs, infrastructure limitations, and labor challenges (KUMAR; SINGH; DWIVEDI, 2020; SILTORI *et al.*, 2021). This issue is particularly complex in Brazil, known for having some of the highest real interest rates globally, thereby restricting SMEs' access to credit and subsequent investment (FEIJO, 2024). Existing literature has addressed digitalization and sustainability processes in Brazil. For instance, Machado *et al.* (2021) investigated barriers to digitalization and sustainability in the country, Ascua (2021) explored the impact of I4.0 on industrial SMEs in Latin America, and Nara *et al.* (2021) examined the technologies with the most significant impact on sustainability in the Brazilian plastics industry. Santos *et al.* (2024) assessed the potential of I4.0 technologies to enhance sustainability in SMEs, while Siltori *et al.* (2021) analyzed the effects of I4.0 on corporate sustainability in Brazilian companies. Despite these contributions, there is still a lack of clear guidance on how SMEs can achieve sustainability with I4.0 technologies, including which areas should be prioritized.

Existing research predominantly explores the relationship between I4.0 and sustainability (BEIER *et al.*, 2020; BROZZI *et al.*, 2020; GHOBAKHLOO, 2020; MACHADO; WINROTH; DA SILVA, 2020) or focuses on the role of I4.0 in SMEs (MITTAL *et al.*, 2018). However, few studies simultaneously address all three aspects: I4.0, sustainability, and SMEs (DENICOLAI; ZUCCHELLA; MAGNANI, 2021). Among studies addressing these three aspects, Narkhede *et al.* (2023), through a review, and Santos *et al.* (2024), via case studies, investigated how technologies can contribute to sustainability in SMEs. Although these studies provide practical examples, they do not offer guidance on where companies should begin their efforts. Costa Melo *et al.* (COSTA MELO *et al.*, 2023a) conducted a literature review focusing on both external and internal variables to assess SMEs' digital and sustainable performance but did not address specific technologies or strategies for achieving sustainability objectives. Ingaldi and Ulewicz (2020) explored the barriers SMEs face in digitization and sustainability, while Jayashree *et al.* (2021) examined how I4.0 determinants affect technology implementation in SMEs.

Santos and Sant'Anna (2024), conducted a Systematic Literature Review to identify sustainability functions that can be supported by I4.0 technologies in SMEs (Table 6). This review helps SMEs achieve sustainability across all three dimensions: social, environmental, and economic. The identified functions can be addressed through I4.0 technologies tailored to the specific needs of SMEs, ensuring they are easy to implement, compatible with existing systems, and cost-effective (ALAYON; SÄFSTEN; JOHANSSON, 2022; MOEUF *et al.*, 2020). However, the study did not prioritize these sustainability functions, leaving SME managers with difficulty determining where to begin or which functions to prioritize on their path to sustainability. Therefore, this study aims to use the sustainability functions identified by Santos and Sant'Anna (2024) as a foundation for developing a pathway to adopt sustainable practices. The goal is to minimize implementation effort and maximize impact. To achieve this, the Fuzzy-DEMATEL method is employed to prioritize the sustainability functions.

Table 6 - Sustainable Functions supported by Industry 4.0 technologies in Small and Medium Enterprises

TBL	Code	Sustainability Function	Definition	Technologies	References
Social	SF1	Employee skill development	Strengthen learning and reduce the time required for employee training by improving ideation, creativity, and critical thinking.	Mobile technologies and virtual and augmented reality	(IAKOVETS; BALOG; ŽIDEK, 2023; YANG *et al.*, 2023)
	SF2	Recruitment, Selection, and Career Planning	Increase recruitment accuracy by aligning candidate skills with job requirements and optimizing career planning through people analytics.	BDA, AI and Human Resource Management	(GHOBAKHLOO, 2020; RONAGHI; MOSAKHANI, 2022)
	SF3	Improving Work Ergonomics - Posture, Movements, Physical Effort	Improve workplace ergonomics by enhancing comfort, safety, and efficiency in work processes.	IoT sensors and Computer Vision	(OJSTERSEK; BUCHMEISTER; HERZOG, 2020; PAPETTI *et al.*, 2020)
	SF4	Improving Work Ergonomics - Environmental Analysis	Enhance workplace conditions by optimizing temperature, lighting, and noise levels.	IoT sensors	(DOSSOU *et al.*, 2022; PAPETTI *et al.*, 2020)
	SF5	Minimizing Effort, Stress, and Monotony	Support employees and reduce errors in administrative and operational tasks while improving accessibility.	Automation of manual activities	(BROZZI *et al.*, 2020; STOCK; SELIGER, 2016)
	SF6	Enhancing Workplace Safety	Monitor work environments and activities, identifying and alerting workers to hazardous situations.	Smart cameras, intelligent sensors, and AI	(CHING *et al.*, 2022; KAMBLE; GUNASEKARAN; GAWANKAR, 2018)
	SF7	Improving Company-Customer Relationship	Strengthen consumer relationships by analyzing consumption habits and preferences.	Customer Relationship Management, enhanced by CCO and BDA.	(PEROTTI *et al.*, 2023; RONAGHI; MOSAKHANI, 2022)

Environmental	SF8	Reducing Energy Consumption and Waste	Monitor energy consumption to detect and prevent potential waste.	IoT sensors	(DENICOLAI; ZUCCHELLA; MAGNANI, 2021; MÜLLER *et al.*, 2018)
	SF9	Reducing Water Consumption and Waste	Monitor water consumption to detect and prevent potential waste.	IoT sensors	(FINDIK; TIRGIL; ÖZBUĞDAY, 2023; JENA; MISHRA; MOHARANA, 2020)
	SF10	Controlling Waste Generation	Enhance visibility of production parameters to monitor process efficiency and identify sources of waste.	Waste management systems boosted by CCO, AI, and Blockchain	(JAYASHREE *et al.*, 2022; MACHADO *et al.*, 2021)
Economic	SF11	Organizing Production Processes	Simplify control and monitoring of production processes through real-time data analysis.	MES and ERP, powered by IoT mobile devices, CCO and BDA	(GHOBAKHLOO, 2020; JAMWAL *et al.*, 2021)
	SF12	Organizing Warehouse	Streamline material and product tracking in warehouses by monitoring movements and quantities, while preventing incorrect storage.	Cloud-based Warehouse Management Systems powered by RFID chips or QR codes	(KAMBLE; GUNASEKARAN; GAWANKAR, 2018; SHARMA *et al.*, 2023)
	SF13	Simplifying Production Planning and Control	Improve precision in production planning and control, while avoiding material shortages.	APS	(DEY *et al.*, 2023; KHAN; PIPRANI; YU, 2022)
	SF14	Optimizing Supply Chain Connectivity	Strengthen relationships with suppliers and customers by sharing inventory and transportation information, fostering a stronger ecosystem.	AI-driven systems based on sensor data and CCO.	(BIRKEL; MÜLLER; MULLER, 2021; RIOSVELASCO-MONROY *et al.*, 2022)
	SF15	Optimization of Maintenance Processes	Minimize unplanned maintenance downtime and extend the lifespan of equipment and machinery.	BDA and AI-based systems, powered by IoT sensors	(DEY *et al.*, 2023; HARIASTUTI *et al.*, 2022)
	SF16	Improve Quality Monitoring	Quickly identify defective products based on predefined standards.	AI-based Computer Vision	(GHOBAKHLOO, 2020; JAMWAL *et al.*, 2021)
	SF17	Enhancing Product Quality	Monitor product performance throughout its lifecycle, predicting maintenance needs and collecting data for potential upgrades.	IoT, CCO, and BDA	(NASCIMENTO *et al.*, 2019; ROSA *et al.*, 2020)

* Internet of Things (IoT); Cloud Computing (CCO); Big Data Analytics (BdA); and Artificial Intelligence (AI); Manufacturing Execution Systems (MES); Enterprise Resource Planning (ERP); Advanced Planning and Scheduling (APS).
Source: Santos and Sant'Anna (2024).

The literature on I4.0 extensively covers the application of MCDM methodologies for prioritizing various factors, such as facilitators of I4.0, the impact of technologies on sustainability, and barriers to I4.0 adoption (Table 7). However, none of these studies have employed the Fuzzy-DEMATEL method to analyze and prioritize sustainable functions achievable through the implementation of I4.0 in SMEs within developing countries. This highlights a significant research gap that this study aims to address.

Table 7 - Multi-Criteria Decision-Making studies that analyze Industry 4.0 and sustainability

Paper	MDCM	Object of Study		Focus
		SMEs	Developing Country	
(GHOBAKHLOO, 2020)	MICMAC			Prioritize the potential impacts of Industry 4.0 technologies on sustainability.
(YADAV *et al.*, 2020a)	RBWM		X	Explore the enablers that facilitate the adoption of sustainability practices using Industry 4.0 technologies.
(BAG *et al.*, 2021)	Fuzzy DEMATEL		X	Explore the barriers of digital manufacturing initiatives in a circular economy.
(KHANZODE *et al.*, 2021)	DEMATEL	X	X	Identify the barriers to implementing Industry 4.0 technologies for sustainable production.
(MACHADO *et al.*, 2021)	Fuzzy DEMATEL	X	X	Analyze the influence of key barriers and enablers in integrating Industry 4.0 and sustainability within supply chains.
(NARA *et al.*, 2021)	Fuzzy TOPSIS		X	Examine the technologies that have the most significant impact on sustainability.
(HARIASTUTI *et al.*, 2022)	ISM	X	X	Determine the primary drivers of technological innovation in manufacturing that support sustainability goals.
(KUMAR; REHMAN; PHANDEN, 2022)	Fuzzy DEMATEL	X	X	Investigate and establish the relationship between the enablers that enhance social performance in the digital era.
(BHATIA; DIAZ-ELSAYED, 2023)	Fuzzy TOPSIS	X		Identify the most appropriate smart manufacturing technologies for adoption.
(JAMWAL; AGRAWAL; SHARMA, 2023)	Fuzzy-AHP-DEMATEL	X	X	Assess the impact of Industry 4.0 challenges on achieving sustainability in manufacturing.
(KUMAR *et al.*, 2023)	ISM	X	X	Identify and correlate the barriers to adopting sustainability and Industry 4.0 technologies.
(PANDYA; KUMAR, 2023)	AHP	X	X	Prioritize Industry 4.0 technologies that contribute to achieving sustainable operations.
(AGARWAL; OJHA, 2024)	ISM-AHP		X	Understand and outline the implications of Industry 4.0 for achieving specific SDGs.
This Work	Fuzzy DEMATEL	X	X	Prioritize sustainability functions supported by I4.0 technologies for sustainability.

Among various MCDM methodologies, the DEMATEL method offers unique advantages. It presents results through matrices and graphs, effectively illustrating the interrelationships among factors and categorizing them into cause-and-effect groups (KAZANCOGLU; OZKAN-OZEN, 2018; KUMAR; REHMAN; PHANDEN, 2022). In contrast, Interpretive Structural Modeling (ISM), which uses binary numbers to capture respondents' sentiments, fails to capture the magnitude of the influences perceived by respondentes (SI *et al.*, 2018). Similarly, the Analytic Hierarchy Process (AHP) involves assigning priority weights to criteria to create a hierarchical structure, but it assumes criteria independence and overlooks their interactions and dependencies (KHANZODE *et al.*, 2021).

As a result, AHP is unsuitable for studies that do not assign priority weights and consider the dependencies between functions. Therefore, this study utilized the Fuzzy-DEMATEL method to leverage expert insights and identify which sustainability functions supported by I4.0 technologies have the greatest prominence and influence on others.

3.3 RESEARCH METHOD

The DEMATEL method was used to analyze the interrelationships among sustainability functions. Based on matrix theory, this method aggregates respondents' inputs (i.e., influence magnitudes) to construct a structured representation of cause-and-effect relationships among factors, identifying the most influential elements (PERÇIN, 2018; SHAKERI; KHALILZADEH, 2020). The output is a hierarchical map, where numerical values denote the strength of influence (prominence), providing a structured understanding of these relationships (SI *et al.*, 2018).

Significant values of preferences and importance derived from expert judgments often face limitations in real-world applications due to challenges in estimating them with precise numerical values (MACHADO *et al.*, 2021). To address this inherent imprecision in subjective decision-making, the Fuzzy-DEMATEL method has emerged as a solution, combining fuzzy set logic with DEMATEL (VINODH; WANKHEDE, 2020). Fuzzy set theory, introduced by Zadeh (1965), provides a mathematical framework for representing and managing vague or imprecise judgments in decision-making processes. In this study, fuzzy set theory has been integrated into DEMATEL to alleviate the imprecision and bias inherent in expert decisions (ZADEH, 1965). Additionally, sensitivity analysis was conducted to assess the robustness of the DEMATEL analysis (JAMWAL; AGRAWAL; SHARMA, 2023; KUMAR; REHMAN; PHANDEN, 2022).

In line with the DEMATEL methodology, experts with a minimum of five years of experience in I4.0, sustainability, or SMEs were consulted. According to the OECD (2005), SMEs are independent enterprises primarily characterized by their number of employees and financial assets. In Brazil, small companies are defined as having up to 99 employees, while medium-sized companies have up to 500 employees (SEBRAE, 2013). All experts were affiliated with organizations based in Brazil, a developing country facing heightened challenges in digitization and sustainability (ASCÚA, 2021; SILTORI *et al.*, 2021).

A comprehensive questionnaire (see Appendix-A) was carefully designed for this study, drawing on previous methodologies (KAZANCOGLU; OZKAN-OZEN, 2018; KUMAR;

SINGH; DWIVEDI, 2020). The first section of the questionnaire included informed consent, study objectives, and procedural information. Respondents were informed that there were no right or wrong answers to minimize subject bias. The second section detailed the expert's profile, while the third focused on correlating the sustainability functions. Industrial respondents included SME managers in executive roles and business owners. Additionally, consultants specializing in digitalization and sustainability projects for SMEs were consulted. Academic experts who had made significant contributions to the research literature were also included. The questionnaire was emailed to fifteen experts (ten from industry and five from academia) for data collection. The experts' profiles are outlined in Table 8.

Table 8 - Experts profile

Experts	Expert field	Current Position	Area field	Experience
Expert 1	Academic	Ph.D. candidate in Industrial Engineering	Operations Management	6 years
Expert 2	Academic	Professor	Operations Management in SMEs	7 years
Expert 3	Industry	General Manager	Rubber and plastic industry (SME sector)	10 years
Expert 4	Industry	Consultant	Digitalization in SMEs	15 years
Expert 5	Industry	Process manager	Perfume industry (SME sector)	7 years
Expert 6	Industry	General Manager	Clothing industry (SME sector)	25 years
Expert 7	Industry	Process manager	Clothing industry (SME sector)	6 years
Expert 8	Academic	Ph.D. candidate in Industrial Engineering	Operations Management in the MSME Sector	5 years
Expert 9	Industry	General Manager	Food industry (SME sector)	7 years
Expert 10	Industry	Consultant	Digitalization in SMEs	7 years
Expert 11	Academic	Ph.D. candidate in Industrial Engineering	Operations Management	6 years
Expert 12	Industry	Consultant	Lean Manufacturing in SMEs	5 years
Expert 13	Academic	Professor	Operations Management	10 years
Expert 14	Industry	Consultant	Sustainability in SMEs	5 years
Expert 15	Industry	Project manager	Metallurgical industry (SME sector)	7 years

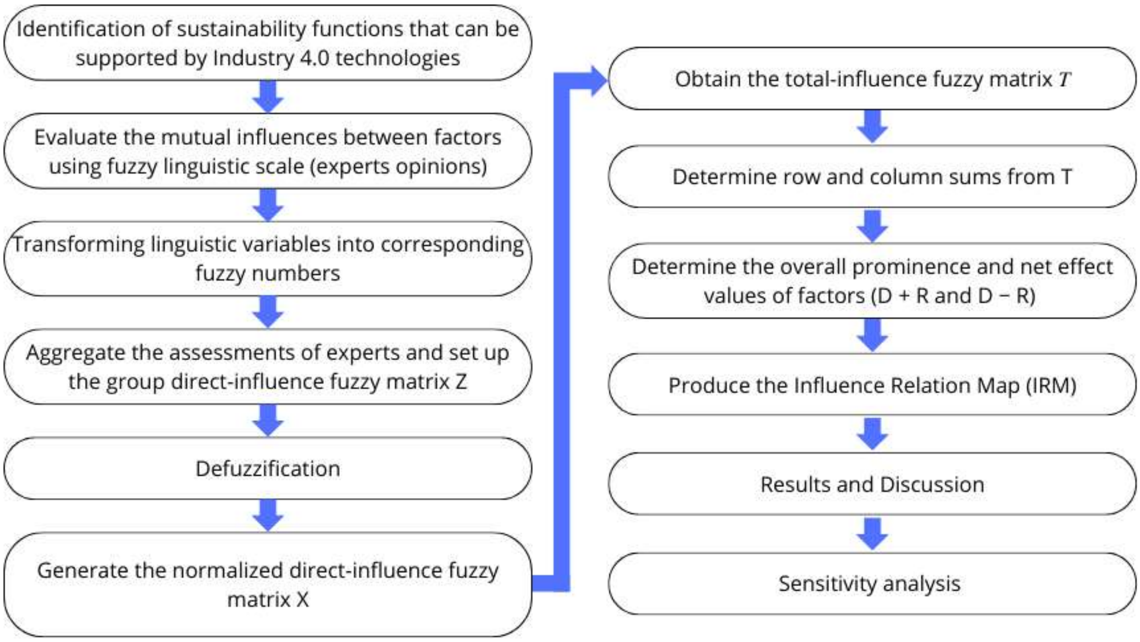
Numerous studies employing the DEMATEL method have varied in the number of participating experts. For instance, Kumar *et al.* (2022) utilized 20 specialists, Khanzode *et al.* (2021) consulted 8 respondents, and Kazancoglu *et al.* (2018) engaged 5 experts. Additionally, Khanzode *et al.* (2021) reported that the DEMATEL method is robust and remains independent of the number of respondents, ensuring the internal consistency of results. Consequently, this study collected and analyzed responses from 15 experts.

3.3.1 Fuzzy-DEMATEL Method

The methodological steps of the Fuzzy-DEMATEL applied in this study are outlined in Figure 11. The research begins with identifying sustainability functions supported by I4.0 technologies in SMEs. This is followed by data collection through consultations with specialists. The calculations were performed according to the approaches of Kazancoglu and

Ozkan-Ozen (2018), Khanzode *et al.* (2021), Perçin (2018) and Si *et al.* (2018). Afterward, the study presents the results and discussion. Finally, a sensitivity analysis was conducted.

Figure 11 – Methodological Steps



1 – Evaluate the mutual influences between functions using fuzzy linguistic scale

Setting up the initial direct relation matrix using linguistic variables is the first stage in Fuzzy-DEMATEL. Utilizing linguistic variables, as presented in Table 9, experts are asked to provide their opinions on the degree to which function i influences function j, and how function j is influenced by function i. Interviewees were instructed to consider that the effect of one sustainability function on another may not necessarily be reciprocal. Additionally, the main diagonal of the resulting matrix should be entirely equal to 0, as sustainability functions do not influence themselves.

Table 9 - Linguistic Terms and their corresponding Triangular Fuzzy Numbers

Linguistic Terms	**Triangular Fuzzy Numbers**
Very High Influence (VH)	(0.75, 1.00, 1.00)
High Influence (H)	(0.50, 0.75, 1.00)
Low Influence (L)	(0.25, 0.50, 0.75)
Very Low Influence (VL)	(0, 0.25, 0.50)
No influence (No)	(0, 0, 0.25)

2 – Transforming linguistic variables into corresponding fuzzy numbers

The second stage of Fuzzy-DEMATEL analysis involves converting linguistic variables into corresponding Triangular Fuzzy Numbers (TFNs), as outlined in Table 9. Consequently, the individual direct-influence fuzzy matrix $\tilde{Z}_k = \left[\tilde{z}_{ij}^k\right]_{nxn}$ is obtained for each respondent $E = \{E_1, E_2, \ldots, E_l\}$, where $\tilde{z}_{ij}^k = \left(z_{ij1}^k, z_{ij2}^k, z_{ij3}^k\right)$ represents the fuzzy assessment provided by expert E_k regarding the influence degree between functions F_i and F_j.

3 – Aggregate the assessments of experts and set up the group direct-influence fuzzy matrix $\tilde{Z}$

After constructing the individual matrixes $\tilde{Z}_k = (k = 1,2, \ldots, l)$, the group direct-influence fuzzy matrix $\tilde{Z} = \left[\tilde{z}_{ij}\right]_{nxn}$ is calculated by averaging the judgments of experts, as there are multiple decision-makers involved. Each $\tilde{z}_{ij}$ can be interpreted as a triangular fuzzy number (0, 0, 0) and $\tilde{z}_{ij}$ is derived by Eq. (1):

$$\tilde{z}_{ij} = \left(z_{ij1}, z_{ij2}, z_{ij3}\right) = \frac{1}{l}\sum_{k=1}^{l} \tilde{z}_{ij}^k = \left(\frac{1}{l}\sum_{k=1}^{l} z_{ij1}^k, \frac{1}{l}\sum_{k=1}^{l} z_{ij2}^k, \frac{1}{l}\sum_{k=1}^{l} z_{ij3}^k\right) \quad (1)$$

4 – Defuzzification

The centroid method (also known as center-of-gravity or center of area) was employed to determine the crisp values of fuzzy numbers of matrix $\tilde{Z} = \left[\tilde{z}_{ij}\right]_{nxn}$ as described in (SI *et al.*, 2018; YOUNESI; ROGHANIAN, 2015). For the triangular fuzzy number $\tilde{z}_{ij} = \left(z_{ij}\ , z_{ij2}, z_{ij3}\right)$, its crisp value can be determined using the following equivalent relations as Eq. (2):

$$COA\ (\tilde{z}_{ij}) = \frac{\left(z_{ij3} - z_{ij1}\right) + \left(z_{ij2} - z_{ij1}\right)}{3} + z_{ij1} \quad (2)$$

5 – Generate the normalized direct-influence fuzzy matrix $\tilde{X}$

The sum of rows and columns of the matrix $\tilde{Z}$ is computed, and the highest value is noted for both rows and columns. Thus, the normalized direct-influence matrix $\tilde{X} = \left[x_{ij}\right]_{nxn}$ can be obtained by using Eq. (3):

$$X = \frac{\tilde{Z}}{s} \text{ and } s = max\left(\max_{1\le j\le n} \textstyle\sum_{j=1}^{n} z_{ij}, \max_{1\le i\le n} \textstyle\sum_{i=1}^{n} z_{ij}\right) \quad (3)$$

All elements in the matrix $\tilde{X}$ are comply with $0 \le x_{ij} \le 1$, $0 \le \sum_{j=1}^{n} x_{ij} \le 1$, and there exists at least one i such that $\sum_{j=1}^{n} z_{ij} \le s$.

6 – Obtain the total-influence fuzzy matrix $\tilde{T}$

Using the normalized direct-influence matrix $\tilde{X}$, the total-influence matrix $\tilde{T} = [t_{ij}]_{nxn}$ is computed by summing the direct effects and all indirect effects as Eq. (4):

$$\tilde{T} = \tilde{X}.(I - \tilde{X})^{-1} \quad (4)$$

where I is denoted as an identity matrix.

7 – Determine row and column sums from $\tilde{T}$

At this stage, the vectors R and C, representing the sum of the rows and the sum of the columns from the total-influence matrix $\tilde{T}$, are defined by the following formulas Eq. (5) and Eq. (6):

$$C = [c_j]_{1xn} = \left[\sum_{i=1}^{n} t_{ij}\right]_{1xn}^{T} \quad (5)$$

$$R = [r_i]_{nx1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{nx1} \quad (6)$$

where r_i represents the sum of the ith row in the matrix $\tilde{T}$, indicating the total of direct and indirect effects originating from function F_i to other functions. Similarly, c_j represents the sum of the jth column in the matrix $\tilde{T}$, illustrating the total of direct and indirect effects received by function F_j from other functions. A hierarchy can be generated by summing all rows R and columns C.

8 – Determine the overall prominence and net effect values of functions (R+C and R-C)

For each function, specific values of R and C are observed and separately recorded in another table, along with the values of $R+C$ and $R-C$ for each function.

- $R+C$, named "Prominence," illustrates the strength/impact of influences that the function both receives and exerts within the system.
- $R-C$, named "Relationship," indicates the net effect the function contributes to the system. A positive sign suggests that the function influences other criteria (causes), while a negative sign suggests that the function is influenced by other criteria (effect).

9 – Produce the Influence Relation Map (IRM)

Finally, the Influence Relation Map (IRM) is constructed based on information derived from the matrix $\tilde{T}$ to elucidate the structural relations among functions. An IRM chart can be generated by plotting a scatter diagram with $R+C$ as the X-axis and $R-C$ as the Y-axis.

Additionally, the value of q is calculated as the average of the matrix $\tilde{T}$, aiding in delineating boundaries within the IRM chart.

3.4 RESULTS AND DISCUSSION

This section presents the categorization of sustainability functions into cause-and-effect groups using the Fuzzy-DEMATEL method, identifying those with the greatest prominence and influence. Sensitivity analysis was conducted to validate the consistency of the results. Subsection 4.1 examines the results of the Fuzzy-DEMATEL analysis, subsection 4.2 discusses the key findings, and subsection 4.3 explores the outcomes of the sensitivity analysis.

3.4.1 Analysis based on DEMATEL method

For the Fuzzy-DEMATEL method calculations, the process begins by developing the average direct-influence fuzzy matrix. Second, the defuzzification process is conducted, and the results are presented in Table 10. Next, the normalized direct-influence fuzzy matrix is calculated, with values expressed on a scale from 0 to 1 (Table 11). Subsequently, the total-influence fuzzy matrix is derived (Table 12). The remaining calculations follow the methodological steps, with results in Table 13. The final step involves constructing and interpreting the IRM chart (Figure 12).

Table 10 - Average Direct-Influence Defuzzified Relation Matrix

DEFZ (CDA)		j	j	j	j	j	j	j	j	j	j	j	j	j	j	j	j	j
		SF1	SF2	SF3	SF4	SF5	SF6	SF7	SF8	SF9	SF10	SF11	SF12	SF13	SF14	SF15	SF16	SF17
i	SF1	0,00	0,82	0,67	0,56	0,70	0,51	0,79	0,66	0,61	0,67	0,86	0,81	0,83	0,71	0,71	0,85	0,87
i	SF2	0,77	0,00	0,34	0,26	0,38	0,33	0,61	0,35	0,30	0,30	0,44	0,41	0,38	0,36	0,40	0,44	0,45
i	SF3	0,58	0,27	0,00	0,75	0,85	0,63	0,31	0,15	0,15	0,20	0,56	0,38	0,31	0,18	0,50	0,42	0,40
i	SF4	0,63	0,31	0,77	0,00	0,85	0,61	0,31	0,42	0,40	0,12	0,65	0,45	0,31	0,22	0,47	0,58	0,53
i	SF5	0,78	0,41	0,89	0,72	0,00	0,59	0,47	0,31	0,26	0,26	0,58	0,53	0,53	0,33	0,51	0,63	0,56
i	SF6	0,54	0,32	0,77	0,69	0,70	0,00	0,38	0,22	0,20	0,26	0,58	0,47	0,35	0,28	0,57	0,45	0,43
i	SF7	0,74	0,59	0,38	0,33	0,52	0,27	0,00	0,40	0,42	0,45	0,61	0,64	0,51	0,74	0,33	0,83	0,87
i	SF8	0,56	0,18	0,27	0,51	0,33	0,40	0,42	0,00	0,58	0,56	0,79	0,60	0,51	0,29	0,69	0,52	0,50
i	SF9	0,46	0,13	0,13	0,18	0,15	0,19	0,40	0,58	0,00	0,60	0,69	0,29	0,39	0,20	0,45	0,33	0,40
i	SF10	0,58	0,24	0,26	0,48	0,26	0,29	0,52	0,63	0,58	0,00	0,81	0,60	0,64	0,46	0,55	0,71	0,59
i	SF11	0,79	0,42	0,70	0,66	0,74	0,58	0,67	0,82	0,82	0,88	0,00	0,85	0,86	0,75	0,85	0,84	0,82
i	SF12	0,66	0,42	0,60	0,49	0,70	0,49	0,60	0,42	0,24	0,53	0,84	0,00	0,89	0,80	0,59	0,65	0,60
i	SF13	0,65	0,37	0,42	0,38	0,58	0,35	0,57	0,65	0,60	0,72	0,88	0,86	0,00	0,78	0,73	0,65	0,69
i	SF14	0,55	0,28	0,23	0,28	0,44	0,28	0,56	0,48	0,39	0,51	0,72	0,83	0,83	0,00	0,56	0,69	0,63
i	SF15	0,63	0,27	0,51	0,48	0,60	0,51	0,47	0,67	0,58	0,72	0,84	0,56	0,67	0,49	0,00	0,77	0,80
i	SF16	0,67	0,42	0,53	0,47	0,63	0,51	0,80	0,51	0,40	0,63	0,86	0,65	0,72	0,67	0,72	0,00	0,88

i	SF17	0,68	0,33	0,44	0,40	0,47	0,31	0,88	0,58	0,50	0,68	0,83	0,57	0,65	0,63	0,69	0,81	0,00

Table 11 - Normalized Direct-Influence Fuzzy Matrix

X	FS1	FS2	FS3	FS4	FS5	FS6	FS7	FS8	FS9	FS10	FS11	FS12	FS13	FS14	FS15	FS16	FS17
SF1	0,00	0,07	0,06	0,05	0,06	0,04	0,07	0,05	0,05	0,06	0,07	0,07	0,07	0,06	0,06	0,07	0,07
SF2	0,06	0,00	0,03	0,02	0,03	0,03	0,05	0,03	0,02	0,02	0,04	0,03	0,03	0,03	0,03	0,04	0,04
SF3	0,05	0,02	0,00	0,06	0,07	0,05	0,03	0,01	0,01	0,02	0,05	0,03	0,03	0,02	0,04	0,03	0,03
SF4	0,05	0,03	0,06	0,00	0,07	0,05	0,03	0,04	0,03	0,01	0,05	0,04	0,03	0,02	0,04	0,05	0,04
SF5	0,06	0,03	0,07	0,06	0,00	0,05	0,04	0,03	0,02	0,02	0,05	0,04	0,04	0,03	0,04	0,05	0,05
SF6	0,05	0,03	0,06	0,06	0,06	0,00	0,03	0,02	0,02	0,02	0,05	0,04	0,03	0,02	0,05	0,04	0,04
SF7	0,06	0,05	0,03	0,03	0,04	0,02	0,00	0,03	0,04	0,04	0,05	0,05	0,04	0,06	0,03	0,07	0,07
SF8	0,05	0,02	0,02	0,04	0,03	0,03	0,04	0,00	0,05	0,05	0,07	0,05	0,04	0,02	0,06	0,04	0,04
SF9	0,04	0,01	0,01	0,02	0,01	0,02	0,03	0,05	0,00	0,05	0,06	0,02	0,03	0,02	0,04	0,03	0,03
SF10	0,05	0,02	0,02	0,04	0,02	0,02	0,04	0,05	0,05	0,00	0,07	0,05	0,05	0,04	0,05	0,06	0,05
SF11	0,07	0,03	0,06	0,05	0,06	0,05	0,06	0,07	0,07	0,07	0,00	0,07	0,07	0,06	0,07	0,07	0,07
SF12	0,05	0,04	0,05	0,04	0,06	0,04	0,05	0,04	0,02	0,04	0,07	0,00	0,07	0,07	0,05	0,05	0,05
SF13	0,05	0,03	0,03	0,03	0,05	0,03	0,05	0,05	0,05	0,06	0,07	0,07	0,00	0,07	0,06	0,05	0,06
SF14	0,05	0,02	0,02	0,02	0,04	0,02	0,05	0,04	0,03	0,04	0,06	0,07	0,07	0,00	0,05	0,06	0,05
SF15	0,05	0,02	0,04	0,04	0,05	0,04	0,04	0,06	0,05	0,06	0,07	0,05	0,06	0,04	0,00	0,06	0,07
SF16	0,06	0,04	0,04	0,04	0,05	0,04	0,07	0,04	0,03	0,05	0,07	0,05	0,06	0,06	0,06	0,00	0,07
SF17	0,06	0,03	0,04	0,03	0,04	0,03	0,07	0,05	0,04	0,06	0,07	0,05	0,05	0,05	0,06	0,07	0,00

Table 12 - Total-Influence Fuzzy Matrix

T	FS1	FS2	FS3	FS4	FS5	FS6	FS7	FS8	FS9	FS10	FS11	FS12	FS13	FS14	FS15	FS16	FS17
SF1	0,18	0,17	0,20	0,18	0,22	0,17	0,22	0,20	0,18	0,20	0,27	0,24	0,24	0,20	0,23	0,25	0,25
SF2	0,17	0,06	0,11	0,10	0,13	0,10	0,14	0,11	0,10	0,11	0,16	0,13	0,13	0,12	0,13	0,14	0,14
SF3	0,15	0,09	0,09	0,14	0,16	0,13	0,12	0,10	0,09	0,10	0,16	0,13	0,13	0,10	0,14	0,14	0,14
SF4	0,17	0,10	0,16	0,09	0,18	0,13	0,13	0,13	0,12	0,11	0,19	0,15	0,14	0,12	0,15	0,17	0,16
SF5	0,20	0,11	0,18	0,16	0,12	0,14	0,15	0,13	0,12	0,13	0,20	0,17	0,17	0,13	0,16	0,18	0,18
SF6	0,16	0,09	0,16	0,14	0,16	0,08	0,13	0,11	0,10	0,12	0,18	0,15	0,14	0,12	0,15	0,15	0,15
SF7	0,20	0,13	0,14	0,13	0,16	0,12	0,12	0,14	0,13	0,15	0,21	0,18	0,17	0,17	0,16	0,21	0,21
SF8	0,17	0,09	0,12	0,14	0,14	0,12	0,14	0,10	0,14	0,15	0,21	0,17	0,16	0,13	0,17	0,17	0,17
SF9	0,13	0,07	0,08	0,09	0,09	0,08	0,11	0,12	0,07	0,13	0,16	0,11	0,12	0,09	0,12	0,12	0,13
SF10	0,18	0,10	0,13	0,14	0,14	0,11	0,16	0,16	0,14	0,11	0,22	0,18	0,18	0,15	0,17	0,19	0,18
SF11	0,25	0,14	0,20	0,19	0,22	0,17	0,22	0,21	0,20	0,22	0,21	0,25	0,25	0,21	0,24	0,26	0,25
SF12	0,21	0,12	0,17	0,16	0,19	0,15	0,18	0,16	0,13	0,17	0,24	0,15	0,22	0,19	0,19	0,21	0,20
SF13	0,21	0,12	0,16	0,15	0,18	0,14	0,18	0,18	0,16	0,19	0,25	0,22	0,15	0,19	0,20	0,21	0,21
SF14	0,18	0,10	0,13	0,12	0,15	0,12	0,17	0,15	0,13	0,16	0,21	0,20	0,20	0,11	0,17	0,19	0,19
SF15	0,20	0,11	0,16	0,15	0,18	0,15	0,17	0,18	0,16	0,18	0,24	0,19	0,20	0,16	0,14	0,22	0,22
SF16	0,22	0,13	0,17	0,16	0,19	0,15	0,21	0,17	0,15	0,18	0,25	0,21	0,21	0,19	0,21	0,16	0,23
SF17	0,21	0,12	0,16	0,15	0,17	0,13	0,20	0,17	0,15	0,18	0,24	0,19	0,20	0,17	0,20	0,22	0,15

The obtained values of 'R,' 'C,' 'R+C,' and 'R-C' are presented in Table 13, providing key insights into the analysis of sustainability functions. The magnitude of 'R+C' reflects the prominence and influence of each sustainability function. Conversely, the magnitude of 'R-C' is used to categorize functions into 'Effect' and 'Cause' groups. The causal relationships suggest that preceding ones can influence certain sustainability functions. This implies that allocating resources to enhance the impact of the influencing sustainability function can reduce the effort required to implement the influenced function.

Table 13 - Categorization of sustainability functions into cause-and-effect groups and the summation of influence given and received on functions

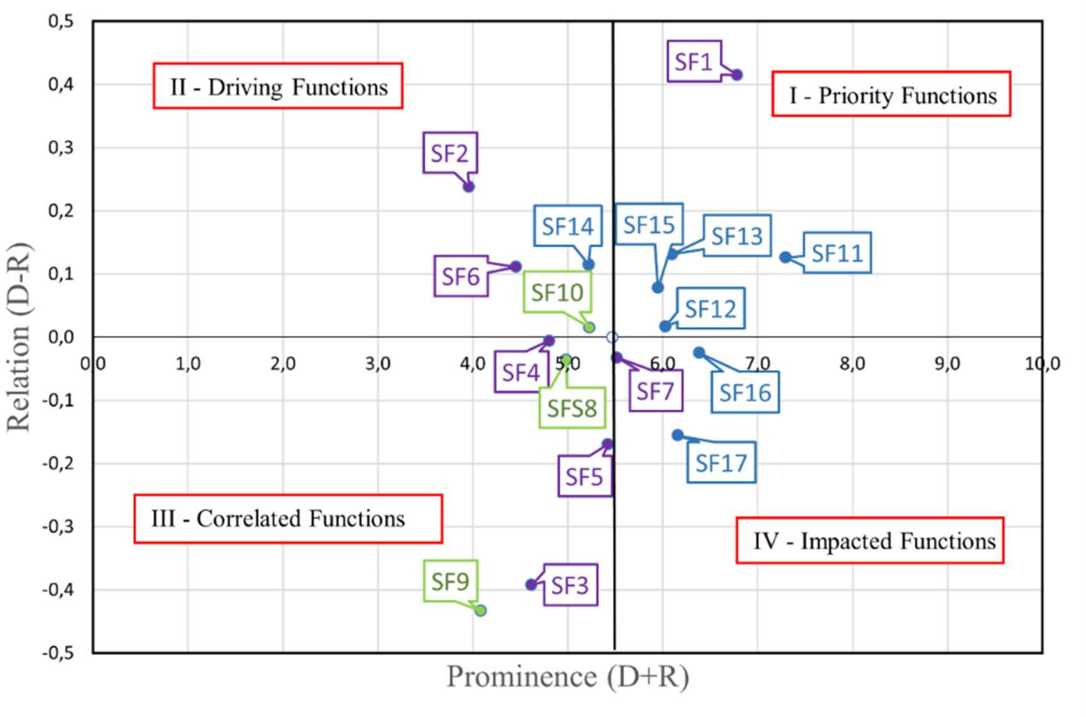
Sustainability Function	R	C	R+C	Overall Ranking	R-C	Group
SF1	3,599	3,184	6,782	2	0,415	Cause
SF2	2,099	1,861	3,960	17	0,238	Cause
SF3	2,114	2,506	4,619	14	-0,392	Effect
SF4	2,400	2,406	4,806	13	-0,005	Effect
SF5	2,626	2,796	5,422	9	-0,169	Effect
SF6	2,283	2,172	4,455	15	0,111	Cause
SF7	2,742	2,775	5,517	8	-0,032	Effect
SF8	2,474	2,510	4,984	12	-0,036	Effect
SF9	1,824	2,257	4,082	16	-0,433	Effect
SF10	2,623	2,607	5,230	10	0,016	Cause
SF11	3,711	3,585	7,296	1	0,126	Cause
SF12	3,024	3,007	6,030	6	0,017	Cause
SF13	3,114	2,983	6,097	5	0,131	Cause
SF14	2,666	2,551	5,217	11	0,115	Cause
SF15	3,014	2,936	5,950	7	0,078	Cause
SF16	3,179	3,204	6,383	3	-0,025	Effect
SF17	3,003	3,159	6,162	4	-0,156	Effect

In this study, it has been observed that Organizing Production Processes (SF11) has the highest value (R+C), making it the most critical sustainability function in the cause category. The exact values for cause-and-effect functions are shown in Table 13. Further, it is observed that Employee skill development (SF1), Simplifying Production Planning and Control (SF13), Organizing Warehouse (SF12), and Optimization of Maintenance Processes (SF15) are the second, third, fourth, and fifth-ranked sustainability functions, respectively in the cause category. Further findings of the study also indicate that it Improve Quality Monitoring (SF16), Enhancing Product Quality (SF17), Improving Company-Customer Relationship (SF7), Minimizing Effort, Stress, and Monotony (SF5), and Reducing Energy Consumption and Waste (SF8) are the top five challenges in the effect category.

3.4.2 Discussions of Findings

Results from the study presented in Section 4.1 reveal that sustainability functions can be categorized into cause-and-effect groups. The IRM was obtained and divided into four quadrants (I to IV), as illustrated in Figure 12, with the divider calculated based on the average of 'R+C' (*q* value) (SI *et al.*, 2018).

Figure 12 - Influence Relation Map



The functions in quadrant I are identified as "priority functions," exhibiting high prominence and strong interrelationships. These functions should be prioritized for investment allocation due to their significant potential to influence the implementation of other sustainable practices within SMEs. As primary drivers within the cause group, they hold the capacity to affect other sustainability functions. "Organizing Production Processes (SF11)" demonstrated the highest prominence among these. Integrating technologies such as RFID and Internet of Things (IoT) sensors (FINDIK; TIRGIL; ÖZBUĞDAY, 2023; PANDYA; KUMAR, 2023) enables SMEs to capture data, improving management software such as Manufacturing Execution System (MES) and Enterprise Resource Planning (ERP) (IAKOVETS; BALOG; ŽIDEK, 2023). This integration allows for real-time monitoring of product location, production status, and parameters like energy and water consumption and waste generation, which are crucial for environmental sustainability (DOSSOU *et al.*, 2022). Additionally, optimizing production processes reduces employee stress and enhances workstation efficiency, contributing to social sustainability (BROZZI *et al.*, 2020; PAPETTI *et al.*, 2020). Ranked second in the quadrant is "Employee Skill Development (SF1)." By training employees for new roles or complementary tasks, SME managers can positively influence all three dimensions of sustainability, highlighting the critical role of this function in the cause group. Investments in this area leverage technologies such as mobile devices for job instructions and augmented and virtual reality for training purposes (CHING *et al.*, 2022; YANG *et al.*, 2023). A more qualified employee will likely perform better, reducing resource waste and physical effort in their activities, thereby enhancing work quality and productivity (DEY *et al.*, 2023; INGALDI; ULEWICZ, 2020).

The third sustainability function in quadrant I is "Simplifying Production Planning and Control (SF13)." This function supports social sustainability by reducing employee stress through more accurate production planning, facilitated by Advanced Planning and Scheduling (APS) software enhanced with Cloud Computing (CCO) and Big Data Analytics (BdA) technologies (KHAN; PIPRANI; YU, 2022; KHANZODE *et al.*, 2021). It also contributes to environmental sustainability by preventing unnecessary energy, water, and raw materials consumption, utilizing demand-driven production planning. APS software, powered by Artificial Intelligence (AI), employs sales data for predictive analysis, ensuring efficient resource management (SHARMA *et al.*, 2023). Economically, it helps maintain updated inventory, production schedules, and maintenance shutdowns, thereby meeting consumer demands (DEY *et al.*, 2023). "Organizing Warehouse (SF12)" is the fourth prominent function in this quadrant. SMEs can enhance relationships with suppliers and customers through continuous inventory monitoring, enabled by RFID technology integrated with the Warehouse Management System (WMS). This prevents product shortages and discrepancies between physical and virtual inventories (MACHADO; WINROTH; DA SILVA, 2020; SHARMA *et al.*, 2023), minimizing production stoppages due to raw material shortages and reducing resource waste (GHOBAKHLOO, 2020; KAMBLE; GUNASEKARAN; GAWANKAR, 2018). Finally, the fifth key function in quadrant I is "Optimizing Maintenance Processes (SF15)." SME managers can simplify tasks for employees, reducing their stress and physical effort, by utilizing IoT technology to monitor equipment and implementing maintenance management software based on BdA and AI to streamline maintenance control. According to Dossou (2022), operators no longer need to shuttle between the real situation and the instructions to be followed as they receive assistance from technology. This function also benefits SMEs economically and environmentally, reducing unplanned production stoppages and excessive energy and resource consumption due to machines operating outside their optimal specifications (HARIASTUTI *et al.*, 2022; KHAN; PIPRANI; YU, 2022).

The functions in quadrant II are classified as "driving functions" due to their low prominence but high interrelation. As part of the cause group, they have the capacity to influence other functions, though not to the same degree as those in quadrant I. Nevertheless, it is essential to map and not overlook these functions so SMEs can invest in them during subsequent phases. The most prominent function in this quadrant is "Controlling Waste Generation (SF10)," which relates to environmental sustainability. This function can utilize IoT sensors to collect data on resource usage and monitor production processes, thereby minimizing waste (MÜLLER *et al.*, 2018). "Optimizing Supply Chain Connectivity (SF14)" represents the economic sustainability dimension within this quadrant. SMEs can employ CCO-based systems to enhance connectivity and data sharing across the supply chain, thereby improving relationships with suppliers and customers. This function also positively impacts planning and production processes by increasing accuracy through real-time information sharing (JAYASHREE *et al.*, 2021b; NARKHEDE *et al.*, 2023; RONAGHI; MOSAKHANI, 2022). Finally, two activities with the lowest levels of prominence are related to social sustainability: "Enhancing Workplace Safety (SF6)" and "Recruitment, Selection, and Career Planning (SF2)." For the first, SMEs can adopt visual computing technologies to improve workplace safety by identifying hazardous behaviors, directly influencing both work activities and the environment (KAMBLE; GUNASEKARAN; GAWANKAR, 2018; OJSTERSEK; BUCHMEISTER; HERZOG, 2020). For the second, Human Resource Management software, enhanced with AI, can help SMEs design effective training programs and career plans for employees, ensuring that individuals are better suited to their roles, thereby reducing stress and role mismatches (GHOBAKHLOO, 2020; PAPETTI *et al.*, 2020).

The study's findings also reveal that "Minimizing Effort, Stress, and Monotony (SF5)," "Reducing Energy Consumption and Waste (SF8)," "Improving Work Ergonomics - Environmental Analysis (SF4)," "Improving Work Ergonomics - Posture, Movements, Physical Effort (SF3)," and "Reducing Water Consumption and Waste (SF9)" compose quadrant III, designated as "correlated functions." These functions exhibit both low prominence and low interrelation and are relatively disconnected from the system (SI *et al.*, 2018). Due to investment constraints in SMEs, these functions should not be prioritized. However, since they belong to the effect group, investments in functions from quadrants I and II could improve the functions within quadrant III.

The results suggest that efforts to develop employee skills and optimize production processes in SMEs can reduce employee effort and stress while improving environmental working conditions. This is because the processes will be more standardized and controlled, and employees will be better prepared with the assistance of technology (OJSTERSEK; BUCHMEISTER; HERZOG, 2020; PAPETTI *et al.*, 2020). Investments in safety measures can also correct employee posture and movement, using computer vision and IoT sensors (IAKOVETS; BALOG; ŽIDEK, 2023; MÜLLER *et al.*, 2018). Lastly, optimizing planning and maintenance processes can reduce energy and water waste by ensuring that machinery operates only when necessary and under optimal conditions (JENA; MISHRA; MOHARANA, 2020).

The functions in quadrant IV, classified within the effect group, exhibit high prominence but low interrelation and are referred to as "impacted functions." This indicates that these functions are influenced by others and face challenges in direct improvement (SI *et al.*, 2018). Therefore, their indices tend to improve through direct investments in the functions of the first quadrant, potentially extending to the second quadrant. This category includes "Improve Quality Monitoring (SF16)," "Enhancing Product Quality (SF17)," and "Improving Company-Customer Relationship (SF7)." The findings highlight the potential for enhancing quality monitoring and product quality by streamlining production and maintenance processes and through employee training. While technologies like computer vision and IoT can assist in quality monitoring, their effective use requires skilled personnel and well-calibrated equipment to reduce detection errors. Improving product quality similarly demands skilled labor to design products incorporating technologies such as IoT and AI, which are used to analyze and predict product performance throughout its lifecycle (NARKHEDE *et al.*, 2023; NASCIMENTO *et al.*, 2019; STOCK; SELIGER, 2016). Finally, to improve company-customer relationships, SMEs should focus on resource allocation in production, warehouse planning, and control. This approach helps prevent product shortages and maintains consistent quality standards (DEY *et al.*, 2023; GHOBAKHLOO, 2020).

The findings confirm that I4.0 technologies can significantly contribute to SMEs across all three dimensions of sustainability. Foundational I4.0 technologies, such as IoT, CCO, BDA, and AI, work in an integrated manner to enhance the performance of pre-existing software like MES, ERP, APS, and WMS, which were in use before the emergence of I4.0. While these systems may not be initially classified as I4.0 technologies, incorporating advanced databases and analytical capabilities from new technologies improves their computational capacity and information-sharing processes. This, in turn, enhances the quality of work and decision-making

(IAKOVETS; BALOG; ŽIDEK, 2023). By integrating existing and new technologies, I4.0 fosters a more interconnected and intelligent approach, simplifying the application of novel technologies in familiar software for SMEs.

3.4.3 Sensitivity Analysis

Sensitivity analysis is employed to assess the robustness of the model and its behavior under varying circumstances (KUMAR; REHMAN; PHANDEN, 2022). It provides decision-makers with valuable insights into how different configurations of weights influence the prioritization of functions (JAMWAL; AGRAWAL; SHARMA, 2023). This analysis can be conducted in two ways: first, by varying the weight assigned to each challenge, and second, by adjusting the weight assigned to each expert. Kumar *et al*. (2020) applied sensitivity analysis by altering the weights assigned to experts to evaluate the robustness of the solution in analyzing cause-and-effect relationships. This step is necessary due to differences in the experts' total industry experience, which may introduce biases into the results.

In this study, sensitivity analysis was performed by varying the weight assigned to each expert. In Case 1, all experts were assigned equal weights, while in Cases 2, 3, and 4, one expert was given a higher weight, with the other two experts' weights remaining constant (Table 14). Calculations were then performed for sensitivity analysis under these different scenarios, and Influence IRM was generated for each case (Figure 13 - Cases 1 to 4). The results suggest that the ranking order remains consistent across all scenarios, with only negligible exceptions (Table 15). This confirms the proposed model's robustness and indicates no significant human bias affecting the outcomes.

Table 14 - Varying the weight of experts in the sensitivity analysis

	Case-1	Case-2	Case-3	Case-4
Expert 1	0.33	0.50	0.25	0.25
Expert 2	0.33	0.25	0.50	0.25
Expert 3	0.33	0.25	0.25	0.50

Table 15 - Sensitivity analysis of results

Sustainability Function	Case-1		Case-2		Case-3		Case-4	
	D+R	Ranking	D+R	Ranking	D+R	Ranking	D+R	Ranking
SF1	5.68	2	5.22	2	6.00	2	5.11	2
SF2	3.95	11	3.41	13	4.30	13	3.67	10
SF3	4.04	10	3.53	10	4.59	10	3.54	11
SF4	3.73	14	3.24	14	4.21	14	3.30	13
SF5	4.64	7	4.20	8	5.17	7	4.02	8
SF6	3.16	17	2.94	17	3.37	17	2.80	16

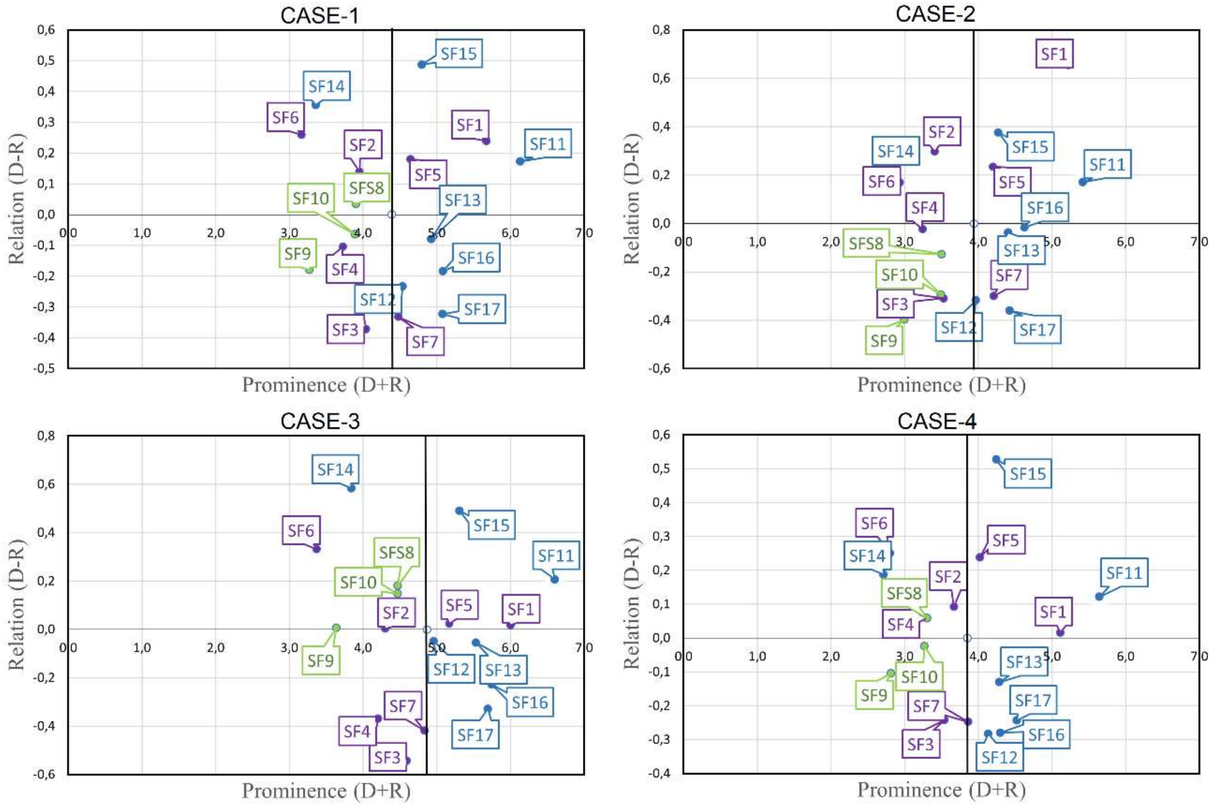
SF7	4.48	9	4.21	7	4.84	9	3.86	9
SF8	3.91	12	3.50	11	4.47	12	3.30	12
SF9	3.27	16	3.00	16	3.64	16	2.81	15
SF10	3.89	13	3.49	12	4.47	11	3.27	14
SF11	6.14	1	5.42	1	6.60	1	5.64	1
SF12	4.54	8	3.97	9	4.96	8	4.13	7
SF13	4.93	5	4.41	5	5.53	5	4.29	5
SF14	3.36	15	3.15	15	3.84	15	2.71	17
SF15	4.80	6	4.27	6	5.31	6	4.24	6
SF16	5.08	3	4.63	3	5.74	3	4.30	4
SF17	5.08	4	4.43	4	5.70	4	4.52	3

3.5 FINAL CONSIDERATIONS

This study aimed to prioritize sustainability functions supported by I4.0 technologies in SMEs. The Fuzzy-DEMATEL method was used to identify the most prominent and influential functions and to categorize them into cause-and-effect groups. The findings highlight the importance of investing in key areas such as Organizing Production Processes (SF11), Employee Skill Development (SF1), and Simplifying Production Planning and Control (SF13), which emerged as the most influential functions in the "cause" group. Managers should prioritize allocating resources to these functions, as they can significantly enhance the impact of sustainable initiatives and improve operational efficiency. In the "effect" group, functions such as Improving Quality Monitoring (SF16), Enhancing Product Quality (SF17), and Improving Company-Customer Relationships (SF7) stand out as those that can benefit from investments in other areas. For the validation of the findings a sensitivity analysis was conducted (KUMAR; SINGH; DWIVEDI, 2020). The analysis revealed no significant differences in the results under varying conditions, indicating the robustness of the proposed model.

The study also emphasizes the potential of I4.0 technologies to support sustainability in SMEs (SANTOS *et al.*, 2024). These technologies align with the specific needs of SMEs by offering low complexity and cost, with a clear understanding of expected returns (ALAYON; SÄFSTEN; JOHANSSON, 2022; MOEUF *et al.*, 2020). Notably, the study recommends leveraging IoT for monitoring workstations, products, and warehouses, as well as using planning and management software enhanced with CCO, BdA, and AI to support managerial decision-making (GHOBAKHLOO, 2020).

Figure 13 - Influence Relation Map (Case 1 to 4)



3.5.1 Theoretical Contributions

The existing literature explores the intersection of I4.0, sustainability, and SMEs (COSTA MELO *et al.*, 2023a; INGALDI; ULEWICZ, 2020; JAYASHREE *et al.*, 2021b; NARKHEDE *et al.*, 2023; SANTOS *et al.*, 2024). However, this study is the first to prioritize sustainability functions, highlighting the most prominent and influential ones. It offers valuable insights into the areas SMEs should focus on when implementing sustainable practices, thus broadening the understanding of effective sustainability strategies for this business segment.

Most research tends to focus on large enterprises in developed countries, creating a gap in the literature concerning SMEs in developing nations, where infrastructure and resource limitations are significant (DENICOLAI; ZUCCHELLA; MAGNANI, 2021; SANTOS *et al.*, 2024; SHARMA; JABBOUR; LOPES DE SOUSA JABBOUR, 2020). This study addresses this gap by consulting experts from Brazil, who bring direct experience with the realities and challenges of a developing country. Notably, Brazil is recognized for its high real interest rates, which create barriers to investment (FEIJO, 2024).

Finally, while the Fuzzy-DEMATEL method is well-established in the literature with applications in studies related to I4.0 and sustainability (BAG *et al.*, 2021; HARIASTUTI *et* *al.*, 2022; KAZANCOGLU; OZKAN-OZEN, 2018), this study is the first to apply it to assess the interrelationship of sustainability functions in the context of SMEs, contributing a novel perspective to the field.

3.5.2 Managerial Contributions

The hierarchical results of the sustainability functions can serve as a roadmap for implementation, allowing managers to maximize the impact of sustainable practices while avoiding the allocation of financial and time resources to low-return activities (MITTAL *et al.*, 2018). To this end, managers should prioritize investments in the most prominent and influential sustainability functions (see Table 13), particularly those in the Priority Functions group (see Figure 12), as these can significantly influence the implementation of other functions.

SMEs possess unique characteristics, such as financial constraints, lack of technical expertise, and infrastructural issues for implementing new processes, making solutions for large enterprises potentially unsuitable for SMEs (DOSSOU *et al.*, 2022; YANG *et al.*, 2023). As a result, this study proposes technologies and sustainability functions that prioritize low-complexity initial implementations and compatibility with standard management and operational processes in SMEs, thereby reducing investment uncertainty (MITTAL *et al.*, 2018; MOEUF *et al.*, 2018).

Consultants and technology suppliers can leverage these results to guide digitization projects in SMEs towards more sustainable objectives. The broad application of IoT-based technologies offers significant opportunities for technology providers to develop innovative solutions (GHOBAKHLOO, 2020; JAYASHREE *et al.*, 2022). Finally, SMEs' key supply chain partners can utilize the findings to concentrate efforts on encouraging the adoption of technologies and sustainability functions with the highest potential for impact, thus contributing to a sustainable production ecosystem (CHEGE; WANG, 2020; SHARMA *et al.*, 2021).

3.5.3 Limitations and Future Research

This study acknowledges certain limitations and highlights opportunities for future research. Firstly, the findings are specific to SMEs and may not be universally applicable to all companies or sectors (KUMAR; SINGH; DWIVEDI, 2020). Therefore, managers should consider the unique characteristics of their own organizations when interpreting and applying the results (BEIER *et al.*, 2020). Secondly, the interviews were limited to experts from Brazil, which may restrict the generalizability of the results to SMEs in other countries with different contexts. Future research could broaden its scope to include additional sectors and countries, thereby enhancing the validation of the findings. Investigating potential differences between microenterprises and SMEs would also be valuable. Such studies could facilitate comparative analysis and improve the generalizability of the results.

A third aspect to consider is that while the DEMATEL method is robust, it has inherent limitations, such as its reliance on the accuracy of expert assessments, which can introduce subjectivity and potentially distort the representation of sustainability functions (MACHADO *et al.*, 2021; VINODH; WANKHEDE, 2020). To address this issue, the study employed sensitivity analysis, enhancing the proposed system's methodological generalizability (KUMAR; REHMAN; PHANDEN, 2022). Additionally, fuzzy set theory was applied (ZADEH, 1965) to account for uncertainties in expert opinions. However, fuzzy logic also has limitations, such as potentially reducing accuracy due to using both precise and imprecise data. Therefore, managers should consider these limitations when applying the study's results to their business decisions. Future research could explore alternative methods and investigate the potential benefits of combining different MCDM methods. Additionally, expanding the number of respondents through surveys could enhance the generalizability of the results.

Fourth, the sequence of implementing sustainability functions proposed in this study is based on expert opinions and lacks empirical validation. Future research could validate these suggestions by empirically investigating the implementation of sustainability functions and related technologies through case studies in specific sectors. Finally, while the Fuzzy-DEMATEL analysis in this study focused on ranking sustainability functions for SMEs identified in the literature (SANTOS; SANT'ANNA, 2024), future research may consider incorporating additional functions, as results may vary depending on the context analyzed.

4 HOW ORGANIZATIONAL FACTORS INFLUENCE THE INDUSTRY 4.0 ADOPTION IN MICRO, SMALL, AND MEDIUM ENTERPRISES

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Abstract

***Purpose* –** Micro, Small, and Medium Enterprises (MSMEs) must improve their organizational readiness to implement Industry 4.0 (I4.0) technologies effectively, ensuring competitiveness and more sustainable processes. However, there is limited guidance on which organizational factors are critical for this transition. This study investigates how organizational, technical, and social factors influence the adoption of I4.0 technologies in MSMEs.

***Design/methodology/approach* –** This research integrates the Natural Resource-Based View (NRBV) and Dynamic Capabilities Theory (DCT). A survey of 80 companies was conducted to assess the influence of various organizational factors on I4.0 adoption. The companies were grouped into clusters based on organizational readiness, with K-means clustering and Analysis of Variance used for data analysis. Ordinal Logistic Regression was also employed to identify significant predictors of I4.0 adoption in MSMEs.

***Findings* –** The study found that company size significantly impacts organizational preparedness for I4.0 adoption. Additionally, the analysis revealed that companies should focus on developing a strategic vision, building a skilled workforce, securing financial resources, and integrating into digital supply chains to facilitate I4.0 adoption.

***Originality/value* –** This study contributes to the existing literature by highlighting the positive influence of organizational factors on I4.0 adoption in MSMEs.

Practical implications – The findings offer practical insights for managers, identifying key organizational factors to prioritize for successful I4.0 implementation. The results provide actionable guidance for companies uncertain about how to begin their I4.0 journey.

Keywords: Smart manufacturing; MSME; Operations Management; Entrepreneurship; ANOVA

4.1 INTRODUCTION

In recent years, the focus on work-life quality and environmental sustainability has gained significant attention in industrial discussions. The challenges arise from heightened pollution, overexploitation of natural resources, and rising expectations from employees, all in the pursuit of economic progress (NASCIMENTO *et al.*, 2019). Consequently, various stakeholders have begun pressuring companies to adopt practices that mitigate the negative impacts of their activities (ROXAS, 2021). Moreover, the introduction of stricter environmental regulations has compelled businesses to adapt their operations to align with sustainable practices (JAMWAL; AGRAWAL; SHARMA, 2023), particularly within micro, small, and medium-sized manufacturing enterprises (MSMEs) (DEY *et al.*, 2023).

While the sustainability impacts of individual MSMEs may initially appear minimal compared to large corporations (CHEGE; WANG, 2020), their collective impact can exceed that of larger companies due to the sheer number of small businesses (LOPES DE SOUSA JABBOUR; NDUBISI; ROMAN PAIS SELES, 2020). Despite increasing interest, the adoption of sustainability practices among MSMEs has been slower than anticipated (DEY *et al.*, 2023). In addition, most tools and analyses supporting sustainable development have been tailored for large corporations (IAKOVETS; BALOG; ŽIDEK, 2023), and are not specifically designed for MSMEs, such as Industry 4.0 (I4.0) technologies (INGALDI; ULEWICZ, 2020; MOEUF *et al.*, 2020).

I4.0, also known as the Fourth Industrial Revolution, encompasses a range of technologies that enhance process efficiency and product quality by enabling real-time data collection for informed decision-making (GHOBAKHLOO, 2020; SAAD; BAHADORI; JAFARNEJAD, 2021). These technologies include augmented and virtual reality, RFID, additive manufacturing, digital twins, and advanced robotics. Foundational technologies like the Internet of Things (IoT), cloud computing, big data analytics, and artificial intelligence (AI) are particularly important for sustainability-focused applications (FRANK; DALENOGARE; AYALA, 2019; SILTORI *et al.*, 2021). However, MSMEs often face challenges in implementing I4.0 due to high costs and complex implementation processes, which are typically designed for larger companies, necessitating adaptations to suit MSMEs' unique characteristics (AMARAL, 2019).

Before embarking on I4.0 implementation, managers must assess their company's current state by evaluating its organizational capabilities for adopting I4.0 (RAFAEL *et al.*, 2020). This evaluation is typically conducted through readiness and maturity models (AMARAL, 2019), which help determine whether an organization is ready to begin implementing I4.0 or its current stage in the adoption process (ANGREANI; VIJAYA; WICAKSONO, 2024; MITTAL *et al.*, 2018; SAAD; BAHADORI; JAFARNEJAD, 2021). However, many of these tools are difficult to apply, requiring time and resources that MSMEs often lack (HÄRING; PIMENTEL, 2023). As a result, assessing MSMEs' readiness for I4.0 can be a significant challenge. Therefore, new methods and tools are required to guide MSMEs in preparing organizationally for these technologies, helping them navigate the uncertainties and challenges of I4.0 implementation (MITTAL *et al.*, 2018; SCHUMACHER; EROL; SIHN, 2016).

4.1.1 Research Gap

The literature reports various studies investigating critical success factors for implementing I4.0. For example, Rafael *et al.* (2020) developed an evolutionary roadmap to assist managers in successfully adopting these technologies. Khin and Kee (2022) examined the factors that enhance MSME readiness for digital transformation, emphasizing the need for strong internal capabilities. Das *et al.* (2020) studied critical factors related to favorable technological environments in developing countries, which positively influence the overall performance of MSMEs. Chonsawat and Sopadang (2020) defined readiness indicators for I4.0 in MSMEs in a literature review, highlighting leadership and infrastructure as crucial. Omrani et al. (2024) highlighted the importance of information technology infrastructure, corporate regulation, and financial resources as fundamental in preparation. Lastly, Jamwal *et al.* (2023) used a Fuzzy DEMATEL analysis to develop a framework for MSMEs to achieve sustainability by utilizing I4.0 technologies, emphasizing the need for infrastructure investments and top management support. However, these studies do not correlate the organizational factors of MSMEs with the increased use of I4.0 technologies.

The literature also reports on readiness and maturity models used to assess companies from various perspectives. For instance, models developed by Schuh (2020) and Schumacher (2016) are similar in that they are divided into levels and dimensions. Managers complete a questionnaire to evaluate their status concerning I4.0, receiving feedback on achieving higher levels. Nonetheless, these models often overlook the characteristics of smaller enterprises, lacking foundational levels for MSMEs with minimal maturity (MITTAL *et al.*, 2018). Mittal *et al.* (2018) identified these gaps and argued that a "level 0" should be established to address the specific needs of MSMEs. Haring and Pimentel (2023) took a similar approach for MSMEs' starting point. Subsequently, Amaral (2019) developed a specialized I4.0 maturity model tailored to MSMEs, incorporating a level 0. However, none of these models correlate organizational factors with the increased use of technologies. Moreover, they require time and resources for completion and analysis, which are often limited in MSMEs (KHAN *et al.*, 2021).

Although the importance of MSME readiness for digital transformation is well-established, understanding the factors that influence their preparedness for Industry 4.0 remains limited (KHIN; HUNG KEE, 2022). This is especially true in developing countries, where companies face numerous challenges—such as suboptimal operational scales, outdated technologies, and limited access to financing—despite their significant growth potential (ASCÚA, 2021; DAS; KUNDU; BHATTACHARYA, 2020). Studies frequently note that MSMEs encounter challenges in adopting I4.0 technologies due to a lack of technological expertise and constrained human and financial resources, leading to reluctance among owner-managers to invest (MULLER *et al.*, 2024). However, this reluctance can be mitigated under certain enabling conditions (ALAYON; SÄFSTEN; JOHANSSON, 2022). These conditions often involve organizational, technical, and social factors, all of which are crucial in preparing for I4.0 (CHONSAWAT; SOPADANG, 2020). Thus, this study's research question (RQ) is: **How do organizational factors influence the adoption of Industry 4.0 technologies in MSMEs?**

This study investigates how organizational, technical, and social factors influence the adoption of I4.0 technologies in MSMEs. Although there are existing studies on holistic models that include organizational, business, and technological factors, most of them only marginally support MSMEs in adopting I4.0 (CHONSAWAT; SOPADANG, 2020; DAS; KUNDU; BHATTACHARYA, 2020; KHIN; HUNG KEE, 2022; RAFAEL *et al.*, 2020). MSMEs know that something needs to be done, but they often do not know how or where to start (ASCÚA, 2021; INGALDI; ULEWICZ, 2020). Therefore, it is important to assess the readiness of MSMEs to implement I4.0 and to identify which organizational factors should be prioritized in this process (SAAD; BAHADORI; JAFARNEJAD, 2021).

This paper is structured as follows: Section 2 presents the literature review and hypothesis development, Section 3 outlines the methodological process, Section 4 discusses the results, Section 5 offers discussions, and Section 6 provides final considerations, including practical and theoretical contributions, limitations, and future research directions.

4.2 LITERATURE REVIEW

4.2.1 Theoretical Lens

Research on the adoption of new technologies has frequently utilized the Technology Acceptance Model (TAM) (MASOOD; SONNTAG, 2020). However, some studies suggest that TAM may not fully capture the complexity of emerging technologies, and relying solely on a single theoretical framework often falls short in comprehensively explaining technology adoption (KHIN; HUNG KEE, 2022). This study, therefore, draws on the Natural Resource-Based View (NRBV), which integrates the Resource-Based View (RBV) and the Dynamic Capabilities View (DCV) to explore how various organizational factors influence the adoption of new technologies (HELFAT; PETERAF, 2003).

The Resource-Based View (RBV) theory explains the relationship between resources and capabilities as a foundation for gaining competitive advantage (BARNEY; ARIKAN, 2008). While resources refer to the assets an organization possesses, capabilities pertain to what it can achieve with them. Competitive advantage arises not simply from possessing resources but from effectively utilizing human, physical, organizational, and financial assets to create value (CHAUHAN; SINGH; LUTHRA, 2021). The NRBV was developed to complement RBV, particularly with a focus on sustainable development (WERNERFELT, 1984). According to NRBV, organizations can develop capabilities like employee involvement, and the use of clean technologies to enhance core areas such as technological capability and organizational structure, thereby gaining a competitive edge (YAVUZ *et al.*, 2023).

To better explain competitive advantage, RBV and NRBV can be complemented by concepts from an evolutionary and dynamic perspective. The Dynamic Capabilities Theory (DCT) builds on RBV by suggesting that, beyond achieving competitive advantage, organizations must continuously integrate and reconfigure internal and external competencies to adapt to dynamic and uncertain environments (DÍAZ-CHAO; FICAPAL-CUSÍ; TORRENT-SELLENS, 2021). This dynamic approach supplements the traditionally static focus of RBV, making DCT particularly relevant for exploring digital transformation in traditional companies and preserving their competitive advantage (LIN; SHENG; JENG WANG, 2020).

This study proposes a research model tailored to MSMEs, integrating the NRBV and DCT frameworks to better understand the factors influencing their readiness for I4.0 implementation. The model identifies three key constructs: strategic, technical, and social factors. The authors argue that a company's practices across these organizational dimensions drive the adoption of new technologies.

4.2.2 Hypothesis Formulation

The first factor influencing the adoption of technologies is strategic. Research indicates that MSMEs with greater financial capacity are generally better equipped to implement digital processes (RAFAEL *et al.*, 2020). The availability of financial resources enables companies to independently secure the necessary tools and infrastructure without relying on government funding (KHIN; HUNG KEE, 2022). However, government support can still play a crucial role by allowing financially constrained MSMEs to make the necessary Investments (WONG; KEE, 2022), underscoring the fact that stronger financial capacity facilitates the adoption of I4.0 technologies.

Another important characteristic of MSMEs is that they are often family-owned, with major decisions concentrated in the hands of the owner (AMARAL, 2019). The literature highlights the critical role of top management's commitment in successfully implementing I4.0 (GONÇALVES *et al.*, 2024). Leadership must fully understand the importance of the transformation process and actively commit to aligning strategic goals with tactical and operational planning (AGOSTINI; NOSELLA, 2020; HÄRING; PIMENTEL, 2023). To drive the company towards achieving its strategic objectives, effective leadership must empower employees, foster innovation, and cultivate adaptable culture—all of which are vital to supporting the adoption of I4.0 technologies (MACHADO *et al.*, 2021).

A third factor is the need for MSMEs to develop a clear strategic vision of their goals and the steps required to achieve them, thus creating a roadmap for I4.0 adoption (WONG; KEE, 2022). Without a well-defined strategy, efforts may become fragmented and fail to meet the intended objectives, leading to frustration (BETTIOL *et al.*, 2023). The focus should extend beyond simply implementing Technologies (HEIN-PENSEL *et al.*, 2023). The strategy must permeate all levels of the organization—from setting process goals to fostering cultural change—in order to fully realize the benefits of I4.0 and ensure successful adoption (ANGREANI; VIJAYA; WICAKSONO, 2024; JAMWAL; AGRAWAL; SHARMA, 2023). Thus, the first hypothesis is:

H1: The better prepared MSMEs are regarding strategic factors, the more they implement Industry 4.0 technologies.

In addition to strategic considerations, MSMEs must also address technical factors in their preparation for I4.0. A key technical factor involves collaboration within the supply chain. Success in the context of I4.0 is increasingly dependent on collaboration, as isolated efforts often lead to limited outcomes (HÄRING; PIMENTEL, 2023). MSMEs are part of global manufacturing chains, so larger companies can assist MSMEs in the implementation process as they possess expertise in the field and can act as motivators, promoting sustainable practices and I4.0 technologies throughout their supply chains (SANTOS *et al.*, 2024).

Research on I4.0 strategies suggests that while companies may demonstrate commitment to adoption, they often lack clear, documented standards to guide their actions (KHANZODE *et al.*, 2021; LASSNIG *et al.*, 2018). This is particularly true for MSMEs, where investments cannot be driven solely by the novelty or cost of technology, as this may lead to unrealistic expectations and subsequent frustration (BETTIOL *et al.*, 2023). Instead, MSMEs should evaluate their organizational needs and develop a strategic, step-by-step plan to gradually implement I4.0 technologies in a structured manner (HÄRING; PIMENTEL, 2023).

Finally, infrastructure is a vital requirement for digitalization (CHONSAWAT; SOPADANG, 2020; OMRANI *et al.*, 2024). However, investments made by MSMEs in infrastructure often lack proper planning, failing to account for the requirements of new technologies, which negatively impacts their finances (KUMAR; SHARMA, 2024). The root of these challenges often lies in limited innovation capacity, which directly hampers their technological capabilities (GONÇALVES *et al.*, 2024). To better prepare for I4.0, MSMEs must prioritize upgrading their existing infrastructure to meet the technological requirements (WONG; KEE, 2022). Based on this, the second hypothesis is formulated:

H2: The better prepared MSMEs are regarding technical factors, the more they implement Industry 4.0 technologies.

The social aspect is the third factor that MSMEs should evaluate when implementing I4.0. MSMEs play a significant social role by providing young individuals with entry points into the job market, offering training and opportunities for both personal and professional development (BEIER; NIEHOFF; HOFFMANN, 2021). Therefore, a combination of diverse skill sets—including professional, social, IT, and personal skills—is essential for employees and contributes to the successful implementation of I4.0 (HÄRING; PIMENTEL, 2023).

Investing in the workforce is critical for MSMEs to attract and retain qualified employees, building teams with both technical expertise and strong interpersonal skills

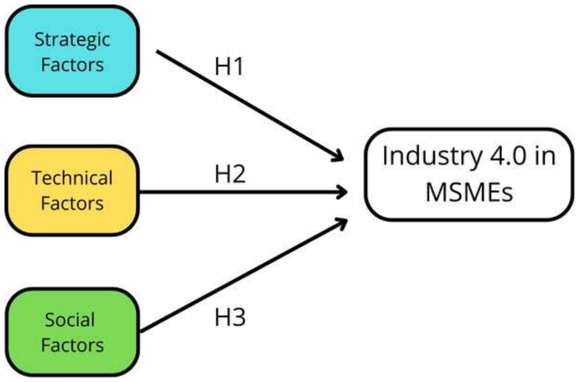
(ALAYON; SÄFSTEN; JOHANSSON, 2022; ASCÚA, 2021). Beyond recruitment, it is vital for MSMEs to offer training programs that prepare employees for the transition to I4.0, as these initiatives can lead to reduced production costs and increased productivity (JAMWAL; AGRAWAL; SHARMA, 2023; KHIN; HUNG KEE, 2022). Such training equips employees with the necessary knowledge to simplify the adoption of I4.0 technologies (GONÇALVES *et al.*, 2024).

Finally, when internal training is not feasible, MSMEs can establish dedicated teams to focus on I4.0 implementation (MITTAL *et al.*, 2018). The literature also emphasizes the importance of partnerships with consultants and university-led projects, which can facilitate the transition to I4.0 (FINDIK; TIRGIL; ÖZBUĞDAY, 2023). These collaborations are particularly valuable in overcoming the workforce limitations that many MSMEs face (ABDULAZIZ *et al.*, 2023). Furthermore, technology providers can offer holistic solutions, combining technological tools with training programs to ensure successful adoption of I4.0 technologies (GARZONI *et al.*, 2020; SANTOS *et al.*, 2024). This scenario leads to the third hypothesis:

H3: The better prepared MSMEs are regarding social factors, the more they implement Industry 4.0 technologies.

The conceptual framework and the relationships between the constructs in this study are developed using NRBV and DCT and are presented in Figure 14.

Figure 14 - Framework of Organizational Factors for Industry 4.0 Adoption in Micro, Small, and Medium Enterprises.



4.3 METHODOLOGY

4.3.1 Sampling

The sample was drawn from the Brazilian Association of Machinery and Equipment Manufacturers (ABIMAQ-Sul), which comprises 117 companies off various sizes, engaged in innovation and technology ecosystems. Given the limited personnel in MSMEs, the survey was directed to owners or individuals responsible for company operations, ensuring that respondents possessed comprehensive knowledge of both administrative and production processes (SANTOS *et al.*, 2024). A total of 80 completed online questionnaires were collected, resulting in a response rate of 68.37%.

4.3.2 Variables Definition

A questionnaire was developed based on the conceptual framework illustrated in Figure 14 to assess the level of adoption of organizational factors among MSMEs, categorized into strategic, technical, and social dimensions (Table 16). Additionally, the survey inquired about the implementation of I4.0 technologies to evaluate the influence of organizational factors on their adoption. The questionnaire also included a question on the number of employees to classify companies by size as micro, small, or medium enterprises. In Brazil, micro-enterprises employ up to 19 individuals, small enterprises up to 99, and medium enterprises up to 499 employees (SEBRAE, 2013).

The Likert scale, a commonly used method for measuring attitudes, was applied in the questionnaire (JAMWAL; AGRAWAL; SHARMA, 2023). The statements were organized into categories, with a consistent scale ranging from 1 (strongly disagree) to 5 (strongly agree) for assessing organizational factors, and from 1 (not at all) to 5 (to a full extent) for evaluating the adoption of I4.0 technologies (JAYASHREE *et al.*, 2021b). A higher score signified better organizational preparedness and a greater degree of I4.0 adoption. Additionally, a sixth option (“n/a”) was provided for respondents who were unsure or had no opinion on a statement.

Table 16 – Organizational Factors.

Code	Organizational Factors	Reference
STR_1	Financial Resources	(KHIN; HUNG KEE, 2022; SHARMA *et al.*, 2023)
STR_2	Leaders Trained	(AGOSTINI; NOSELLA, 2020; MACHADO *et al.*, 2021)
STR_3	Strategic Vision	(ANGREANI; VIJAYA; WICAKSONO, 2024; HEIN-PENSEL *et al.*, 2023)
TEC_1	Competitive Suppliers	(BIRKEL; MÜLLER; MULLER, 2021; LARDO *et al.*, 2020)

TEC_2	Implementation Model	(ALAYON; SÄFSTEN; JOHANSSON, 2022; KHANZODE *et al.*, 2021)
TEC_3	Equipment And Infrastructure	(CHONSAWAT; SOPADANG, 2020; MACHADO; WINROTH; DA SILVA, 2020)
SOC_1	Qualified Employees	(IAKOVETS; BALOG; ŽIDEK, 2023; JAYASHREE *et al.*, 2021b)
SOC_2	Training And Education Programs	(GHOBAKHLOO, 2020; JAMWAL; AGRAWAL; SHARMA, 2023)
SOC_3	Support Team for Implementation Process	(MITTAL *et al.*, 2018; SANTOS *et al.*, 2024)

To refine the questionnaire, interviews were conducted with 15 academics and seven industry professionals. The academics, members of research and development groups focused on I4.0 technologies, and the industry professionals, representing companies from ABIMAQ-Sul, helped ensure the questionnaire was aligned with the terminology and practices used in MSMEs (FRANK; DALENOGARE; AYALA, 2019).

4.3.3 Analysis Method

To mitigate common method bias (PODSAKOFF *et al.*, 2003), the order of the organizational factors was randomized to prevent respondents from linking them to a predefined sequence. Additionally, respondents were assured that no "correct" answers existed, further reducing the likelihood of response bias (WONG; KEE, 2022). Anonymity was emphasized through a cover letter accompanying the questionnaire.

To assess the presence of common method bias, Harman's single-factor test was conducted using exploratory factor analysis (FRANK; DALENOGARE; AYALA, 2019; WONG; KEE, 2022). The results indicated that a single factor explained 44% of the observed variance, demonstrating that no single factor dominated the variance. A significant issue would have arisen if this factor had explained more than 50% of the observed variance (DEY *et al.*, 2023).

4.3.4 Data Analysis

The first step in data analysis was to categorize companies based on their levels of organizational factors and examine how these levels influenced the adoption of I4.0. A two-step cluster analysis was performed to identify at least two distinct groups that could be compared to analyzing the correlation between organizational factors and technology adoption. Hierarchical clustering analysis (HCA) was initially conducted using Ward's method, with Euclidean distance as the similarity measure, to determine the optimal number of groups

(SILTORI *et al.*, 2021). In the second step, the clusters were refined using a non-hierarchical K-means clustering algorithm based on the variables that distinguished each group.

Following the cluster formation, a demographic analysis was conducted to explore whether the clusters displayed distinct patterns regarding organizational factors. Pearson's chi-squared test was applied to assess the null hypothesis that no relationship existed between the variables. This test compared observed values with expected values in a contingency table (YADAV *et al.*, 2020b). Rejecting the null hypothesis supported the idea that different patterns of organizational factor adoption exist, influencing I4.0 technology adoption.

Data processing and analysis were performed using the R statistical software. ANOVA was used to compare the means of organizational factors between clusters (p-value < 0.05), determining if the variances were statistically different (LASSNIG *et al.*, 2018). Finally, to identify which organizational factors are significant predictors of I4.0 adoption in MSMEs (Figure 14), logistic regression was employed based on Wang, Zhang & Guo (2021). As the dependent variable is ordinal, the ordinal multinomial logistic regression model is adopted for analysis, and the model is as Equation 1:

$$P(y = j|X_i) = \frac{1}{1+e^{-(\alpha+\beta X_i)}} \tag{1}$$

where X_i = the i^{th} indicator; y = the degree of organizational factions in MSMEs (ranging from 1 – Strongly Disagree to 5 – Strongly Agree). The cumulative logistic model is established as Equation 2:

$$Logit(P_j) = \ln[P(y \leq j)/P(y \geq j + 1)] = \alpha_j + \beta X \tag{2}$$

where P_j = P (y = j); j = 1, 2, 3, 4, 5; X = the influencing factor of I4.0 adoption level; a_j = a constant term; β is a set of regression coefficients corresponding to X. The probability of a particular situation (e.g. y = j) can be obtained by Equation 3:

$$P(y \leq j|X) = \frac{e^{-(\alpha+\beta X_i)}}{1+e^{-(\alpha+\beta X_i)}} \tag{3}$$

4.4 RESULTS

4.4.1 Industry 4.0 Adoption by Companies

Questionnaires from 80 companies were analyzed to assess the organizational factors influencing their operations. Responses to 11 questions were compiled in an Excel spreadsheet.

The findings revealed that 29% of respondents rated their company's adoption of I4.0 technologies as moderate, assigning a score of 3 on a 5-point scale. Respondents were asked to evaluate the extent of their company's implementation of technologies such as sensors, cloud computing, big data, and artificial intelligence, as well as their integration into software systems like Warehouse Management Systems (WMS) and Enterprise Resource Planning (ERP). Notably, only 6% of respondents indicated that I4.0 technologies were not implemented at all, suggesting relatively high levels of I4.0 adoption among the surveyed companies. Figure 15 presents a Pareto chart summarizing the survey results.

4.4.2 Assessing the Current Status of Organizational Factors

Figure 16 displays a dendrogram derived from hierarchical cluster analysis, using the organizational factors listed in Table 16 as selection criteria. The dendrogram visualizes the similarities between companies based on their adoption profiles across strategic, technical, and social dimensions. The analysis identified three distinct clusters, facilitating a clearer understanding of adoption patterns among the companies. More refined cluster divisions were avoided to prevent low representation due to the limited sample size (FRANK; DALENOGARE; AYALA, 2019).

Figure 15 – Pareto chart about Industry 4.0 adoption level

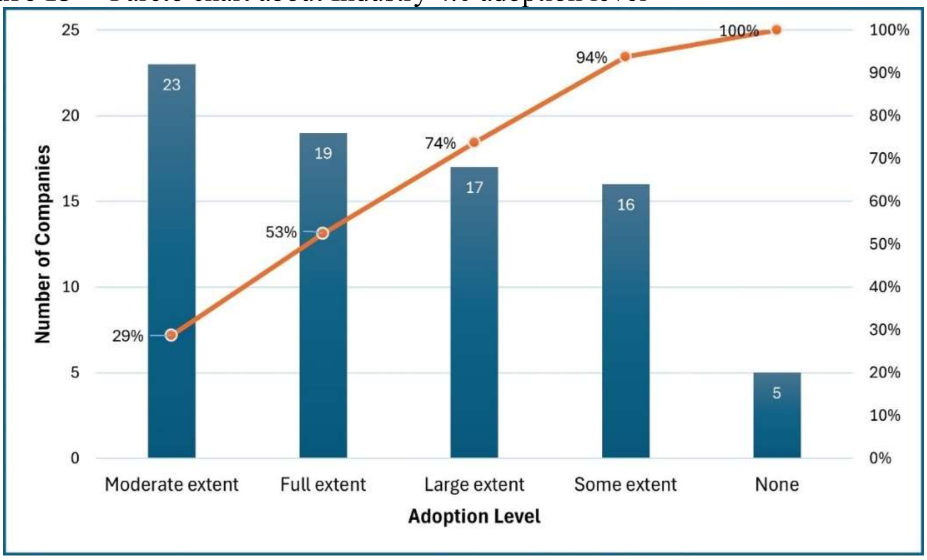
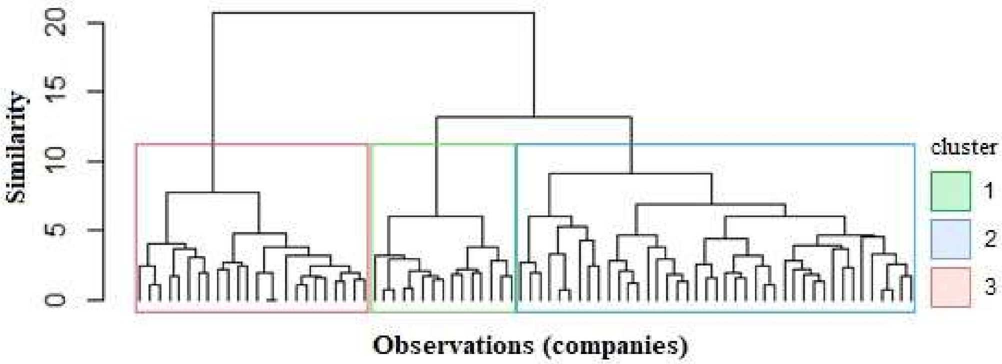


Figure 16 - Dendrogram for Determining the Number of Clusters



After determining the appropriate number of clusters, a K-means analysis was conducted to refine the cluster associations. Table 17 illustrates the contribution of each organizational factor to the cluster composition, along with the respective levels of I4.0 adoption. The average levels of organizational factors varied significantly across the three clusters, as indicated by the ANOVA F-values. Cluster 1, labeled as "Less Prepared," had low levels of adoption (≤ 3.00), Cluster 2, classified as "Moderately Prepared," exhibited higher levels (≤ 4.00), and Cluster 3, identified as "Most Prepared," displayed the highest levels of organizational factors (≥ 4.00). Furthermore, it was observed that larger companies tended to concentrate more on the advanced clusters, indicating a correlation between organizational preparedness and company size.

Table 17 - K-means results for cluster variables

Organizational Factors	Cluster Mean + S.D.						ANOVA F-value
	Cluster 1 *Less Prepared*		Cluster 2 *Moderately Prepared*		Cluster 3 *Most Prepared*		
STR_1	1.53	± *0.99*	3.14	± *1.28*	3.96	± *0.90*	20.37 ***
STR_2	2.30	± *0.72*	3.07	± *0.86*	4.14	± *0.64*	25.74 ***
STR_3	2.40	± *0.99*	3.42	± *1.01*	4.68	± *0.48*	30.83 ***
TEC_1	1.60	± *0.63*	3.14	± *1.06*	3.82	± *1.26*	20.07 ***
TEC_2	2.00	± *0.93*	3.28	± *1.08*	4.18	± *0.96*	20.45 ***
TEC_3	1.40	± *0.63*	3.05	± *1.02*	4.50	± *0.60*	58.41 ***
SOC_1	2.33	± *0.82*	3.09	± *0.84*	4.23	± *0.61*	28.50 ***
SOC_2	1.53	± *0.74*	2.07	± *0.91*	4.09	± *0.81*	53.03 ***
SOC_3	1.47	± *0.74*	2.65	± *1.07*	4.18	± *0.66*	41.27 ***
Industry 4.0	2.00	± *0.76*	3.28	± 0.98	4.46	± *0.86*	32.66 ***
Nº of companies	15		43		22		
Micro Size	6.7%		14.0%		13.6%		
Small Size	66.7%		37.2%		31.8%		
Medium Size	26.7%		48.8%		54.5%		

***p < 0.001

The results from the K-means analysis, shown in Table 17, reveal that higher levels of strategic, technical, and social organizational behaviors are linked to more advanced I4.0 technology implementation. Specifically, the most significant factors among top adopters were STR_3, TEC_3, and SOC_1. This highlights a strong interrelationship between organizational factors and technology adoption, with statistically significant differences between the clusters.

4.4.3 Evaluation of the Relationship Between Organizational Factors and Industry 4.0

Initially, Pearson's chi-squared test further confirmed the association between I4.0 adoption and the organizational factors of the companies (Chi-squared = 25.206, df = 2, p-value < 0.05). The analysis of adjusted standardized residuals indicated that companies in the "Less Prepared" (Cluster 1) category exhibited fewer instances of I4.0 adoption, while those in the "Most Prepared" (Cluster 3) category showed higher levels of adoption.

The second phase of analysis involved logistic regression to further investigate the relationship between organizational factors and I4.0 adoption. A p-value below 0.05 indicated a statistically significant relationship between the response variable (I4.0 adoption) and the predictor variables (organizational factors). Table 18 highlights that only STR_1, STR_3, TEC_1, and SOC_1 were statistically significant predictors of I4.0 adoption. These findings suggest that MSME managers should prioritize the development of these specific organizational factors to facilitate the smoother adoption of I4.0 technologies. Conversely, efforts directed toward other factors were not statistically significant and, therefore, should not be prioritized. The results partially support hypotheses H1, H2, and H3, as not all components of the strategic, technical, and social factors proved to be significant predictors of I4.0 adoption in MSMEs.

Table 18 – Logistic Regression Results for Organizational Factors

Characteristic	OR[1]	95% CI[1]	p-value
STR_1	1.702	1.131, 2.609	0.010*
STR_2	0.741	0.401, 1.333	0.300
STR_3	1.812	1.089, 3.060	0.022*
TEC_1	1.604	1.062, 2.455	0.025*
TEC_2	0.956	0.628, 1.457	0.800
TEC_3	1.184	0.737, 1.887	0.500
SOC_1	1.883	1.046, 3.476	0.035*
SOC_2	1.130	0.689, 1.859	0.600
SOC_3	1.013	0.621, 1.637	>0.90

[1] OR = Odds Ratio, CI = Confidence Interval. *p-value < 0.05

4.5 DISCUSSION

The findings of this study align with several suggestions from the existing literature. One prominent insight is that the extent of I4.0 implementation depends on company size, as proposed by Kagermann *et al*. (2013) and Schuh *et al*. (2020). Table 17 illustrates the relationship between company size and I4.0 adoption, showing that as companies grow, they tend to improve their organizational factors across the strategic, technical, and social dimensions. This relationship is even more evident in the higher concentration of medium-sized companies in Cluster 3. Implementing these factors demands substantial effort and the allocation of time and resources, including human and financial capital, which can pose challenges for micro and small enterprises (ABDULAZIZ *et al.*, 2023).

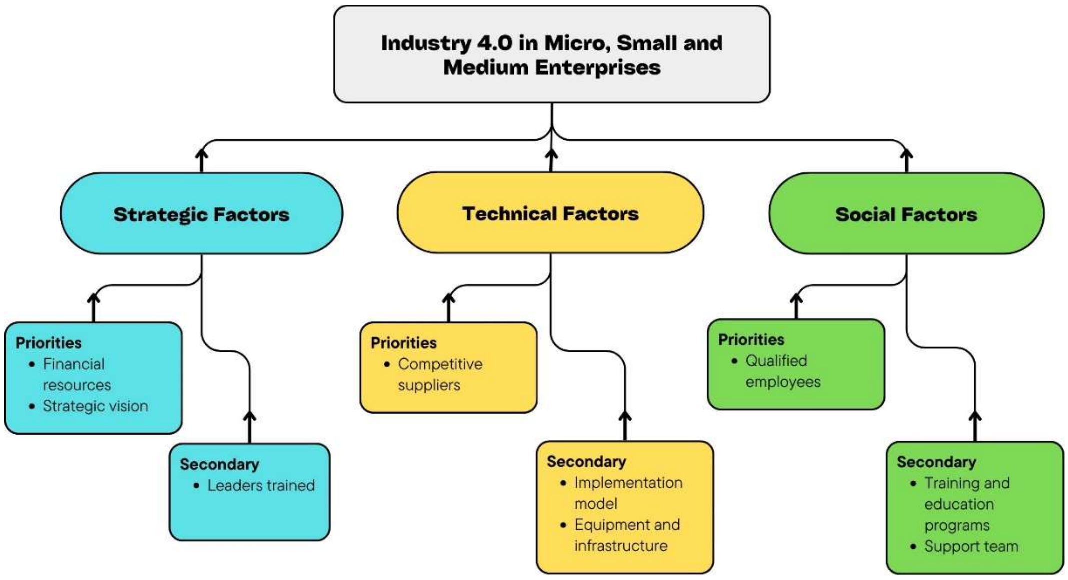
Table 17 also highlights the organizational factors where companies are most prepared: strategic vision (STR_3), adequate equipment and infrastructure (TEC_3), and qualified employees (SOC_1). These factors are critical for preparing MSMEs for I4.0 adoption. Strategic vision plays a pivotal role in directing company actions, and when top management prioritizes I4.0, this focus tends to permeate other sectors, leading to investments geared toward (WONG; KEE, 2022). Additionally, having the necessary equipment and infrastructure is fundamental for adopting I4.0. The literature suggests that while MSMEs require simple-to-implement solutions, a basic infrastructure is essential for technologies like sensors to be integrated effectively (JAYASHREE *et al.*, 2021b; MITTAL *et al.*, 2018). Moreover, qualified employees are crucial for implementing and operating new technologies (IAKOVETS; BALOG; ŽIDEK, 2023). Involving these employees in the I4.0 process not only facilitates adoption but also reduces resistance and enhances operational efficiency (AMARAL, 2019).

The Logistic Regression reveals that only **Financial Resources (STR_1)**, **Strategic Vision (STR_3)**, **Competitive Suppliers (TEC_1)**, and **Qualified Employees (SOC_1)** are statistically significant (p-value < 0.05) (see Table 18). The lowest scores in Cluster 3 for STR_1 and TEC_1 suggest that companies should prioritize these factors, as they directly impact their ability to adopt I4.0. Regarding financial resources (**STR_1**), MSMEs embarking on the I4.0 journey should assess their investment capacities and technological needs to avoid unnecessary expenditures (HÄRING; PIMENTEL, 2023; MITTAL *et al.*, 2018; RAFAEL *et al.*, 2020). Governments can support this process by formulating policies and regulations that promote I4.0 technologies, such as tax incentives, infrastructure investments, and training programs tailored to MSMEs (GONÇALVES *et al.*, 2024; ROXAS, 2021). Strategic vision (**STR_3**) highlights the importance of a focused approach to I4.0, with management evaluating the potential benefits of new technologies, particularly in areas related to sustainability and performance (GHOBAKHLOO, 2020; STOCK; SELIGER, 2016).

Competitive suppliers (**TEC_1**) underscore the need to leverage human and financial resources within the supply chain to strengthen the I4.0 ecosystem among participating firms (LARDO *et al.*, 2020; SANTOS; SANT'ANNA, 2024). Mittal *et al.* (2018) recommend that companies and industry associations organize workshops, consulting sessions, and collaborative projects that include academics and researchers to share success stories and innovative approaches to I4.0, thereby guiding smaller organizations (GARZONI *et al.*, 2020). Finally, qualified employees (**SOC_1**) remain a crucial factor in effectively utilizing these technologies. This entails building a specialized team equipped with the necessary skills, authority, and resources to achieve the company's I4.0 goals (ALAYON; SÄFSTEN; JOHANSSON, 2022).

The findings of this study are summarized in Figure 17, which outlines the key organizational factors from Tables 17 and 18, emphasizing those that are statistically significant predictors of I4.0 adoption in MSMEs. However, the decision was made not to exclude other organizational factors from the framework, as they are presented in the literature as potential influencers of I4.0 adoption. While they did not yield significant results in this sample, these factors tend to grow in importance as company size increases (Table 17). This framework can be compared with others in the literature (CHONSAWAT; SOPADANG, 2020; DAS; KUNDU; BHATTACHARYA, 2020; KHIN; HUNG KEE, 2022; RAFAEL *et al.*, 2020). The primary distinction is that this model is grounded in empirical evidence from MSMEs in a developing country, making it more applicable to companies that lack the resources to simultaneously invest in all organizational factors (DEY *et al.*, 2023).

Figure 17 - Framework with the Influencing of Organizational Factors Industry 4.0 Adoption in MSMEs



4.6 FINAL CONSIDERATIONS

This paper examines how strategic, technical, and social factors influence the adoption of I4.0 technologies in MSMEs. The findings support the premise that adopting I4.0 is shaped by the development of these three organizational dimensions. However, the analysis reveals that only specific factors within these dimensions should be prioritized, as they are the most significant predictors of I4.0 adoption. Given the limited resources of MSMEs, efforts should primarily target Financial Resources (STR_1), Strategic Vision (STR_3), Competitive Suppliers (TEC_1), and Qualified Employees (SOC_1), as these factors offer the greatest potential to facilitate I4.0 implementation. Once these key areas are addressed, attention can then shift to complementary factors.

Consequently, hypotheses H1, H2, and H3 were partially accepted, as not all factors were significant predictors in the logistic regression analysis. The results also confirm findings from previous literature, which suggest that as company size increases, so does the level of technology adoption (FRANK; DALENOGARE; AYALA, 2019). This suggests that larger companies are better positioned to implement I4.0 technologies due to their ability to allocate more resources—time, financial, and human—toward improving organizational factors.

4.6.1 Theoretical Contributions

The literature has already explored the use of I4.0 in MSMEs (ASCÚA, 2021; MITTAL *et al.*, 2018; MOEUF *et al.*, 2020; SANTOS *et al.*, 2024). However, this study is the first to reveal the positive relationship between the organizational factors of MSMEs and their level of I4.0 adoption (WONG; KEE, 2022), underscoring the importance of dedicating time and resources to organizational readiness for successful implementation.

Several studies have suggested organizational factors companies should implement to adopt I4.0 (CHONSAWAT; SOPADANG, 2020; DAS; KUNDU; BHATTACHARYA, 2020; KHIN; HUNG KEE, 2022; RAFAEL *et al.*, 2020). However, these studies often do not specify which factors should be prioritized or empirically demonstrate the direct relationship between organizational development and implementation of I4.0. This study fills that gap, providing a significant contribution to literature by offering a conceptual framework (Figure 17) that researchers can use to analyze organizational factors. The organizational factors examined here are practical for MSMEs to implement because they are within the companies' control, use accessible language, and have clear, achievable objectives.

Finally, this study contributes by exploring the challenges faced by MSMEs in developing countries—an underexplored area, as most existing research focuses on developed nations and larger enterprise (SHARMA; JABBOUR; LOPES DE SOUSA JABBOUR, 2020).

4.6.2 Practical Contributions

The results of this study offer valuable insights for companies seeking to implement new technologies, particularly in the context of I4.0 adoption. First, the study emphasizes that MSMEs should begin their I4.0 journey by preparing and planning around three key groups of factors: strategic, technical, and social (KHIN; HUNG KEE, 2022). This is essential because managers often face challenges in understanding how to effectively prepare their organizations for these technologies and what requirements need to be met to avoid failure (BETTIOL *et al.*, 2023). The proposed framework in this study can help managers identify which factors are already in place and which require further development. The framework can also serve as a maturity model, guiding managers as they progress toward achieving I4.0 adoption in MSMEs.

The study further highlights the importance of aligning with supply chain partners to strengthen the overall ecosystem. As competition now extends beyond individual companies, organizations must collaborate to reinforce management practices and improve the competitiveness of the entire sector (BIRKEL; MÜLLER; MULLER, 2021; LARDO *et al.*, 2020). Additionally, financial resources are identified as a priority for consolidating I4.0 within MSMEs—a significant barrier frequently discussed in the literature (INGALDI; ULEWICZ, 2020; KHANZODE *et al.*, 2021). Companies, governments, and the banking sector need to work together to create financing and investment alternatives that facilitate the adoption of I4.0 technologies in MSMEs (ABDULAZIZ *et al.*, 2023; KHAN *et al.*, 2021; MACHADO; WINROTH; DA SILVA, 2020). Moreover, governments can use these organizational factors as benchmarks when awarding benefits, ensuring that MSMEs meet specific governance prerequisites to qualify for assistance.

4.6.3 Limitations

This research acknowledges several limitations, which suggest opportunities for future studies. First, the analysis is based on a sample from a specific industrial sector with unique characteristics, potentially limiting the generalizability of the findings. Future research could be extended to other developing countries, or different regions and industrial sectors within Brazil, to validate and expand upon these results. Furthermore, while the study identified the key organizational factors necessary for MSMEs to adopt I4.0, it did not provide guidance on how to develop these factors within companies. Therefore, future research could focus on methodologies that assist MSMEs in enhancing their organizational readiness. Finally, this study focused solely on manufacturing companies, leaving room for future studies to examine I4.0 adoption in service-based MSMEs, further enriching the understanding of digital transformation across different business models.

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5 INDUSTRY 4.0 AS AN ENABLER OF SUSTAINABILITY FOR SMALL AND MEDIUM ENTERPRISES

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Abstract

Purpose – This paper aims to investigate the potential impact of Industry 4.0 digital technologies on promoting sustainability in small and medium-sized enterprises (SMEs) within developing economies such as Brazil. Additionally, we present a comprehensive framework that consolidates this correlation.
Design/methodology/approach – Qualitative research was conducted through semi-structured interviews with leaders of SMEs to identify the specific challenges in achieving sustainability. Additionally, interviews were conducted with technology provider firms to evaluate the existing solutions available to SMEs. The interview results were analyzed, and technological solutions were proposed through a focus group session involving four experts in Industry 4.0. These proposed solutions were then compared with the offerings provided by the technology providers. Based on this, a second round of meetings was conducted to gather feedback from the SMEs.
Findings – The findings of this study confirm the feasibility of implementing Industry 4.0 and sustainable practices in SMEs. However, it is crucial to tailor the technologies to the specific circumstances of SMEs. The study presents propositions on how specific applications of technology can address the economic, environmental, and social demands of SMEs. Furthermore, a framework is proposed, emphasizing the integration of smart technologies as essential components across sustainability dimensions.
Originality/value – This study makes a significant contribution to the current body of literature as it pioneers the examination of the relationship between Industry 4.0 technologies and sustainability, focusing specifically on SMEs in a developing country context.
Keywords: Manufacturing Industry; SME; Entrepreneurship; Sustainable Development; Technology Adoption
Management Area: Strategy and Entrepreneurship
Paper-Type: Research Paper

5.1 INTRODUCTION

The Industry 4.0 (I4.0) is characterized by a set of advanced digital technologies that work together to improve performance in the short term, but also impact sustainability in the long term (GHOBAKHLOO, 2020). Several models have been proposed in the literature to explain I4.0, and one of the most popular is the model for operations management proposed by Frank *et al*. (2019). These authors suggest that I4.0 technologies can be divided into four smart dimensions: smart manufacturing, smart working, smart supply chain, and smart products and services, which are supported by four base technologies: the Internet of Things (IoT), Cloud Computing, Big Data, and Analytics. However, this model overlooks the influence of I4.0 on sustainability for small and medium enterprises (SMEs) context.

Previous industrial revolutions failed to measure the environmental and social impacts (TSENG *et al.*, 2018). This is even more problematic when considering SMEs (ABDELWAHED; SOOMRO; SHAH, 2022). These companies are important actors in the social and economic growth of countries, as they employ many people. However, when it comes to sustainable development, SMEs tend to neglect their impacts (ALAYON; SÄFSTEN; JOHANSSON, 2022). In this context, the literature highlights the convergence of I4.0 and sustainability (BAI *et al.*, 2020; EJSMONT; GLADYSZ; KLUCZEK, 2020; STOCK; SELIGER, 2016). However, this relationship tends to focus on a particular sustainability dimension or a single I4.0 technology, without considering the specificities of SMEs (MUKHUTY; UPADHYAY; ROTHWELL, 2022). These challenges encompass limitations in investment capacity, a dearth of expertise, and resistance among employees (MOEUF *et al.*, 2020).

While the significance of both I4.0 and sustainability for SMEs is widely acknowledged (BAI *et al.*, 2020; EJSMONT; GLADYSZ; KLUCZEK, 2020; KUNKEL; MATTHESS, 2020), these subjects are frequently approached independently in research (DENICOLAI; ZUCCHELLA; MAGNANI, 2021). When these topics are examined collectively, existing studies primarily concentrate on addressing barriers related to digitalization and sustainability within SMEs (KHANZODE *et al.*, 2021; KUMAR *et al.*, 2023) or identifying factors that facilitate technology adoption by SMEs (JAYASHREE *et al.*, 2021b). However, these studies typically lack practical examples illustrating how these technologies can achieve sustainability goals or how they can be tailored to the specific needs of SMEs (CHEGE; WANG, 2020; LOPES DE SOUSA JABBOUR; NDUBISI; ROMAN PAIS SELES, 2020; MITTAL *et al.*, 2018).

The literature tends to overlook the distinct requirements of SMEs, particularly in developing nations like Brazil, where research in this area remains limited (COSTA MELO *et al.*, 2023b; JAYASHREE *et al.*, 2021a). These countries are still in the early stages of digitization and encounter obstacles such as restricted investments, a shortage of skilled labor, digital infrastructure, education and economic challenges, as well as issues related to political security and uncertainty (ASCÚA, 2021; DOSSOU *et al.*, 2022; JAYASHREE *et al.*, 2021a). Therefore, the question remains: ***How can the digital technologies of Industry 4.0 promote sustainability within the context of SMEs in a developing country like Brazil***?

To investigate this research question, we conducted qualitative research by interviewing leaders of multiple SMEs across various industrial sectors, as well as technology provider firms that cater to SMEs. The results indicate that digital technologies have significant potential in helping SMEs achieve sustainability goals, including creating safer work environments, reducing waste, and increasing productivity. However, it is essential for these technologies to align with the specific requirements of SMEs, focusing on ease of implementation and cost-effectiveness to encourage adoption.

This paper aims to investigate the potential impact of Industry 4.0 digital technologies on promoting sustainability in SMEs within developing economies such as Brazil. As theoretical contributions, we propose a framework that consolidates smart technologies tailored to SMEs requirements for achieving sustainability. Furthermore, the paper outlines propositions that illustrate how I4.0 technologies can assist SMEs in addressing sustainability challenges. In terms of practical implications, this work serves as a valuable guide for SMEs managers in emerging economies. It assists them in navigating the digitalization process to make advancements in social, environmental, and economic aspects.

The structure of this paper is as follows. The next section examines the correlations between SMEs, sustainability, and Industry 4.0. Section 3 provides a summary of the research methodology. The analysis of interviews and technological propositions for sustainability in SMEs, along with the consolidated framework, is presented in Section 4. Finally, Section 5 presents conclusions drawn from the research and discusses the implications, limitations, and potential future research directions.

5.2 LITERATURE REVIEW

5.2.1 Sustainability in Small and Medium Enterprises

Sustainable manufacturing involves the integration of processes that can produce high-quality products and services while using fewer natural resources, ensuring safety for stakeholders, mitigating environmental and social impacts, and maintaining economic benefits throughout the life cycle (MACHADO; WINROTH; DA SILVA, 2020). To better track their objectives, sustainability is divided into three dimensions: economic, social, and environmental, known as the Triple Bottom Line (TBL) (LOPES DE SOUSA JABBOUR; NDUBISI; ROMAN PAIS SELES, 2020). While larger companies may have greater visibility and face more pressure from stakeholders to implement sustainable processes, many of the concerns about environmental impacts come from SMEs (CHEGE; WANG, 2020).

The sustainability impact of SMEs is often disregarded due to their smaller size and revenue. However, despite their individual scale, their collective influence surpasses that of larger organizations (LOPES DE SOUSA JABBOUR; NDUBISI; ROMAN PAIS SELES, 2020). Surprisingly, SMEs account for a significant share, generating up to 70% of global pollution and employing over 60% of the global workforce (WSF, 2022). This emphasizes the pressing need to address their sustainability contributions (NDUBISI; ZHAI; LAI, 2021). To facilitate the implementation of sustainable practices within SMEs, a unified standard and tailored tools are essential to their unique context. Such an approach would conserve resources, simplify implementation complexities, and promote broader adoption (CHEGE; WANG, 2020; CHOWDHURY; SHUMON, 2020).

Among the challenges hindering sustainability implementation in SMEs are several key hurdles: a lack of awareness regarding the associated impacts and benefits of sustainability, scarcity of time and resources, and a deficiency in skills and expertise (JOURNEAULT; PERRON; VALLIÈRES, 2021). Moreover, there is a prevailing perception among managers of limited financial gains from environmental investments (CHOWDHURY; SHUMON, 2020). Alayon *et al*. (2022) also highlight the significant obstacle of insufficient training among employees and SME managers in sustainable manufacturing. Despite these obstacles, research indicates that integrating sustainable practices can yield favorable outcomes for small enterprises. This includes improved productivity, decreased waste, and more efficient use of raw materials (EWEJE, 2020). Additionally, digital technologies can serve as crucial tools for monitoring and control, empowering SMEs to better manage their sustainability objectives

(CHEGE; WANG, 2020). Few studies, however, comprehensively explore the three pillars of sustainability while considering the specific characteristics of SMEs (LOPES DE SOUSA JABBOUR; NDUBISI; ROMAN PAIS SELES, 2020). Nonetheless, it remains crucial to delve into the applications of these technologies, particularly for SMEs in developing nations (ALAYON; SÄFSTEN; JOHANSSON, 2022; GHOBAKHLOO *et al.*, 2021; MACHADO *et al.*, 2021).

5.2.2 Digital technologies for Small and Medium Enterprises

Industry 4.0 is a complex and structured model that encompasses various interconnected technologies in real-time with manufacturing processes and services, providing data for informed decision-making (FRANK; DALENOGARE; AYALA, 2019). To classify and converge the various Industry 4.0 technologies, Frank *et al*. (2019) proposed a theoretical framework divided into four smart dimensions: (i) the smart manufacturing dimension includes technologies for product processing, such as tools for vertical integration, virtualization, automation, traceability, flexibility, and energy management; (ii) the smart products and services dimension includes product-related technologies with smart components that enable digital services; (iii) the smart supply chain dimension considers technologies that support the horizontal integration of the factory with external suppliers and customers; (iv) finally, the smart working dimension includes technologies that support workers' tasks, optimizing health, safety, and productivity. These are supported by foundational technologies such as IoT, Cloud Computing, Big Data, and Analytics, which provide connectivity and intelligence.

Despite their crucial role in fostering industrial growth in developing countries, SMEs often encounter obstacles when it comes to embracing advanced technologies. These barriers include insufficient capital for investment, outdated infrastructure, and limited access to education (DE LUCAS ANCILLO *et al.*, 2022; INGALDI; ULEWICZ, 2020). After a pertinent literature review, it was found that one of the most observed strategies for adopting I4.0 in SMEs is production control and monitoring through software, such as modules of Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP). These are integrated with IoT sensors and connectivity, capable of monitoring machines and scanning products (MITTAL *et al.*, 2020). Cloud computing is another technology widely applied in SMEs, with software that offers personnel, production, and accounting management systems (ASCÚA, 2021). However, cyber-physical systems and Machine-to-Machine communication are rarely explored by SMEs due to the high investments required (MOEUF *et al.*, 2018). Table

19 presents the main reported applications of 4.0 technologies in SMEs found in the literature. However, it is necessary to identify how they can contribute to sustainability in these companies.

Table 19 - Applications of 4.0 technologies in Small and Medium Enterprises

	Technology	Application	Reference
Smart Manufacturing	Actuators, sensors, IoT components	Real-time production control and machine utilization.	(KUMAR; SINGH; DWIVEDI, 2020; MITTAL *et al.*, 2020)
	Cloud Computing	Access to data from different electronic devices and document sharing.	(ASCÚA, 2021; CHEN, 2019; MITTAL; ROMERO; WUEST, 2018; MOEUF *et al.*, 2018)
	Additive Manufacturing	Product prototypes and component manufacturing.	(ASCÚA, 2021; KAARTINEN; PIESKA; VAHASOYRINKI, 2017)
	Big Data	Marketing and after-sales tasks and generating information for smart systems on the shop floor.	(ASCÚA, 2021; DUTTA *et al.*, 2020)
	MES/ERP	Vertical integration with factory sectors.	(TABIM; AYALA; FRANK, 2021)
	Simulation	Scenario-based simulation.	(KAARTINEN; PIESKA; VAHASOYRINKI, 2017; MOEUF *et al.*, 2018)
	Advanced robotics	Automation of production areas.	(DUTTA *et al.*, 2020; KAARTINEN; PIESKA; VAHASOYRINKI, 2017; MITTAL *et al.*, 2018)
Smart Products and Services	Artificial Intelligence	Enhancing user experience by facilitating product customization.	(KAPPES; NESTOR FABIAN, 2023)
Smart Supply Chain	Digital systems and platforms	Real-time sharing of inventory management data.	(KAPPES; NESTOR FABIAN, 2023)
Smart Working	Augmented and Virtual Reality	Used for training and maintenance.	(DORNELLES; AYALA; FRANK, 2022)
	Environmental Sensors	Workplace monitoring to prevent unhealthy conditions.	(DORNELLES; AYALA; FRANK, 2022)
	Computational Vision	Quality control and monitoring.	(DORNELLES; AYALA; FRANK, 2022)

5.2.3 Digital technologies and Sustainability

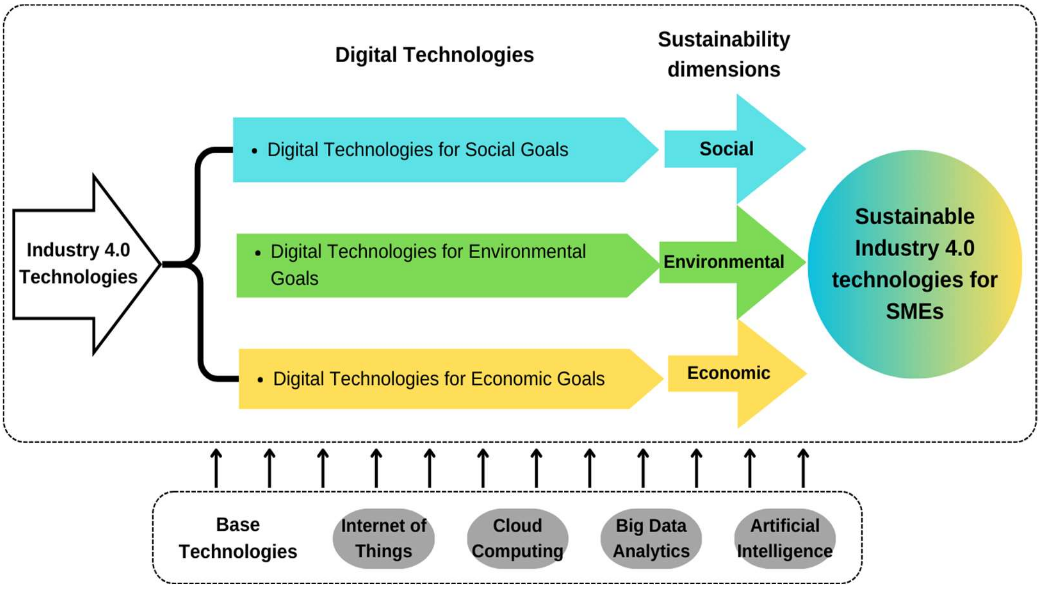
Even though I4.0 models for large and small firms (FRANK; DALENOGARE; AYALA, 2019; MITTAL *et al.*, 2020; SCHUH *et al.*, 2020) are well-known, they often fail to consider sustainability aspects. For example, Kamble *et al*. (2018) conducted a systematic literature review and proposed a framework that integrates I4.0 with sustainability tools to achieve TBL goals. Similarly, Ejsmont *et al*. (2020) proposed a Sustainable I4.0 reference framework that serves as a manual and guideline for I4.0. Finally, Bai *et al*. (2020) utilized fuzzy logic to identify technologies that could have the most impact on sustainability, with mobile technology standing out. However, these studies do not consider the specificities of SMEs. One of the earliest works to mention SMEs was the literature review study by Stock and

Seliger (2016), although they only referred to SMEs as a field of future study of I4.0 and sustainability. In this context, Brozzi *et al*. (2020) investigated the driving factors for companies, including SMEs, to adopt sustainable-focused I4.0 technologies. They found that the main motivators are economic aspects, while social and environmental aspects are neglected. However, they do not specifically address technologies and their applications in the routine of SMEs.

The literature has already identified some benefits of using I4.0 technologies for sustainability. From an environmental perspective, they include better resource utilization (INGALDI; ULEWICZ, 2020), increased energy efficiency, and reduced waste and CO2 emissions (BAI *et al.*, 2020). From an economic perspective, I4.0 offers more accurate planning, lower lead times (EJSMONT; GLADYSZ; KLUCZEK, 2020), and increased productivity (FRANK; DALENOGARE; AYALA, 2019). From a social perspective, I4.0 can provide a more comfortable workspace (EJSMONT; GLADYSZ; KLUCZEK, 2020), assist employees in terms of health and safety (BAI *et al.*, 2020).

Therefore, this analysis is particularly important in developing country, like Brazil, where these discussions are limited (KUNKEL; MATTHESS, 2020). To analyze how the I4.0 can contribute to the sustainability of SMEs, this paper presents the propose dual framework that maintains the structure of the four base technologies, considering sustainability focus for small and medium enterprises context, as depicted in Figure 18.

Figure 18 - Conceptual framework for Industry 4.0 as an enabler of sustainability for Small and Medium Enterprises



5.3 RESEARCH METHOD

To make the elements of the conceptual framework shown in Fig. 18 clearer, it is used a qualitative approach guideline from Voss *et al*. (2002), which we will describe next.

5.3.1 Case Study Selection

We used theoretical sampling to select the cases for our study, meaning we chose cases that were particularly suited to shed light on the constructs we were interested in (EISENHARDT; GRAEBNER, 2007). We intentionally selected SMEs from different industry segments to produce contrasting results that could offer a broader overview of the phenomenon and facilitate the generalization of our findings. In Brazil, small companies are defined as having up to 99 employees, while medium-sized companies have up to 500 employees (SEBRAE, 2013). Using this criterion, we reached out to companies participating in an innovation program focused on productivity, which is a Brazilian service designed to support SMEs. The primary goal of this program is to boost SMEs' productivity through the monitoring of key performance indicators of the companies involved.

As a first step to identify companies for our study, we conducted a survey on the implementation of innovative technologies and sustainability practices. The survey was carried out with 125 participants in the innovation program in the state of Rio Grande do Sul, Brazil. From this initial group of companies, we refined our selection to only include manufacturing companies with industrial processes that use or could use technologies to improve performance indicators and benefit from sustainable practices. This resulted in a total of 35 companies. From this group, we've reached a final list of 16 industries across diverse sectors that have agreed to participate in our research. They possess the potential to offer valuable insights, aiding our understanding of how technologies can optimize sustainable practices within SMEs. Table 20 provides a brief description of the selected cases. To preserve anonymity, we adopted codenames to represent the names of companies and respondents.

Table 20 - Background of the cases

Case Company	Nº of employees	Sector	Interviewer's role
ClothingCo1	8	Clothing	Owner
ClothingCo2	5	Clothing	Owner
ClothingCo3	15	Clothing	Production Manager
ClothingCo4	5	Clothing	Production Manager

FoodCo1	6	Food	Owner
FoodCo2	5	Food	Owner
FoodCo3	5	Food	Production Manager
FoodCo4	5	Food	Production Manager
MetalCo	80	Metal	Plant Manager
BagCo	10	Rubber and Plastic	Co-owner
PlasticCo	15	Rubber and Plastic	Owner
ChemicalCo	11	Chemicals	Owner
NauticalCo	6	Nautical	Owner
BeerCo	12	Beverage	Owner
ChairCo	99	Machines and Equipment	Technology Director
MedicalCo	98	Electric machines	Technology Director

In addition to the case studies listed in Table 20, we conducted interviews with technology providers who offer solutions related to I4.0 and have SMEs as their customers. In total, we interviewed eight technology providers, more information about these interviews is provided in Table 21.

5.3.2 Research Instruments and Data Collection Procedures

We used semi-structured interviews as the main data collection method to identify the potential of technologies for improving productivity and sustainable practices. Our approach aimed to delve deeply into the perceptions of local participants, fostering an empathetic understanding of the discussed topics from an insider's viewpoint (MILES; HUBERMAN; SALDAÑA, 2014). An initial version of the interview script was tested with two participants from different companies and then revised before conducting the main interviews, it can be seen in Appendix B. The questions focused on identifying the operational and management practices of the companies to understand their sustainable impact, and to identify the challenges that could be overcome with the help of I4.0 technologies.

We conducted semi-structured interviews with key representatives of SMEs, such as production managers and owners. We did not interview employees from non-technical or peripheral areas. Therefore, due to the limited number of people in management positions in these companies, we could not interview more than one representative per organization. Each interview lasted approximately one hour and was conducted via videoconference. Additionally, we interviewed representatives from companies that provide technological solutions associated with I4.0 and serve SMEs as customers, including Chief Executive Officer (CEO) (Table 21). These representatives are involved in diagnosing and implementing new technologies in SMEs and have a good understanding of their main demands. During the interviews, we asked about existing technologies, how they were offered to SMEs, and what objectives they aimed to achieve.

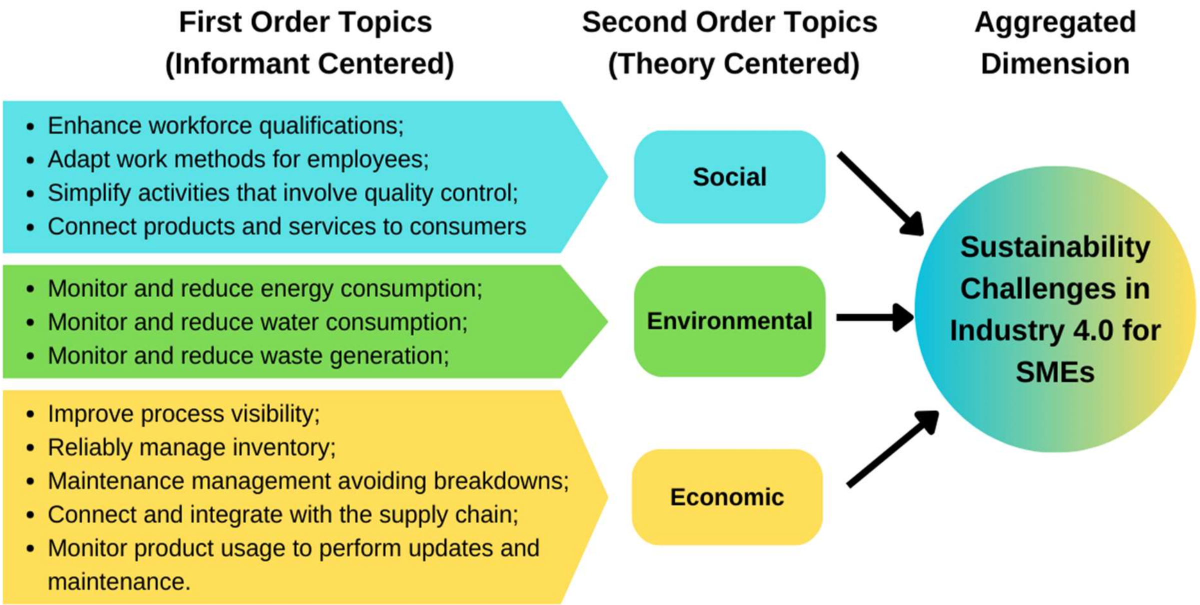
Table 21 - Technology providers

Institution/Company	Role	Technology Offered
Supplier 1	Product Manager	ERP; MES; Warehouse Management Systems (WMS); Artificial Intelligence; Cloud Computing.
Supplier 2	Development Director	Artificial Intelligence; IoT; Automation Technology; Horizon, and Vertical Integration.
Supplier 3	Development Manager	ERP; Simulation; Supply chain Cloud.
Supplier 4	Regional ecosystem executive	Cybersecurity; Predictive analytics; Cloud Computing; IoT; ERP systems.
Supplier 5	CEO	IoT; Cloud Computing; Computational Vision.
Supplier 6	CEO	Artificial Intelligence; IoT; Vertical Integration.
Supplier 7	CEO	WMS and MES.
Supplier 8	CEO	Computational Vision; Artificial Intelligence.

During data collection, we recorded the interviews and took notes on the participants' impressions and comments. Three researchers, including the authors of this paper, made these notes to provide a more comprehensive view of each case and minimize observer bias (YIN, 2018). To understand the phenomenon in question, we adopted a data triangulation approach, which involves using different data collection sources (VOSS; TSIKRIKTSIS; FROHLICH, 2002; YIN, 2018). To enable data triangulation, we also reviewed documents made available by the companies, including internal procedures and information from their websites.

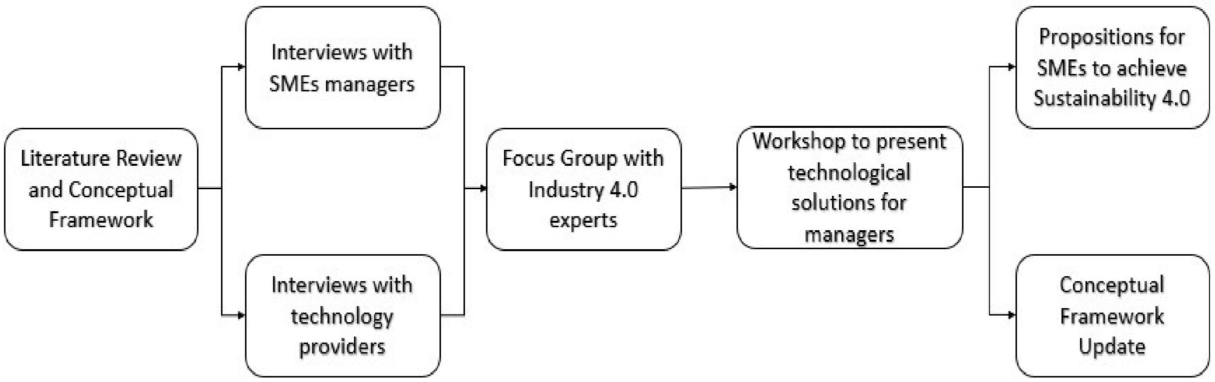
To analyze the results of the interviews, a focus group session was conducted with four experts in Industry 4.0. The aim was to understand the challenges and realities faced by the 16 companies. The researchers presented the interview notes and reports to the experts, who collectively identified the feasible technologies to facilitate sustainability through a group discussion. The Gioia *et al*. (2013) method was used, which involved aggregating passages in the interview transcripts into first-order informant-centric concepts and then grouping them in a theory-centric manner. Twelve concepts were identified, as shown in Figure 19, which was based on relevant literature (MACHADO; WINROTH; DA SILVA, 2020). These aggregated dimensions formed the basis for discussing the main problems and proposing technological solutions.

Figure 19 - Identification of Main Challenges of Small and Medium Enterprises



Afterwards, the experts suggested technologies that could be implemented by these companies to tackle sustainability challenges. These proposals were compared to the solutions presented by the technology providers interviewed to verify whether they are commercially viable and if their products are adaptable to the realities of SMEs. Based on this, a second round of meetings in the form of a workshop was conducted with the same 16 companies, where solutions were presented, discussed, and feedback was collected about the suitability and applicability of the proposed solutions. The methodological stages of the research are illustrated in Figure 20.

Figure 20 - Methodological stages of the research

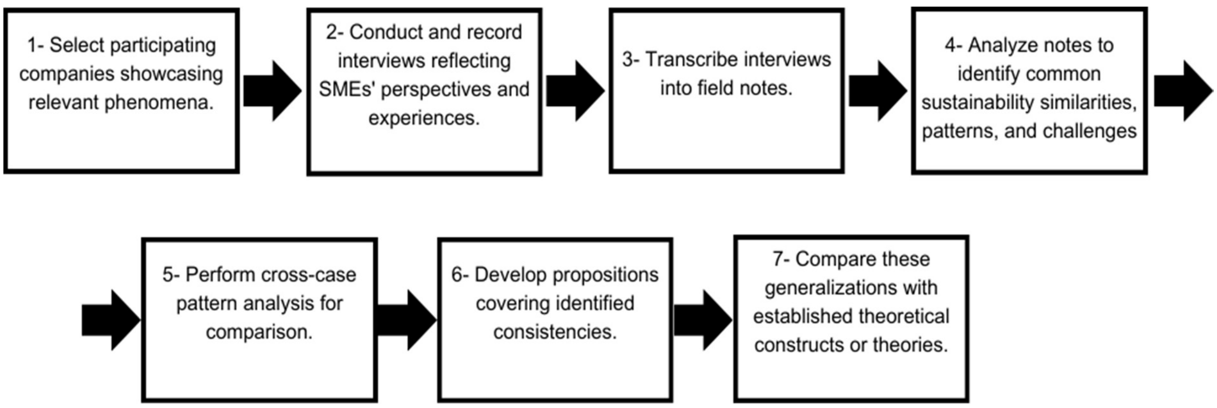


5.3.3 Data Analysis - Validity, Reliability, and Interpretation

To ensure construct validity, the questionnaire used in semi-structured interviews was reviewed and refined by four I4.0 specialists who were not involved in data collection. Additionally, the questionnaire was fine-tuned after conducting the first round of interviews with two companies. It uses crafted questions in a uniform sequence for comparability across respondents (PATTON, 2014). To establish external validity, we conducted multiple case studies and compared the evidence of SMEs that adopted I4.0 technologies to improve sustainability (VOSS; TSIKRIKTSIS; FROHLICH, 2002). Analyzing various cases enhances generalizability, ensuring that observed events are not singular occurrences (MILES; HUBERMAN; SALDAÑA, 2014).

To ensure reliability, we followed a case study protocol presented in Figure 21 (MILES; HUBERMAN; SALDAÑA, 2014; PATTON, 2014), and a final report was created based on transcriptions of the recorded interviews. For data analysis and interpretation, the first step was transcribing the recorded interviews, which were then analyzed to identify potential applications of technologies for sustainability. The findings were organized in a final report, and a cross-case analysis was conducted. We then conducted a second round of interviews with the same participants to report our conclusions and gather feedback. This workshop served to validate the coherence of our results from an external perspective of the managers. Finally, we compared the results of the cross-case analysis with the literature and developed a final theoretical framework based on our conceptual model, which improved the research framework shown in Fig. 18.

Figure 21 - Case study protocol



Adapted from (MILES; HUBERMAN; SALDAÑA, 2014; PATTON, 2014)

5.4 RESULTS AND DISCUSSIONS

The data gathered from the interviews has provided valuable insights into the primary challenges that companies face in achieving sustainable objectives and the technologies that can facilitate this process, particularly within the context of SMEs. In this section, we will identify and describe these challenges, using the conceptual research framework outlined in Figure 18, which encompasses each dimension of sustainability.

5.4.1 Social Dimension

The main challenge reported in the literature for SMEs to achieve social sustainability is to enhance workforce qualifications by making better use of employees' mental and physical abilities in their activities (ALAYON; SÄFSTEN; JOHANSSON, 2022). This challenge is also observed in the companies studied, as MetalCo stated, "*We face a major training challenge, making sure that employees understand and use new technologies.*" According to experts, the most recommended technologies to assist SMEs in this regard are virtual and augmented reality, which provide innovative and safer training methods that can enhance the speed of learning. These technologies can also provide additional information to workers, such as identifying hazardous areas or risky actions, thereby improving workplace safety (BELTRAMI *et al.*, 2021; GHOBAKHLOO, 2020).

The experts indicated that the solution involves aspects beyond technology, such as implementing an integrated human capital management approach. This includes extracting information and data about employees to assist in offering career plans, skill development, and utilizing technology for training and recruitment purposes (GHOBAKHLOO, 2020). Therefore, Supplier 1 offers a Human Experience Management, which includes gamification tools and virtual or hybrid learning paths. This Smart Working Technology is customizable as each company has its own specific production processes.

The second challenge for SMEs to achieve social sustainability involves adapting work methods and positions to make them safer, more comfortable, and ergonomic. In the investigated companies, it was observed that many activities are still performed manually, underutilizing employees. Some examples of these tasks include peeling onions and cleaning ovens. Moreover, there are situations that put employees at risk, as reported by FoodCo4, "*We have to monitor the temperature of the freezers, we measure the temperature at the entrance* *and at the end of the day,*" where the employee is exposed daily to sudden temperature variations.

The experts suggested that for these challenges, it is ideal to start with basic automation, as many of these companies are still in the second or third industrial (KUMAR; SINGH; DWIVEDI, 2020). Supplier 2 offers Automation Technology services that provide control systems to customers based on received process specifications, carried out by skilled professionals. On the other hand, Supplier 8 has developed Computer Vision for the Study of Methods, which aims to use technology to determine activity details, separate them into elements and micro-movements, and improve comfort, safety, and ergonomics without the need for a process analyst. Additionally, the experts recommended the use of IoT, for example, in the temperature monitoring process to prevent employees from entering the cold room environment. Supplier 5 has an IoT device to measure temperature and humidity, which sends information via Bluetooth Low Energy (BLE) at configurable time intervals. These Smart Manufacturing technology solutions are characterized by their simple implementation and connectivity via mobile devices, which pleased the managers. In the social aspect, simplified processes related to IoT, and automation bring benefits to working conditions, reducing psychological stress, and increasing employee well-being (BELTRAMI *et al.*, 2021).

A third point of observation regarding social sustainability is that employees are subjected to elevated levels of tension and stress, especially in activities that involve quality control, where errors should be avoided. This is reported by MetalCo, who stated, "*In quality control, the operator separates a part per lot 3 to 4 times a day, and if there is a problem, a suspicious batch is identified.*" Additionally, since the control is done in batches, defective items can be identified late. To address this challenge, the experts suggest the use of intelligent work tools such as Machine Vision to monitor the quality of metal profile surfaces, minimizing the need for batch checking, reducing human intervention, and resulting in fewer errors (ASCÚA, 2021). For this demand, Supplier 4 and Supplier 5 have technologies that inspect components, or finished products, identifying defects by comparing them with pre-classified images. The safety control solution can analyze patterns in detail, constantly monitoring production areas in industrial plants, and generating alerts for any violations (PASI; MAHAJAN; RANE, 2020).

The social aspect of sustainability also has an external component, however, in the interviews conducted, it was observed that monitoring consumer habits in SMEs still relies on manual methods that are not updated in real-time. The experts suggested that data intelligence can be used to tailor negotiations based on purchase frequency. However, the first step is to register customers online and create a consumption history, which can be achieved using Customer Relationship Management (CRM) tools. Supplier 1 offers a CRM solution that covers the entire sales cycle, from pricing tables and orders to quotations, contracts, and a sales portal. Secondly, companies can utilize the intelligence provided by Smart Services technologies for recommendation systems, allowing them to be more accurate in meeting customer needs (DE LUCAS ANCILLO *et al.*, 2022). Supplier 4 has developed a tool capable of identifying trends and seasonal patterns, even in the face of growing complexity, using Big Data and Analytics. Table 22 presents the consolidate the interview quotes. Considering these analyses and suggestions, we have the first proposition:

Proposition 1: *Industry 4.0 contributes to the social pillar of sustainability for SMEs by employing technologies that enhance the safety, comfort, and well-being of their employees while bringing the company closer to the consumers to better serve them.*

Table 22 - Challenges and representative quotes supporting Proposition 1

Challenges	Representative Quotes
Enhance workforce qualifications	"We face a major training challenge, making sure that employees understand and use new technologies."
	"While there is machine-guided training, individuals are predominantly learning through trial and error, which is inefficient and leads to improper learning."
Adapt work methods for employees	"Numerous manual processes persist, prolonging production timelines and limiting the allocation of employees to other tasks."
	"We have to monitor the temperature of the freezers, we measure the temperature at the entrance and at the end of the day,"
Simplify activities that involve quality control	"In quality control, the operator separates a part per lot 3 to 4 times a day, and if there is a problem, a suspicious batch is identified."
Connect products and services to consumers	"We started making a manual folder where we put all the data and customer history, but besides finding inconsistencies, we do not make proper use of the data."
	"With a digital approach, proactive communication becomes crucial since foot traffic won't drive store visits; we need to actively engage our audience."

5.4.2 Environmental Dimension

The first challenge to address environmental sustainability relates to energy consumption. It was observed that companies do not have the habit of monitoring this consumption in real-time, only relying on the monthly electricity bill. Not monitoring equipment that may be consuming more energy than usual could conceal maintenance needs and productivity issues. Experts suggest that in this case, starting with IoT implementation on the main machines is ideal. Smart devices can address energy demand fluctuations more easily by combining industrial flexibility with energy production (KUNKEL; MATTHESS, 2020). If energy consumption is a major concern for the company, the next steps involve integrating this IoT infrastructure with an information system, such as a MES. An MES is an integrated system that consolidates information from the production process, providing a Smart Manufacturing solution (MOEUF *et al.*, 2018). The integration of IoT and MES, as offered by Supplier 5. Control is achieved through programmed settings that generate alarms or stop machines in case of unusual energy consumption (JENA; MISHRA; MOHARANA, 2020).

A second challenge for the environmental pillar of sustainability is the monitoring of water consumption. Many companies (ChemicalCo, ClothingCo1, FoodCo3) only monitor their consumption through the water bill at the end of the month, without identifying waste or variations in consumption. Moreover, some companies operate in the food or beverage industry and need to monitor the quality of the water. Considering this, experts have suggested low-cost solutions. One approach involves collecting data such as pH, turbidity, and chlorine levels using sensors, enabling real-time monitoring (JENA; MISHRA; MOHARANA, 2020). Supplier 2 offers this technology for water control, utilizing IoT and sensors capable of collecting properties and detecting leaks. By implementing these measures, the risk of producing contaminated batches is minimized, and the company gains agility in conducting quality tests on raw materials.

The third challenge for environmental sustainability relates to proper waste disposal. The companies investigated have a practice of visually monitoring waste generation, which can harm the environment due to inefficient processes that require more raw materials, increase waste, and consume more energy. Regarding waste management issues, experts acknowledged that there is no single technology that can solve the entire problem. However, technology can provide greater visibility into waste generation, quantity, and enable investigations aimed at minimizing waste. One possibility is the use of Lean Manufacturing (LM) principles, which focus on combating waste in various forms. Studies have shown that the concurrent use of LM and I4.0 technologies brings several benefits to companies (TORTORELLA; FETTERMANN, 2018).

According to experts, technologies such as sensors can identify product anomalies or quantify the amount of waste generated in each production order, and IoT, combined with Radio

Frequency Identification (RFID) technology, can optimize the classic Value Stream Mapping by managing flows (MOEUF *et al.*, 2018). In this sense, Supplier 6 offers a Smart Manufacturing solution that utilizes Artificial Intelligence (AI) for production optimization. AI facilitates the detection of quality pattern changes, anticipates critical issues, and provides visibility into process and machine malfunctions (BAI *et al.*, 2020). Table 23 presents the consolidate the interview quotes. Drawing from these analyses and prior discussion, we arrive at Proposition 2:

Proposition 2: *Industry 4.0 contributes to the environmental pillar of sustainability for SMEs through technologies that enhance visibility into raw material consumption and waste generated during production processes.*

Table 23 - Challenges and representative quotes supporting Proposition 2

Challenges	Representative Quotes
Monitor and reduce energy consumption	"Monitoring energy only on the electricity bill, I do not track wastage or deviations from normalcy."
	"The fluctuations in my energy consumption are staggering. Equipment burns out yearly. I attempted to install markers at key energy points to track maintenance needs and seasonal fluctuations, but without success."
Monitor and reduce energy consumption	"I solely monitor water consumption via the monthly bill and do not actively check for leaks."
	"For water, I manually measure chlorine and pH levels during production. After manufacturing, I conduct physical-chemical tests on samples and send them to the lab every six months."
Monitor and reduce waste generation	"We monitor certain aspects through the waste bin where the machine discards waste, providing visual alerts, but without defined quantities."

5.4.3 Economic Dimension

In order to survive in the competitive market and achieve economic sustainability, SMEs must initially organize their internal processes. However, during the interviews, it was observed that there is a lack of production standardization, which makes it difficult for managers to identify what is being produced, as reported by ClothingCo3: "*We do not know where things are, we have to ask everyone.*" This leads to communication problems, rework, and a lack of visibility into production parameters, as emphasized by ChemicalCo. The experts have evaluated that a possible solution is the use of a MES, but not in an integrated way with all modules and dimensions (MESA, 2011), only the production programming module, to reduce acquisition costs and the complexity of use. Supplier 7 offers a solution that can monitor, and control production processes based on data collection directly from production. The experts suggest complementing the MES with sensors and connectivity that would be able to scan the product and update its position in the system as it goes through the production process (MITTAL *et al.*, 2020). This Smart Manufacturing solution features intuitive and user-friendly screens, can be easily accessed, and does not require the installation of specific software on the user's computer.

A second challenge is to effectively manage inventory and respond quickly to consumer demands. However, difficulties in inventory management were identified during the interviews, as managers lack confidence in system data and sometimes execute sales and production orders without the necessary materials in stock. This was exemplified by BagCo, stating that their finance team needs to physically check the inventory once a week to compare it with a spreadsheet, and inconsistencies are often found. The experts analyzed that this problem primarily stems from human errors, and the main challenge lies in the correct utilization of management tools, such as Warehouse Management System (WMS). Supplier 7 offers a WMS that enables improvements in material and information flows within warehouses, leading to cost reduction, higher levels of organization, and increased customer satisfaction. However, to avoid system input errors, the experts suggested the use of Quick Response (QR) codes or RFID tags on each package and location. The reader will indicate if the correct item is being selected, making it a relatively cost-effective way to track components and products (KAARTINEN; PIESKA; VAHASOYRINKI, 2017). Supplier 1 offers a solution in this regard, where each item is identified with a unique label. Integrated with the WMS, it sends an alert to the designated employee's mobile device, directing them to the indicated location for order picking. The software bears similarities to spreadsheets, which are more familiar to employees in SMEs' daily routines, thus facilitating adaptation (DE LUCAS ANCILLO *et al.*, 2022).

The third challenge identified is related to the maintenance of machinery and equipment, aiming to prevent production stoppages. However, in the studied SMEs, the identified practice is primarily corrective maintenance, with few investments in preventive or predictive maintenance. The experts suggest that the first step is to understand the parameters that need to be measured for each machine and process, and then utilize technology such as IoT to collect this data automatically. With real-time monitoring of parameters such as machine vibration, temperature, and energy consumption, the data can be used to feed an artificial intelligence system capable of predicting ideal maintenance points (MOEUF *et al.*, 2018). Suppliers 6 and

7 offer solutions for Maintenance Control. The system is based on AI, which facilitates the detection of abnormal behaviors and increases the scope of alerts (ASCÚA, 2021).

Another aspect is that SMEs needs to integrate a value network with connectivity to respond more rapidly to market demands and fluctuations. However, in the studied companies, a lack of connectivity with suppliers and customers was occasionally observed, generating waste in terms of manpower, time, and materials. An example is the practice described by BeerCo: "*We ask for CO2 when it runs out, and cooking gas is delivered every 15 days.*" Running out of CO_2 before placing an order can led to production stoppages, and the periodic need to replenish cooking gas without a defined quantity causes inconvenience for the supplier. In this context, sharing information is crucial for all components of the supply chain. The experts recommended the use of Smart Supply Chain solutions, which are cloud-based platforms capable of collecting lifecycle data and sharing information among supply chain members (ZHANG *et al.*, 2020). Supplier 4 and 5 offer cloud computing-based solutions developed with Big Data, Analytics and cloud computing. These solutions enable manufacturing partners to proactively plan raw materials and production capacity, achieving a balance between supply and demand (CHEN, 2019).

Finally, companies face the challenge of getting closer to their customers, monitoring product usage to perform updates as well as providing faster maintenance services. In this context, there is potential in utilizing Smart Products technologies. The experts emphasize that the first step is to identify the parameters and data that the company needs to collect to implement IoT sensors. Subsequently, connectivity and integration software must be designed for these products. Ideally, IoT sensors should be integrated with the product's software, which incorporates AI, blockchain, and big data to offer an integrated and secure information exchange platform for all stakeholders involved in the product (GHOBAKHLOO *et al.*, 2021). The usage data collected during the post-sale phase can provide opportunities for remote corrections and optimizations, as well as offer production histories, leading to improvements in product development (CHEN, 2019; DUTTA *et al.*, 2020). We compile the interview quotes onto Table 24, aiming toward the third proposition:

Proposition 3: *Industry 4.0 contributes to the economic pillar of sustainability for SMEs through plug-and-play technologies that provide visibility into internal production issues, collect product usage data, and enable supply chain integration.*

Table 24 - Challenges and representative quotes supporting Proposition 3

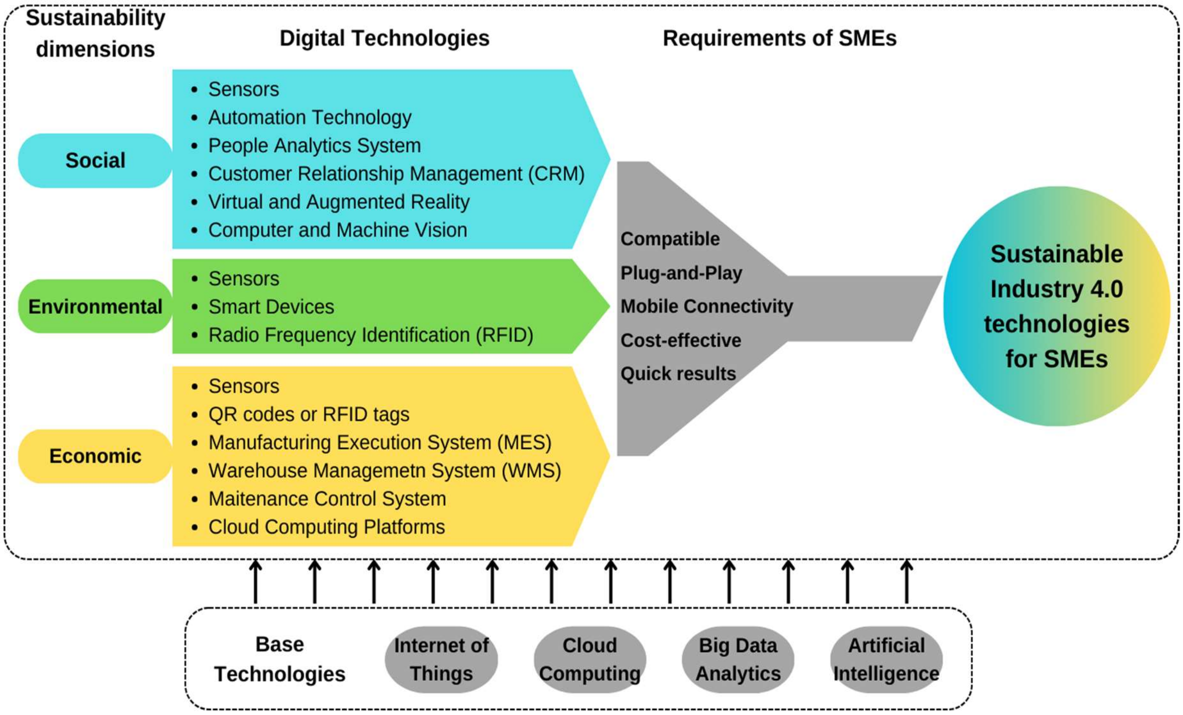
Challenges	Representative Quotes
Improve process visibility	"We do not know where things are, we have to ask everyone."
	"Currently, production orders are distributed manually."
	"We require an automated Production Order process capable of initiating, recognizing inventory, without constant human intervention throughout."
Reliably manage inventory	"Relying on system information is tough; parts seem to disappear."
	"Financial checks the inventory weekly against a spreadsheet for matching."
	"Items nearing expiry are discarded; close-to-spoiling goods are donated to shelters. While we aim for FIFO, daily oversight is necessary for control."
Maintenance management avoiding breakdowns	"In several production orders, we generate waste from uncalibrated machines, which we do not utilize. We only monitor how much is left over per week."
Connect and integrate with the supply chain	"We need to utilize collected process information to directly improve communication with customers, informing them about production timelines."
	"We ask for CO2 when it runs out, and cooking gas is delivered every 15 days."
	"One of the biggest challenges as a manager is projecting production not just for tomorrow but for the next 15 days."
Monitor product usage to perform updates and maintenance	"There is a need for customers to monitor the product and avoid unnecessary displacements for simple maintenance."

5.4.4 Proposed Framework Update

We have summarized our previous discussion in Figure 22, which shows the different technologies that facilitate SMEs in achieving the three dimensions of sustainability. In the social dimension, the focus lies in bridging the gap with consumers, enhancing employee well-being, streamlining training processes, and reducing physical exertion (JAYASHREE *et al.*, 2021b). Within the environmental dimension, the focus is on waste reduction, decreased consumption of natural resources, and enhanced energy efficiency (DOSSOU *et al.*, 2022). Lastly, in the economic dimension, the goal is to provide visibility into productive and organizational processes, facilitating decision-making, and bringing SMEs closer to the supply chain (ASCÚA, 2021; DUTTA *et al.*, 2020). These technologies are supported by base technologies, making it easier to collect, store, and analyze productive and operational data for sustainable applications.

However, not all technologies are adaptable to the context of SMEs due to the complexity of implementation, investment needs, and cultural change, which is even more critical in developing countries (COSTA MELO *et al.*, 2023b; DUTTA *et al.*, 2020; MITTAL *et al.*, 2018). As a result, technologies must align with specific SME requirement such as compatibility with existing systems to facilitate the implementation process (JAYASHREE *et al.*, 2021a). They should embody plug-and-play features enabling swift operational integration (MITTAL *et al.*, 2018), support mobile device connectivity for rapid information dissemination aiding informed decision-making (JENA; MISHRA; MOHARANA, 2020), and be accessible in terms of cost (SHARMA *et al.*, 2023). It is observed that these elements of sustainability and I4.0 should not be worked separately but thought of by SMEs in a convergent way, aiming to maintain the growth of the business and preservation of sustainable principles. In this way, the inclusion of 16 cases from various sectors provides the study with a comprehensive approach to different challenges and diverse proposed solutions. This approach offers the advantage of tailoring technologies to tackle sustainability challenges directly, a feature that has been well-received by entrepreneurs. The positive feedback garnered from entrepreneurs in response to the solutions presented during workshops is attributed to the "plug and play" implementation and the lack of necessity for specialized expertise. Entrepreneurs typically prioritize I4.0 technologies that are straightforward to implement and offer clear benefits without prolonged periods for tangible advantages to manifest (TAMVADA *et al.*, 2022).

Figure 22 - Proposed framework considering sustainable aspects for Small and Medium Enterprises



5.5 CONCLUSIONS

The main objective of this study was to investigate how I4.0 technologies are integrated into the environment of SMEs with the purpose of achieving sustainable objectives. By analyzing case studies, we have developed the framework presented in Figure 22, which considers technologies as cross-cutting elements among dimensions of sustainability.

5.5.1 Theoretical Contributions

The literature has extensively discussed the integration of I4.0 technologies and sustainability (BAI *et al.*, 2020; BROZZI *et al.*, 2020; GHOBAKHLOO, 2020; KAMBLE; GUNASEKARAN; GAWANKAR, 2018; STOCK; SELIGER, 2016). However, this study represents the first attempt to bridge these themes with the reality of SMEs, which are often overlooked in technological development and underestimated in terms of their impact on sustainability (DENICOLAI; ZUCCHELLA; MAGNANI, 2021).

SMEs possess unique characteristics, such as limited investment and workforce constraints, and require solutions that are easily implementable and provide quick returns (ASCÚA, 2021). These requirements have been considered in the technological proposals of this study to make the use of I4.0 technologies for sustainable goals feasible. Our proposals pinpoint an interconnected system of technologies that are both cost-effective and easily implementable. The identification of more viable processes and technologies to achieve sustainability in SMEs constitutes a new contribution to the literature (COSTA MELO *et al.*, 2023b; MACHADO *et al.*, 2021). Furthermore, the propositions regarding how technologies facilitate the implementation of sustainability in SMEs also contribute to the existing body of literature. These contributions are consolidated in a conceptual framework that researchers can adopt to analyze production processes from a sustainable perspective and further explore the potential of these technologies.

Another significant contribution of this study is to highlight the main challenges faced by SMEs in implementing sustainable practices and adopting new technologies. We identify several barriers reported by managers of the studied SMEs, many of which are supported by existing literature (INGALDI; ULEWICZ, 2020; KHANZODE *et al.*, 2021; MOEUF *et al.*, 2020) and propose alternatives using technologies so that companies are not excluded from sustainable development.

5.5.2 Managerial Contributions

Our findings also offer practical insights for managers, indicating that SME entrepreneurs should prioritize sustainable issues, particularly environmental and social concerns, and view technology as a facilitator in this process. We present viable I4.0 technologies that prioritize ease of implementation, quick returns, and affordability, demonstrating that the use of these technologies can become a part of daily operations for SMEs. In situations where technology becomes excessively intricate, users often experience confusion and uncertainty regarding its utilization. This complexity can potentially have adverse effects on their decision to adopt new technology (JAYASHREE *et al.*, 2021b). Thus, the simplicity of the technologies proposed in our study plays a pivotal role in persuading managers, who are the primary decision-makers and the driving force behind SMEs (JAYASHREE *et al.*, 2021b; KUMAR; SINGH; DWIVEDI, 2020).

Secondly, the study reveals that technology alone does not solve all sustainability-related problems. It is necessary for companies to simultaneously foster cultural and behavioral changes alongside technology implementation, overcoming internal resistance to digitization (DENICOLAI; ZUCCHELLA; MAGNANI, 2021; MACHADO *et al.*, 2021; SHUKLA; SHANKAR, 2023). This imperative is even more pronounced in developing countries, where resistance tends to be more pronounced (NARWANE *et al.*, 2022). Moreover, they should structure their internal processes to ensure that technology investments are not underutilized (DOSSOU *et al.*, 2022). Thus, entrepreneurs need to cultivate a culture of sustainability within the company, utilizing digital technologies as facilitators in this process.

Finally, we highlight to technology providers that there is a significant potential market within SMEs, with demand for products and services specifically designed for small businesses. The study identifies certain challenges faced by SMEs in achieving sustainable goals, which can be attained through technology, if it possesses characteristics that make implementation feasible, such as "plug-and-play" technologies, low cost, connectivity across multiple devices, and quick results.

5.5.3 Limitations and Future Research

Our study acknowledges certain limitations and provides opportunities for future research. Firstly, we did not analyze the companies after suggesting the most suitable technologies. Given that I4.0 encompasses an interconnected set of technologies and solutions, the success of future implementation stages can serve as a valuable measure of how sustainable practices and technologies have been adopted and implemented. Therefore, future studies could focus on analyzing the post-implementation stage of these technologies to conduct a retrospective analysis and assess the success of their integration with sustainability in the context of SMEs.

It is important to note that our propositions were derived from case studies and the insights of selected experts, which suggests that further empirical evidence would enhance the robustness of these propositions. Further research can expand upon our findings by conducting larger-scale studies involving a wider range of SMEs to validate and enhance the proposed framework. In addition, the paper focuses on cases from Brazil. To better generalize and confirm the results, authors should expand the analysis to other developing countries.

Research predominantly correlates I4.0 with economic sustainability, even in SMEs (COSTA MELO *et al.*, 2023b). Therefore, exploring I4.0 within SMEs with a social and environmental focus presents a promising avenue. This gap serves as a vital resource for researchers, emphasizing the ongoing need to raise awareness about the potential of I4.0 in boosting sustainability and performance (BROZZI *et al.*, 2020). Finally, our study focused solely on manufacturing companies, leaving an opportunity for future research to explore sustainability and I4.0 within service-based SMEs.

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6 DRIVING SMALL FIRMS TOWARDS INDUSTRY 5.0 IN EMERGING COUNTRIES: THE ESSENTIAL ROLE OF INDUSTRY 4.0 TECHNOLOGIES

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Abstract

The objective of this paper is to explore how Industry 4.0 digital technologies can assist small firms (SFs) in achieving the Industry 5.0 in emerging countries across three dimensions: human-centricity, sustainability, and resilience. To accomplish this, qualitative research was conducted through semi-structured interviews with 17 leaders of SFs from various industrial sectors from Brazil, aiming to identify the challenges they face in reaching Industry 5.0 goals. Additionally, interviews were conducted with 9 technology providers that serve SFs to understand how their products and services can assist these companies. These interviews were analyzed by a focus group consisting of four experts in digital transformation, to propose technological solutions for SFs to overcome the challenges of Industry 5.0. Finally, a second round of meetings was held with SFs managers to present the proposals and collect feedback on the feasibility of the solutions. The results showed that digital technologies can help SFs achieve Industry 5.0 objectives. Propositions and a framework were presented on how this can be achieved, including creating a safer and more ergonomic work environment, improving sustainability by reducing environmental impacts, and strengthening the resilience of the entire supply chain through increased integration among companies. However, the study identified that these technologies must meet the requirements of SFs, which include simple implementation and low cost. Therefore, this paper can serve as a guide to assist SFs managers and stakeholders in their digitization efforts, and it contributes to the theory by identifying appropriate digital technologies for SFs in emerging countries to become human-centric, sustainable, and resilient.

Keywords: Sustainability; Small and Medium Enterprises; Industry 5.0; Smart manufacturing; Sustainable Operations Management; SME.

6.1 INTRODUCTION

Industry 4.0 has led to technological advancements in manufacturing companies as they have invested in the implementation of new technologies, such as sensors, cyber-physical systems, internet of things, cloud computing, big data analytics, artificial intelligence and others (KAGERMANN; WAHLSTER; HELBIG, 2013; MEINDL *et al.*, 2021; SANTOS; SANT'ANNA, 2024). As a result, Industry 4.0 has contributed to enhancing productivity, increasing visibility of processes, and reducing costs in operations (FRANK; DALENOGARE; AYALA, 2019; SANTOS; SANT'ANNA, 2024; XU *et al.*, 2021). Nevertheless, Industry 4.0 has received several criticisms, as its emphasis has been more on leveraging technology to promote economic indicators; with less attention to principles of social justice and sustainability (GHOBAKHLOO *et al.*, 2022a; IVANOV, 2022; XU *et al.*, 2021).

To overcome the technology-centered approach of Industry 4.0 (IVANOV, 2022), the Industry 5.0 concept has recently emerged, combining advanced technology with three other dimensions: resilience, sustainability, and a human-centric approach (GHOBAKHLOO *et al.*, 2022a; IVANOV, 2022). Indeed, Industry 5.0 does not replace Industry 4.0; rather, it complements Industry 4.0 by highlighting new technologies as drivers of a sustainable, human-centric, and resilient industry (EUROPEAN COMMISSION, 2021; LU *et al.*, 2022). In doing so, Industry 5.0 emphasizes a sociocultural dimension that aims to redefine how value is created, produced, and captured through new technologies (IVANOV, 2022). Its goal is to provide prosperity that goes beyond job creation and economic growth, but also considering the environmental limits and prioritizing the well-being of industry workers (EUROPEAN COMMISSION, 2021).

Many large companies still face difficulties to implement Industry 4.0 as it requires large amount of investment, high level of capabilities, and changes in companies´ organizational structures and cultures (JAMWAL; AGRAWAL; SHARMA, 2023; MEINDL *et al.*, 2021). Moreover, Industry 5.0 also adds new challenges to those companies, such as placing the individuals at the center of industrial value-creation; promoting human-machine interactions, the adoption of sustainable practices for energy efficiency, renewables, storage and autonomy (ALVES; LIMA; GASPAR, 2023; TALLAT *et al.*, 2024). Consequently, Industry 5.0 advances Industry 4.0, emphasizing sustainable development.

The literature on Industry 4.0, and mainly on Industry 5.0, have extensively focused on large companies; while only marginally addressing small firms (SF) (MULLER *et al.*, 2024;

SANTOS; SANT'ANNA, 2024). However, SFs account for about 90% of businesses and over 50% of employment globally. These numbers are more significant for emerging economies (SILTORI *et al.*, 2021; WORLD BANK, 2019). For instance, by 2030, it is expected that 600 million jobs will be needed to accommodate the growing workforce, which makes SFs a potential solution for many governments (WORLD BANK, 2019). Therefore, SFs are crucial for achieving economic, social, and environmental benefits. Due to its relevance, it is not possible to consider the progress of Industry 5.0 without its implementation in SFs (SANIUK; GRABOWSKA; STRAKA, 2022; SILTORI *et al.*, 2021).

Scholars have made contributions to understanding Industry 5.0 and its dimensions (IVANOV, 2022; LENG *et al.*, 2022; MADDIKUNTA *et al.*, 2022; SINDHWANI *et al.*, 2022). However, its implementation in SFs has been neglected despite their economic value to the global economy. Considering that SFs have limited investment capacity and a lack of human resources and managerial expertise (ABDELWAHED; SOOMRO; SHAH, 2022; MULLER *et al.*, 2024); they face even greater challenges in implementing Industry 5.0 approach compared to larger companies (HEIN-PENSEL *et al.*, 2023; MADHAVAN; SHARAFUDDIN; WANGTUEAI, 2024). Consequently, examining the SF perspective on the feasibility of Industry 5.0 offers a more comprehensive understanding of the implications of this concept within the industrial context.

Only a few articles have explored the implementation of Industry 5.0 in SFs, typically focusing on specific topics such as maturity models (HEIN-PENSEL *et al.*, 2023; KRAJČÍK, 2021; MADHAVAN; SHARAFUDDIN; WANGTUEAI, 2024), or sustainable practices (ALI; JOHL, 2023). However, this article offers a holistic approach by proposing a framework that outlines which affordable Industry 4.0 technologies can support the implementation of Industry 5.0 dimensions in SFs. In particular, it answers the following research question: ***how can Industry 4.0 digital technologies facilitate the adoption of Industry 5.0 among SFs?***

To address this research question, we conducted a multiple case study involving 15 Brazilian SFs and 9 technology providers. Our main goal was to evaluate Industry 4.0 technologies (FRANK; DALENOGARE; AYALA, 2019) and their alignment with the characteristics of SFs and the three pillars (human-centricity, sustainability, and resilience) of Industry 5.0 (EUROPEAN COMMISSION, 2021). Furthermore, by focusing on Brazil, we also offer insights about the adoption of Industry 5.0 within an emerging economy, which may have implications for other countries with similar socio-economic contexts. In terms of company size, Brazilian SFs include firms which have less than 50 employees and, therefore, are characterized by low levels of innovative capabilities. The Brazilian context is interesting as SFs play a vital role in the economy, contributing significantly to job creation and innovation (IAKOVETS; BALOG; ŽIDEK, 2023; SANTOS; SANT'ANNA, 2024). Thus, we need to better understand how to fosters Industry 5.0 in more challenging contexts.

The contributions of this article are threefold. First, our findings suggest that to enable SFs to effectively adopt Industry 5.0, they require low complexity and plug-and-play technologies that can be easily adapt to SF characteristics. Thus, it helps to overcome one of the main barriers for SFs in adopting Industry 4.0 technologies (SANTOS *et al.*, 2024; TAMVADA *et al.*, 2022) to support Industry 5.0. Second, this study identifies boundary conditions in the implementation of Industry 5.0 by assessing SFs in emerging economies, thereby expanding the contexts in which Industry 5.0 is applied (ALVES; LIMA; GASPAR, 2023; SILTORI *et al.*, 2021). Lastly, we present a conceptual framework and formulate propositions that can serve as a guide for both academics and practitioners, helping them gain a clearer understanding of Industry 5.0 within the context of SFs.

The remainder of the article is structured as follows: The next section provides the theoretical background. Section 3 introduces the proposed conceptual model. The methodology is detailed in Section 4, while the results are presented in Section 5. Finally, the paper concludes with theoretical and practical contributions.

6.2 LITERATURE REVIEW

6.2.1 Industry 4.0 and Industry 5.0

Industry 5.0 envisions a scenario where environmental and societal needs coexist with industry. It builds upon the technology components of Industry 4.0 by combining classic and emerging technologies to create hyper-connected business ecosystems (DANA *et al.*, 2022; XU *et al.*, 2021). The Industry 4.0 technologies can be categorized into four smart dimensions as stated by Frank's et al. (2019) theoretical framework. First, the smart manufacturing dimension focuses on product processing technologies. According to Kusiak (2018), Smart Manufacturing combines present and future manufacturing assets through the integration of sensors, computing platforms, communication technology, data-intensive modeling, control, simulation, and predictive engineering. It leverages concepts such as cyber-physical systems, the internet of things (IoT), cloud computing, service-oriented computing, artificial intelligence (AI), and data science. Second, the Smart Working dimension refers to technologies that optimize worker tasks, improving safety and productivity. According to Meindl et al. (2021) Smart Working encompasses operational activities carried out by smart operators as well as flexible and remote tasks involving a wider range of workers, such as managers, engineers, and supervisors. These individuals are involved in the cognitive aspects of manufacturing processes.

Third, the Smart Supply Chain dimension focuses on technologies that support the horizontal integration of the factory with external suppliers and customers. Industry 4.0 enhances supply chain visibility, enabling effective risk management through end-to-end mapping. Integrity control technologies like sensors, big data analytics, and decentralized agent-driven control ensure accurate product delivery in terms of quantity, timing, location, condition, and price and monitoring customers (BARRETO; AMARAL; PEREIRA, 2017; DANA *et al.*, 2022; IVANOV *et al.*, 2014). The Smart Supply Chain dimension includes also Industry 4.0 technologies applied to internal logistic, such as autonomous vehicles, tracking systems, and inventory control for warehouse operations (MEINDL *et al.*, 2021).

Lastly, the Smart Products and Services dimension deals with technologies related to smart components that enable digital services. Smart products are objects that, in addition to their physical components, leverage key Industry 4.0 technologies (IoT, cloud computing, big data analytics, and artificial intelligence) to gather, track, control, and optimize the uses of the product. On the other hand, smart services refer to companies utilizing the digital technologies embedded on products to provide various services to their users, such as cloud services, remote assistance and monitoring, and AI-driven support (MARCON *et al.*, 2022a) .

While Frank et al.'s (2019) comprehensive framework on the smart dimension effectively illustrates the numerous opportunities presented by Industry 4.0, it overlooks the significance of technologies in terms of sustainability and resilience. This necessitates the need for adaptation and consideration within the context of the Industry 5.0 environment. Industry 5.0 has redefined the scope of Industry 4.0 concepts with technological and regulatory advancements, resulting in a techno-social transformation that meets current business needs (GHOBAKHLOO *et al.*, 2022b). Industry 5.0 goes beyond being just a technological shift; it is changing the way we create, produce, and consume value (GHOBAKHLOO *et al.*, 2022a). To succeed in Industry 5.0, firms must integrate stakeholders' green expectations into their innovation processes (HEIN-PENSEL *et al.*, 2023; XU *et al.*, 2021). However, the real challenge for firms is finding a balance between integrating classic and emerging technologies with the sociocultural objectives of Industry 5.0 (GHOBAKHLOO *et al.*, 2022a).

The discussion on Industry 5.0 is still in its early stages, with existing articles primarily focusing on understanding the concepts and applications of new disruptive technologies, identifying key enablers, and addressing the challenges companies face in transitioning to Industry 5.0. Additionally, they explore the main differences between this new approach and Industry 4.0 (Appendix C). However, a review of the literature shows that these articles often overlook the needs and potential of SFs, particularly in developing countries. Therefore, it is crucial to analyze how these companies can be integrated into the Industry 5.0 framework, considering its three core dimensions: human-centricity, sustainability, and resilience, as outlined below.

6.2.2 Industry 5.0 and Small firms

6.2.2.1 Human-Centricity

Industry 4.0 has been successful in increasing manufacturing rates, but it has overlooked the human cost of optimizing processes. This neglect has resulted in employee resistance, which has become a primary obstacle to implementing new technologies. This resistance has also reduced employment opportunities and impeded the full adoption of Industry 4.0, as noted by Maddikunta et al. (2022). However, Industry 5.0 aims to address this issue by prioritizing the participation of humans and placing them at the center of the production process (LENG *et al.*, 2022). This new approach recognizes the importance of considering workers' skills and capabilities when incorporating advanced technologies (EUROPEAN COMMISSION, 2021).

According to Dornelles et al. (2023), there are four ways that technology can be integrated into jobs: substitution, deskilling, upskilling, and reskilling. Substitution involves replacing workers with technology, while deskilling involves simplifying tasks with technology. Upskilling enriches tasks with technology, and reskilling requires workers to receive training to handle new activities. Industry 5.0 can use technology in various ways to improve employee well-being and performance without replacing them with machines, as suggested by Nahavandi (2019). The OECD (2011) technology intensity definition classifies industry sectors, showing that some sectors are more prone to implement technologies while others are more labor-intensive. Thus, small firms in sectors that heavily rely on the direct participation of humans in production processes—often involving significant manual work that can be enhanced with technology (i.e., firms where human labor is already central)—can benefit greatly, or may even be in a better position than highly automated firms, by applying smart working Industry 4.0 technologies for the transition to Industry 5.0.

Lu et al. (2022) propose Industry 5.0 as a model of manufacturing that prioritizes human well-being and integrates technological advancements within smart social factories. For SFs, where many jobs remain manual and low-skilled, it is crucial to consider the social and technological implications of these jobs to enhance employee quality of life and integrate them as integral parts of the organizational process (GHOBAKHLOO *et al.*, 2022b). Technological advancements have the potential to improve the work environment, ensuring employee safety, comfort, and ergonomics (MACHADO; WINROTH; DA SILVA, 2020). Under Industry 5.0, rather than technology dictating human behavior, technology should be designed to serve people and society. By prioritizing employee well-being, technology can increase social impact, boost morale, utilize productive capabilities, and enhance stakeholder satisfaction (EUROPEAN COMMISSION, 2021). Therefore, there is a need to study how digital technologies can be effectively integrated with human workers in the context of SFs and Industry 5.0.

6.2.2.2 Sustainability

The concept of sustainable manufacturing involves producing high-quality products and services while using fewer natural resources, ensuring the safety of stakeholders, reducing environmental and social impacts, and maintaining economic benefits throughout the product life cycle (MACHADO; WINROTH; DA SILVA, 2020). SFs may face less pressure than large companies to implement sustainable practices; however, they still play a significant role in environmental impact. In fact, SFs are responsible for a large portion of global pollution and have a substantial economic impact, including employment and income (NDUBISI; ZHAI; LAI, 2021). The Triple Bottom Line (TBL) is the foundation of sustainability, consisting of the economic, social, and environmental pillars (LOPES DE SOUSA JABBOUR; NDUBISI; ROMAN PAIS SELES, 2020). In this study, we will concentrate on the environmental and economic variables of sustainability, as the social aspect is already included in the human-centric dimension of Industry 5.0.

Society is under increasing pressure to develop sustainable production processes that preserve resources for future generations, and the emergence of Industry 5.0 seeks to address this need (MADDIKUNTA *et al.*, 2022). Even the most well-known Industry 4.0 models for large firms (FRANK; DALENOGARE; AYALA, 2019; SCHUH *et al.*, 2020) or SFs (MITTAL *et al.*, 2020) often fail to consider sustainability aspects. Although the use of 4.0 technologies can lead to improved sustainability metrics, such as better resource utilization (INGALDI; ULEWICZ, 2020), increased energy efficiency, and reduced waste and CO_2 emissions (BAI *et* *al.*, 2020), these benefits are often secondary to profit generation (SINDHWANI *et al.*, 2022). Industry 5.0, in contrast, prioritizes sustainable practices in the digitalization process, such that technologies must enable economic and environmental goals with equal weight. This can be achieved through the reduction of waste, reduction of energy consumption, minimization of the use of raw materials such as water, and the promotion of a circular economy that operates with greater efficiency and effectiveness (EUROPEAN COMMISSION, 2021).

In addition to the often-neglected challenges of environmental sustainability, economic sustainability remains an ongoing concern that requires constant attention. Industry 5.0 recognizes that new production models must involve a closer relationship with consumers, delivering products tailored to their individual preferences to promote sustainability by avoiding overproduction and reducing the creation of products without demand (MADDIKUNTA *et al.*, 2022). On one hand, SFs are known for providing customized solutions, relying primarily on their human workforce, which grants them a high level of flexibility. However, on the other hand, many SFs still face significant obstacles in monitoring production, maintenance, and waste processes to achieve this goal (XU *et al.*, 2021).

Although there are challenges associated with sustainable practices, such as implementation costs (CHEGE; WANG, 2020) and insufficient employee and management training (ALAYON; SÄFSTEN; JOHANSSON, 2022), numerous studies have shown that these practices can improve the performance of small enterprises and provide a competitive advantage (CHEGE; WANG, 2020; DANA *et al.*, 2022; EWEJE, 2020; HANDRITO; SLABBINCK; VANDERSTRAETEN, 2021; JENA; MISHRA; MOHARANA, 2020). Digital technologies can support the achievement of environmental goals, allowing for accurate planning, reduced lead times and setup times, increased flexibility, and productivity (EJSMONT; GLADYSZ; KLUCZEK, 2020; FRANK; DALENOGARE; AYALA, 2019; KAMBLE; GUNASEKARAN; GAWANKAR, 2018). Nevertheless, SFs face unique sustainability challenges, and there is a need for research into the effective integration of digital technologies that prioritize sustainability, a critical dimension of Industry 5.0, into the reality of SFs.

6.2.2.3 Resilience

In Industry 5.0, organizational resilience means that companies maintain, change, or take action to endure adversity, grow stronger, and gain a competitive edge (EUROPEAN COMMISSION, 2021). This involves a focus on business continuity and risk management, which helps companies maintain operations during tough times (XU *et al.*, 2021). For instance, the COVID-19 pandemic has demonstrated the importance of resilience as companies had to adapt to new working conditions and create networks to provide products and services even in crises (IVANOV, 2022). The industry must be agile enough to quickly adapt to geopolitical changes, natural emergencies, and changes in consumer preferences (LENG *et al.*, 2022). In this way, resilience enables companies to improve their skills, manage operational risks through timely information processing, and reduce supply chain risks in uncertain times (MCCARTHY; COLLARD; JOHNSON, 2017).

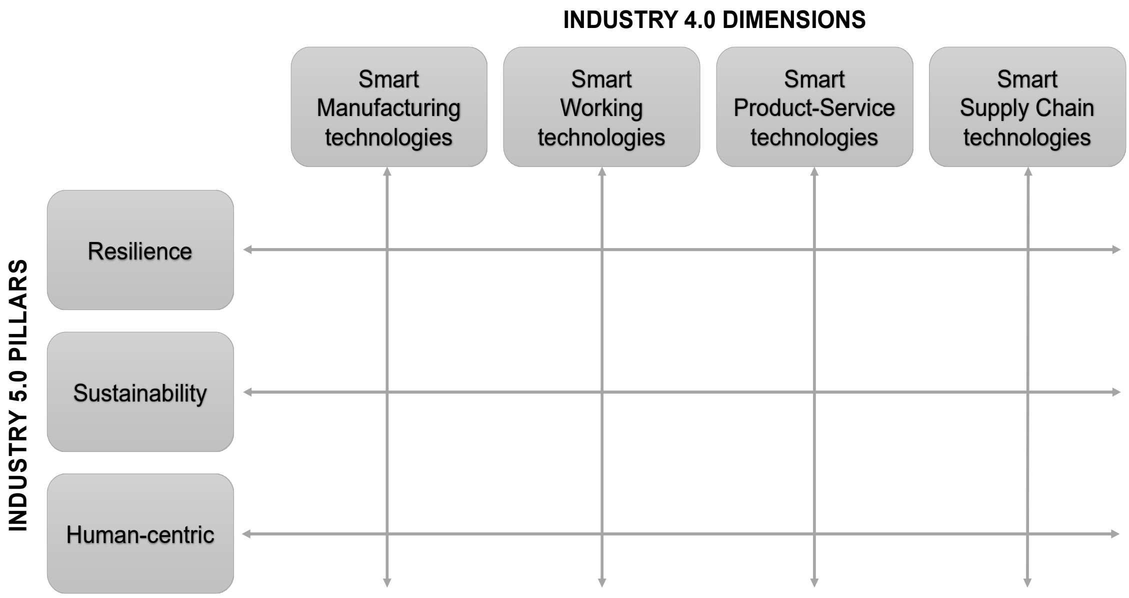
Industry 5.0 requires connected stakeholders to be integrated throughout the entire value chain, expanding the scope of corporate responsibility (GHOBAKHLOO *et al.*, 2022b; SANIUK; GRABOWSKA; STRAKA, 2022). To survive in adverse conditions, production chains must be reconfigurable, cyber-physical, and digital, while promoting regional development and environmental sustainability through resilience and circularity (GHOBAKHLOO *et al.*, 2022a; XU *et al.*, 2021). Digital technologies facilitate this process by allowing real-time interaction and communication between manufacturing partners, enabling the preparation of raw materials and production capacity in advance, finding a balance between supply and demand, and enabling joint product development (CHEN, 2019).

SFs are known for their flexibility and adaptability, which gives them an advantage regarding resilience. However, some critical management processes, such as production and purchasing planning, inventory, and product management, are still done manually. As a result, business decisions are often based on the intuitions of SFs owners and managers, rather than data analysis. This can lead to errors and a loss of competitiveness (MITTAL *et al.*, 2020). Fortunately, there are key technologies that can help SFs become more resilient and develop robust, efficient, and productive systems. For example, IoT can monitor production and identify bottlenecks, risks, and potential interruptions. Cloud-based collaborative systems can expand the reach of enterprise resource planning (ERP) and improve responsiveness to supply chain demands. Big data can identify customer needs and desires and integrate data with suppliers to make the entire industrial system more interconnected (GHOBAKHLOO *et al.*, 2022b; SINDHWANI *et al.*, 2022). Despite the potential benefits of these digital technologies, it remains unclear how feasible and useful they are for SFs to achieve the goals of Industry 5.0 and strengthen the resilience of the entire supply chain.

6.2.3 Conceptual Framework

In this study, we aim to analyze the impacts of digital technologies in the context of Industry 5.0, with a particular focus on SFs. This analysis is especially important for developing countries, where debates on sustainable digital transformation are limited (KUNKEL; MATTHESS, 2020; SILTORI *et al.*, 2021; TAMVADA *et al.*, 2022), and where investments in digital technologies often prioritize economic goals over resilient, human-centered, and sustainable ones (EL BAZ *et al.*, 2022; NARA *et al.*, 2021; SATYRO *et al.*, 2022). To address this issue, we propose a conceptual framework (Figure 23) that combines the four smart dimensions of Industry 4.0 (FRANK; DALENOGARE; AYALA, 2019) with the three key pillars of Industry 5.0 (EUROPEAN COMMISSION, 2021). Within each intersection, our aim is to examine the digital technologies that can be beneficial for SFs in achieving Industry 5.0 objectives.

Figure 23 - Conceptual framework for the link between Industry 5.0 and Industry 4.0 smart dimensions



6.3 RESEARCH METHOD

In line with our research objective, we adopt a qualitative, multiple case approach (EISENHARDT; GRAEBNER, 2007; VOSS; TSIKRIKTSIS; FROHLICH, 2002; YIN, 2018) to understand how SFs can use digital technologies to achieve Industry 5.0 goals. In particular, this approach allowed us to explore each dimension of Industry 5.0 in the SF specific context, deriving real-world practice conditions for research and allowing for the formulation of direct recommendations for action based on these findings (YIN, 2018). Moreover, a multiple case approach is appropriate for replication logic that uses a series of cases to confirm or disconfirm the theoretical insights of the research (EISENHARDT; GRAEBNER, 2007).

Throughout the research process, several measures were taken to ensure the validity and reliability of the multiple case approach. For construct validity: (i) the conceptual framework and, thereby, the interview questions were based on the literature, and (ii) primary and secondary sources were used; and (iii) we conducted initial interviews with two companies to refine the instrument and, (iv) data were gathered with key informants from 17 SFs and 9 technology providers in Brazil's manufacturing sector. For internal and external validity: (i) the case selection was based on predefined criteria; (ii) triangulation approach was based on different sources of data and informants; and (iii) we looked for a sample of cases that could provide an analytical rather than a statistical generalization. For reliability, we employed data collection protocols, followed a well-defined coding process and, prepared a final report based on recorded interview transcripts (YIN, 2018). These measures will be better explained in the next sections.

6.3.1 Case Study Selection

According to the Organization for Economic Cooperation and Development (2005), SFs are independent companies with differences in the number of employees and financial assets. In Brazil, small companies are classified as having up to 99 employees (SEBRAE, 2013). However, one of the main characteristics of SFs is that they generally lack the technological infrastructure and capabilities necessary to implement Industry 4.0 (ABDELWAHED; SOOMRO; SHAH, 2022). For this reason, we employed the theoretical sampling method, which means that we selected SFs that would help us to understand the concepts we were investigating (EISENHARDT; GRAEBNER, 2007).

To find suitable cases, we followed the intensity sampling approach (PATTON, 2014), selecting cases that could be considered good examples of the phenomena of interest. Intensity sampling also involves prior information of the potential cases and judgment on the part of the researcher team (PATTON, 2014). Thus, firstly, we contacted companies participating in an innovation program focused on productivity, which is a Brazilian service designed to support Small and Medium-sized Enterprises (SMEs). This program aims to improve the productivity of small businesses by tracking performance indicators and proposing practical actions related to production management and digital technologies. Therefore, companies in this program would be more aligned with the research objectives. One of the researchers in our team worked as an innovation agent in the innovation program and provided us with a reliable list of potential case studies to investigate, which resulted in 125 participants.

In order to analyze how Industry 4.0 digital technologies can assist SF in achieving the Industry 5.0, we selected cases that fulfilled the following criteria: (i) manufacturing firms only, (ii) firm size in terms of number of employees (only small firms) and, (iii), SFs that have already implemented digitalization initiatives and that could provide information on the questions asked. We acknowledge that the participation of SFs in the mentioned innovation program could introduce bias into our sample, potentially limiting the generalizability of our findings to the broader population of small firms in Brazil. However, according to the Theory of Diffusion of Innovation (ROGERS; SINGHAL; QUINLAN, 2019), firms must first become aware of the potential of new digital technologies to develop openness toward their adoption. Therefore, selecting firms involved in an innovation program ensured that the companies in our study were well-prepared to discuss how Industry 4.0 digital technologies could facilitate the transition to Industry 5.0. Based on these criteria, we selected 35 potential manufacturing companies, excluding SFs with underdeveloped or completely manual manufacturing processes. Lastly, after consulting the owners and managers of these 35 SFs to double-check if they were really suitable, we achieved a final list of 17 companies. In this final sample, we deliberately picked SFs from different industries (variation) to provide a broad overview of the phenomenon. Table 25 provides a brief description of the selected companies. To maintain anonymity, we used codenames instead of real names for both the companies and the respondents.

Table 25 - Background of the cases

Case Company	Size	Sector	Interviewer’s role
ClothingCo1	8	Clothing & Accessories	Owner
ClothingCo2	5	Clothing & Accessories	Owner
ClothingCo3	15	Clothing & Accessories	Production Manager
ClothingCo4	5	Clothing & Accessories	Production Manager
FoodCo1	6	Food	Owner
FoodCo2	5	Food	Owner
FoodCo3	5	Food	Production Manager
FoodCo4	5	Food	Production Manager
MetalCo	80	Metal Products	Plant Manager
BagCo	10	Rubber and Plastic Material	Co-owner
PlasticCo	15	Rubber and Plastic Material	Owner
ChemicalCo	11	Chemicals	Owner

NauticalCo	6	Nautical Products	Owner
BeerCo	12	Beverage	Owner
ChairCo	99	Machines and equipment	IT Director
MedicalCo	98	Electric machines, appliances, and materials	IT Director
MoldsCo	17	Manufacturing of molds for tools.	Owner – CEO Owner – COO

In addition to the case studies listed in Table 25, we also interviewed technology providers offering Industry 4.0 solutions to SFs. In total, nine technology providers were interviewed, as shown in Table 26. The purpose of these interviews was to gain a deeper understanding of the digital solutions they offered and how these solutions could meet the demands of SFs. Small firms in Brazil, like those in many emerging economies, face several challenges, including limited funds for digital technology investments, low digital literacy, and a lack of robust IT infrastructure (ASCÚA, 2021; SILTORI *et al.*, 2021). Recognizing these limitations, the technology providers selected for our study offer affordable, user-friendly, plug-and-play digital solutions tailored to the needs of SFs. For example, Supplier 7 offers a service for approximately $60 USD per month, providing real-time production visibility (OEE - Overall Equipment Effectiveness) and transparency into key productivity challenges. Similarly, Supplier 4 provides smart sensors that can be easily attached to machines using just a magnet, along with an AI-powered platform for predictive maintenance, available for around $70 USD per month. These solutions include installation service and require only a Wi-Fi connection and a smartphone, tablet, or basic computer.

Table 26 - Technology providers

Institution/Company	**Role**	**Technology Offered**
Supplier 1	Product Manager	ERP; MES; WMS systems; Artificial Intelligence; Cloud Computing; RFID.
Supplier 2	Innovation Consultant CTO; R&D Director	Artificial Intelligence; Digital Twins; Robotics; IoT; Automation Technology; Horizon, and Vertical Integration.
Supplier 3	Development Manager	ERP; Simulation; Horizon, and Vertical Integration; Supply chain Cloud; Digital Performance management.
Supplier 4	Regional ecosystem executive	Cybersecurity; Predictive analytics; Cloud Computing; IoT; Track and trace for supply chain visibility; ERP systems.

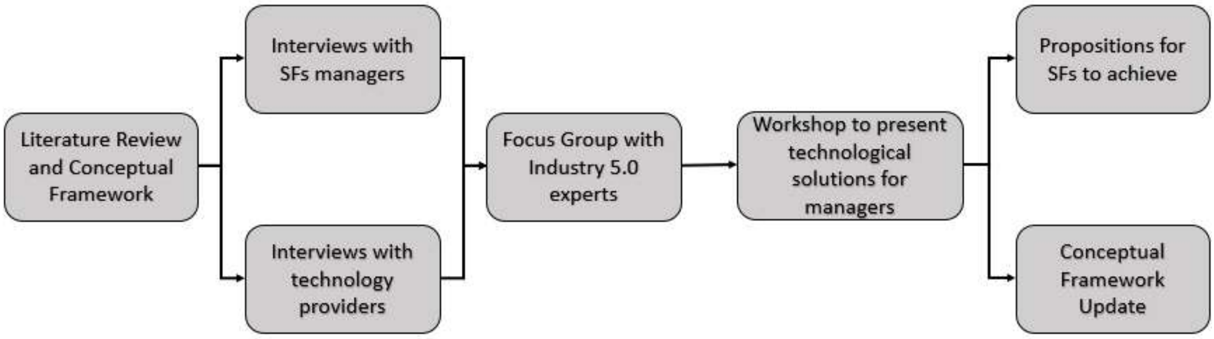
Supplier 5	CEO	IoT; Cloud Computing; Track and trace for supply chain visibility; Visual computing.
Supplier 6	CEO and CTO	Artificial Intelligence; IoT; Vertical Integration.
Supplier 7	CEO	WMS and MES systems; Manufacturing View.
Supplier 8	CEO	Visual computing; Artificial Intelligence.
Supplier 9	Sales manager	Advance planning and scheduling (APS) software.

6.3.2 Research Instruments and Data Collection Procedures

To identify the potential of digital technologies for Industry 5.0 goals, semi-structured interviews were conducted with key representatives of the selected companies. Before the main interviews, an initial version of the interview script was tested with production managers and owners from two other SFs (not included in the final sample). After this, we targeted key informants from SFs with knowledge of I4.0 technologies and production systems used by the SFs. The idea was to capture operational and strategic aspects. Since SFs generally have few individuals in top management positions, only one representative per organization was interviewed (see Table 25). However, the interviewees were key representatives from those companies with a strong understanding of the firm's business model and the interlinkages between technology infrastructure and production systems. Each interview, which lasted approximately one hour, was conducted via videoconference. This step allowed us to identify the challenges of SFs and summarize them for analysis from the perspective of Industry 5.0.

In addition to the interviews with SF key informants, we also conducted other rounds of data collection that provided complementary information and helped us reduce bias while obtaining a richer and more detailed model (CUI *et al.*, 2019). In the following, we interviewed the representatives from technology solution companies (Table 26) who worked with SFs to diagnose and implement digital technologies. Our objective was to assess the viability of the experts' recommendations, examining whether the suggested digital solutions were commercially applicable and adaptable to the specific circumstances and requirements of SFs. After this second round of data collection, we conducted a focus group session with four experts in Industry 4.0 and Industry 5.0 to analyze the results of the interviews and understand the challenges of the 17 SFs. The experts provided recommendations for digital technologies that could be adopted by these companies to enhance their productivity objectives, while also aligning with the goals of Industry 5.0. Then, we compiled all the information obtained from the companies regarding the problems and challenges they encountered in relation to the dimensions of Industry 5.0. Finally, utilizing the gathered information, we facilitated a workshop involving the same 17 SFs. During this final workshop, researchers and managers presented and discussed potential solutions, while feedback was gathered from experts and technology companies regarding the suitability of these solutions within the SFs' specific context. Data collection was comprehensively carried out over a span of 18 months, beginning in December 2021 and concluding in June 2023. Figure 24 shows the Methodological stages of the research, highlighting the rounds of data collection.

Figure 24 - Methodological stages of the research



Noteworthy, during all the data collection process, we recorded interviews and took notes on participants' impressions and comments. The notes were made by three researchers, who then compared interview impressions to obtain a complete view of each case while reducing observer bias (YIN, 2018). Additionally, secondary data were collected for later analysis, including the companies' internal procedures, business reports, internal slideshows, and information from the companies' websites. Therefore, we employed data triangulation (using different sources and actors) and investigator triangulation (involving multiple researchers in data collection and analysis) to mitigate bias and enhance the quality of the research (DENZIN, 2009).

6.3.3 Data analysis - Validity, Reliability, and Interpretation

We employed thematic analysis techniques to interpret the interview materials (transcripts and field notes) as well as secondary data (SEURING; GOLD, 2012). Thematic analysis, a widely recognized qualitative research method, serves to analyze large sets of textual data by coding them into various empirical themes based on theoretical constructs (BRAUN; CLARKE, 2006). For data analysis, we transcribed recorded interviews and analyzed the data to identify challenges, realities, and potential for applying technology to improve human well-being, sustainability, and resilience. Firstly, we analyzed each interview individually and performed a cross-case analysis to identify similarities, contrasts, and patterns between cases. The results were organized in a final report. We then contacted interviewees again to report our findings and collect feedback when convergence was not reached. Secondly, we compared the cross-case analysis with the literature and developed proposals for SFs to achieve Industry 5.0 goals through digital technologies.

For systematizing the collected data, we used the categories showed in conceptual framework (Figure 23). Microsoft Excel software facilitated the categorization of textual data and the coding process. Two authors were involved in the coding process, and the final categorization was discussed and validated by the entire research team. In the first round, text fragments were coded using an open approach to structure the data according to challenges and technologies. In the second round, the fragments were coded using an axial approach to classify the data into themes (second-order codes). Then, they were grouped in aggregated dimensions representing the three pillars of Industry 5.0 (human-centric, sustainability and resilience) and technologies. The final coding structure is shown in Figure 25.

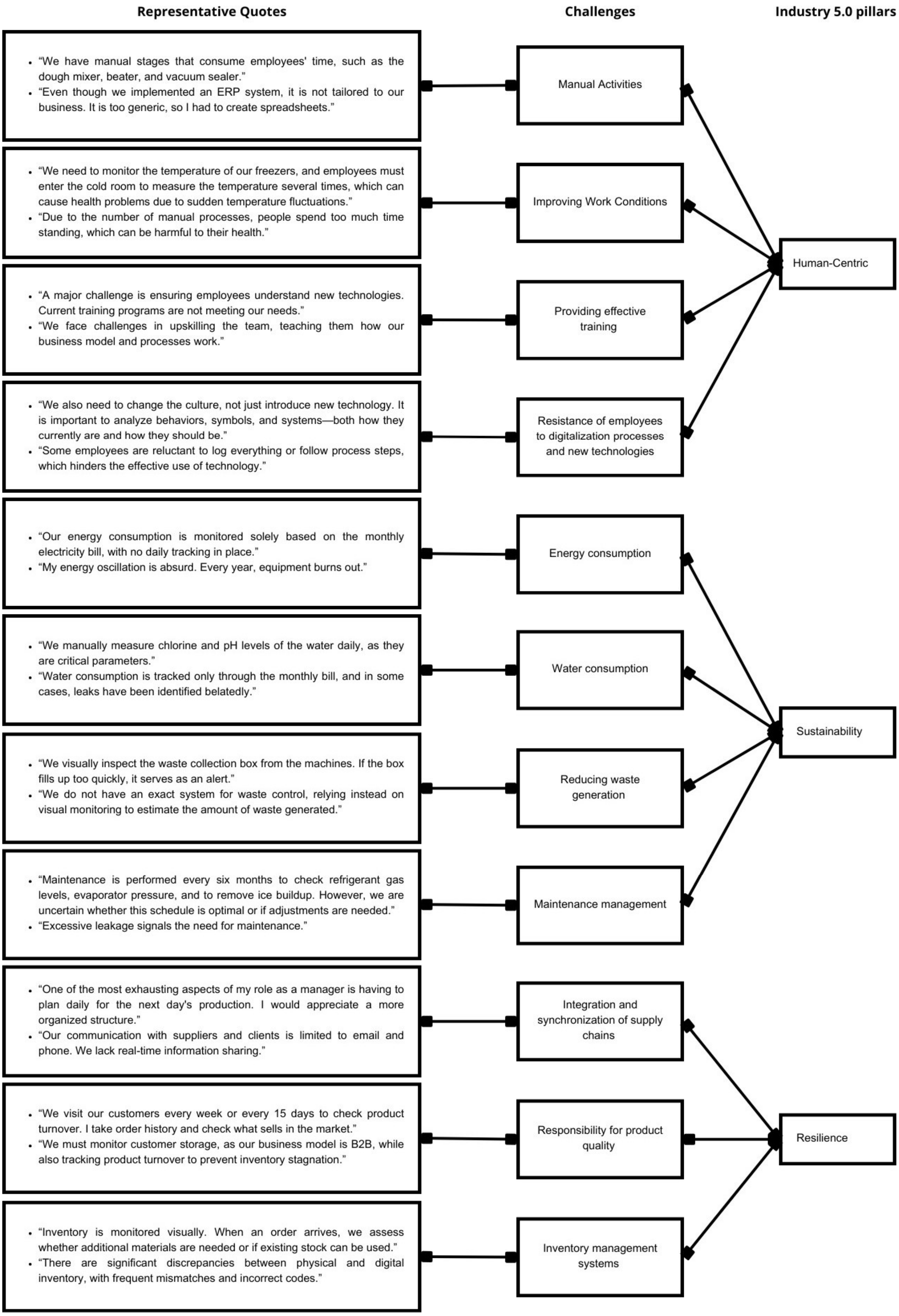
6.4 RESULTS AND DISCUSSIONS

In order to answer the research question of our study, i.e., how can digital technologies facilitate the adoption of Industry 5.0 among SFs from emerging countries, in this section, we present the findings of the case studies conducted according to each dimension of Industry 5.0. Based on these findings and extant literature, we have developed proposals that highlight the potential of digital technologies in assisting SFs in achieving the goals of Industry 5.0. These proposals aim to provide practical recommendations on how SFs can leverage digital technologies to enhance their operations and competitiveness in the context of Industry 5.0.

6.4.1 Human-centric production systems for Small Firms

To achieve a human-centric approach in their work processes, SFs must consider improving not only the production process's efficiency but also the employees' comfort, well-being, and safety (MADDIKUNTA *et al.*, 2022). The SFs of our case studies reported various manual activities in the production process, such as food preparation, chemical mixing, and document issuance, that can lead to production bottlenecks, harm ergonomics, and underutilize employee potential. For example, FoodCo2 indicated: *"My process of getting polenta out of the ovens is inefficient. I need to improve the quality of work and utilize my employees better."*

Figure 25 – Coding Structure



It is worth noting that SFs, especially those in developing countries, encounter challenges related to infrastructure, education, and resources, as they predominantly rely on manual activities (KUMAR; SINGH; DWIVEDI, 2020). Therefore, technologies implemented in SFs processes should be affordable and user-friendly, avoiding complexity.

Experts and technology suppliers were consulted on how to improve manual jobs. Technology suppliers first recommendation was to simplify tasks by using automation to promote the deskilling of workers (DORNELLES; AYALA; FRANK, 2023). However, SFs expressed their concern about the necessary investments and the need to preserve their flexibility (TAMVADA *et al.*, 2022). Then, experts proposed a new approach not focused on deskilling or substitution by automation but a one focused on improving workers productivity by upskilling (DORNELLES; AYALA; FRANK, 2023). For instance, supplier 8 offered an automated chronoanalysis technology using IoT sensors and smart cameras to collect data on working conditions in manufacturing processes. The data is analyzed in the cloud using AI and visual computing, providing insights to enhance posture and optimize movement. When brought to the SFs, they declared that the proposed technology could offer several benefits to them, including reduced non-production time, prevention of workplace accidents, and compensation for the lack of process analysts in their firms. The technology was user-friendly, could deliver fast results, and shows that significant investments are not required to leverage technology for job improvement.

Second, improving working conditions and ensuring employees safety is a significant challenge for SFs (BELTRAMI *et al.*, 2021; NARA *et al.*, 2021). However, limited investments often hinder SFs' ability to provide optimal working conditions. For instance, FoodCo4 stated: "*We need to monitor the temperature of our freezers, and employees must enter the cold room to measure the temperature several times, which can cause health problems due to sudden temperature fluctuations"*. To address this challenge, experts recommend utilizing IoT devices with temperature sensors to monitor environmental conditions. Supplier 5 then offered a cost-effective IoT device that measures temperature and humidity, transmitting the data via Bluetooth Low Energy to a smartphone or computer. This user-friendly technology can be easily installed, promoting a safer work environment and enhancing employees' well-being.

In the pursuit of human-centric approaches, SFs face a third challenge, which involves prioritizing the well-being and maximizing the productive and intellectual capacity of their employees (KUMAR; SINGH; DWIVEDI, 2020; MASOOD; SONNTAG, 2020). Many SFs encountered difficulties in providing effective training and standardizing processes. For instance, ClothingCo3's manager shared his experience, noting that "*although recorded training materials are available for new equipment, employees still struggle to learn the correct and standardized procedures, resulting in inconsistencies and inefficiencies*". To address this qualification challenge, experts recommend utilizing visualization and simulation technologies, such as virtual reality. These technologies can be particularly valuable for manual activities and remote training, enhancing the learning experience and improving the qualification of employees (NAHAVANDI, 2019). When consulted, technology providers have confirmed the existence of free software in the market that enables the creation of virtual reality training programs easily, based on technical specifications documents. These programs can be played on commonly available smartphones, making them accessible and cost-effective for SFs.

Customized training programs are crucial for meeting the specific needs of SFs. Alongside technology, experts recommend implementing an integrated human resources management system that can analyze and monitor employees' skills, expectations, health, and satisfaction in real-time. Supplier 1 offers a user-friendly tool based on people analytics, providing insights into key work indicators, including learning management modules, skills maps, and performance analysis. SFs managers can simply record and input data, as the software's artificial intelligence and data analytics capabilities extract vital information, facilitate career development, and optimize task allocation. This technology may contribute to building a stronger and more cohesive work team within the SFs (KAASINEN *et al.*, 2022).

In addition to the challenges mentioned, we identified employee resistance to digitalization processes and new technologies as a significant obstacle that could jeopardize the implementation of any digital technology or initiative. Similar to large firms (VAN DUN; KUMAR, 2023), employees in SFs express concerns about the surveillance implications of smart cameras or wearables, as well as potential job losses due to automation—an issue that should not be underestimated. Moeuf et al. (2020) highlight the importance of SF`s managers motivating their teams by clearly explaining the objectives of new technologies and involving employees in the digitalization process. As previously mentioned, SF managers were initially resistant to automation and job replacement during the early stages of their Industry 4.0 journey. Instead, they urged technology suppliers to provide solutions that focused on deskilling or upskilling (DORNELLES; AYALA; FRANK, 2023), rather than replacing workers. Avoiding job displacement can thus be a prudent strategy to reduce socio-cultural resistance. Furthermore, communication and transparency are crucial in this process, fostering a Smart

Working environment that enhances productivity, working conditions, cognitive skills, and inclusion, as advocated by the Industry 5.0 concept.

The challenges highlighted on case studies indicate that realizing the potential of digital technologies for SFs requires a shift in focus from costly automation and worker substitution to the utilization of basic digital technologies accompanied by an upskilling of workers. By adopting this approach, SFs can enhance productivity and improve working conditions (DORNELLES; AYALA; FRANK, 2023; JENA; MISHRA; MOHARANA, 2020). Thus, based on the insights from case studies, expert opinions, technology providers, and relevant literature, we can summarize the observations related to the first pillar of Industry 5.0 in the following proposition.

Proposition 1: *Small firms can achieve human-centric production systems by shifting their focus from costly automation and worker substitution to the adoption of affordable, user-friendly digital technologies that enhance productivity through upskilling employees and improving working conditions. This approach not only leverages basic digital tools to overcome resource limitations but also involves employees in the digitalization process, thereby reducing resistance and fostering a more inclusive and efficient work environment aligned with the principles of Industry 5.0.*

6.4.2 Environmental sustainability for Small Firms

Ensuring environmental sustainability is a significant challenge that primarily involves better management of energy consumption, particularly with the increasing number of digitally connected devices (MADDIKUNTA *et al.*, 2022). However, during interviews, SFs reported that they lacked the resources to conduct proper follow-up and only checked monthly electricity bills for costs. This practice not only conceals consumption waste but also makes it challenging to detect defective equipment, as BeerCo attested: "*My energy oscillation is absurd. Every year, equipment burns out. I tried installing markers to monitor energy expenditure, maintenance needs, and seasonal fluctuations, but without success.*"

To tackle the challenge of monitoring and reducing wasteful energy consumption, experts recommended using IoT technology on main machines, which is both easy to apply and affordable. Supplier 2 presented then a solution using IoT sensors to collect energy consumption data, allowing for continuous monitoring and historical recording. It can also generate alerts for non-standard consumption, reducing the need for constant monitoring by a collaborator. An IoT-based infrastructure allows for visibility at the factory level, creating intelligent connections for Industry 5.0 (IVANOV, 2022). Companies that integrate IoT with the cloud can identify opportunities for improvement in energy efficiency indicators with an Energy Monitoring System (MACHADO; WINROTH; DA SILVA, 2020).

A second challenge for SFs achieving sustainability is controlling water consumption. The companies studied reported difficulties in monitoring water consumption and only monitored it through monthly bills, which made it challenging to identify waste or non-standard consumption. To overcome this challenge, experts recommended using low-cost solutions like Andon panels to monitor water quality in real-time. These panels use sensors to track critical variables, an if any of them falls outside the specified range, the flow of water can be automatically interrupted using a PLC (JENA; MISHRA; MOHARANA, 2020). Experts also recommended using Smart Meters, as those proposed by Fetterman et al. (2020), to measure water consumption and quality, sharing this information online. For this purpose, Suppliers 2 and 6 proposed solutions that collects flow and pressure data every second to identify faults and unexpected behavior in the water distribution system. This technology can be integrated with employees' mobile devices to send alerts, simplifying the process for SFs. Any anomalies are automatically analyzed to ensure the accurate identification, prevent environmental and economic waste.

A third challenge for SFs facing Industry 5.0's environmental sustainability pillar is reducing waste generation (MADDIKUNTA *et al.*, 2022). Our interviews revealed that SFs lack quantitative practices to monitor waste generation and instead rely on visual qualitative management. This approach can obscure serious process efficiency problems. For example, ClothingCo1 stated: "*We just observe the garbage box where waste from the machines goes. If the box fulfils too fast, is an alert for us, but we do not have any defined quantity*". BagCo and NauticalCo also mentioned similar practices.

Experts stated that no single technology can solve the challenge of keeping up with waste generation. However, providing more visibility to waste can help to reduce its generation. One approach to waste reduction is Lean Manufacturing (LM). Studies show that combining LM with digital technologies can benefit companies (TORTORELLA *et al.*, 2021; TORTORELLA; FETTERMANN, 2018). Tools such as Poka Yoke devices to alert workers when out-of-spec parts are manufactured. These kinds of devices can be digitized and integrated into the system. In this sense, Supplier 6 proposed AI algorithms that enhance the availability and efficiency of production lines. This is done by using historical data collected by sensors to identify optimal parameters and variable values for configuring machines and processes.

The sustainability pillar of Industry 5.0 aims to prioritize environmental considerations while maintaining economic competitiveness. This is particularly crucial for SFs that often face limited budgetary resources (TAMVADA *et al.*, 2022). In relation to this, SFs commonly highlight a significant challenge related to machine inefficiencies and breakdowns caused by inadequate monitoring of key parameters and insufficient maintenance management. To tackle the challenge of keeping equipment efficient and operational, experts recommend that SFs first understand the parameters that need to be measured in each machine and then implement IoT-based monitoring to enable preventive maintenance. As the maturity level of the system increases and historical data becomes available, predictive maintenance can be adopted.

Several suppliers, including 1, 4, 6, and 7, proposed asset maintenance solutions that leverage data from factory floor devices to manage maintenance routines and generate key indicators such as MTBF (Mean Time Between Failures) and MTTR (Mean Time To Repair). The SFs managers were pleased with the solution because it reduces the need for employees to constantly monitor the machines and perform periodic tests. In this way, the SFs define the parameters and feed the system, which autonomously monitors equipment and generates alerts and analyses (JENA; MISHRA; MOHARANA, 2020). This approach aligns with the principles of Industry 5.0, which focuses on proactively avoiding problems through maintenance activities, rather than reacting to issues after they arise (MADDIKUNTA *et al.*, 2022).

The challenges explored indicate that SFs can benefit from reducing waste using digitization and sensors, which can aid in optimizing environmental parameters (EJSMONT; GLADYSZ; KLUCZEK, 2020), reducing waste (MADDIKUNTA *et al.*, 2022) and increasing equipment efficiency (JENA; MISHRA; MOHARANA, 2020). The proposed technological solutions were easy to use and affordable for SFs. Thus, based on the insights from case studies, expert opinions, technology providers, and relevant literature, we can summarize the observations related to the second pillar of Industry 5.0 in the following proposition.

Proposition 2: *Small firms can achieve environmental sustainability by adopting affordable, user-friendly digital technologies—such as IoT sensors, smart meters, and AI algorithms—to monitor and manage energy and water consumption, reduce waste generation, and enhance equipment efficiency through preventive and predictive maintenance. This approach enables small firms to overcome resource limitations, optimize environmental parameters, and proactively address inefficiencies, aligning with Industry 5.0 principles that prioritize environmental considerations alongside economic competitiveness.*

6.4.3 Resilience for Small Firms

Business resilience, the third pillar of Industry 5.0, is primarily built upon the integration and synchronization of supply chains for SFs (IVANOV, 2022). Take, for example, MoldsCo, a company specializing in complex mold manufacturing for major tool manufacturers. These molds can consist of up to 50 parts, some of which are outsourced to other SFs. Once all processes are completed, these parts must come together for the final mold assembly. However, MoldsCo faces challenges in effectively managing this process, as they struggle to precisely locate all mold parts due to tracking difficulties and schedule updates.

To tackle this issue, experts suggested using Advanced Planning and Scheduling (APS) software, but they cautioned against its high cost. Supplier 9, a technology provider, stepped in with an innovative approach. Rather than recommending the costly APS solution from their portfolio, they proposed an APS system that would utilize real-time productivity data from IoT sensors installed on the machinery, combined with AI, to determine the optimal production combination. Remarkably, this solution cost only 25% of what larger firms were offered. By implementing this software, the company can boost its ability to monitor and manage production across its supply chain, ultimately resulting in reduced delays and increased productivity.

A second challenge for improving resilience in SFs is linked to their ability to maintain strong connections throughout their supply chains. They need to align with all stakeholders, given their responsibility for product quality from manufacturing to consumption (GHOBAKHLOO *et al.*, 2022a; TAMVADA *et al.*, 2022; TORTORELLA *et al.*, 2021). SFs, such as FoodCo3, expressed difficulties in tracking product parameters when dealing with intermediaries, noting, "*Storage parameters are not always respected by our business partners, but it is still our product, and it must be of quality*."

Experts suggest integrating IoT sensors into user-friendly apps to address this. The IoT can offer crucial data, such as temperature levels, streamlining logistics, enhancing adaptability and resilience (MACHADO; WINROTH; DA SILVA, 2020; MADDIKUNTA *et al.*, 2022). Real-time data sharing can foresee potential issues, ensuring quality stability (GHOBAKHLOO *et al.*, 2022b; TORTORELLA *et al.*, 2021). However, IoT implementation requires coordination with supply chain partners (MEHRJERDI; SHAFIEE, 2021). Clear communication is crucial to clarify IoT device benefits for all supply chain entities (KUNKEL; MATTHESS, 2020).

Improved communication and data sharing can also be achieved by utilizing digital platforms and collaboration portals. Despite this, many still rely on manual information sharing, causing delayed responses. As noted by FoodCo4's manager, "*We visit our customers every week or every 15 days to check product turnover. I take order history and check what sells in the market*," resulting in potential overproduction or material shortages.

Building resilience in SFs requires effective inventory management systems for rapid response to market changes and customer needs, arising as a third challenge. Some SFs reportedly keep low inventory for agility without adequate monitoring, leading to differences between actual stock and digital records. For instance, the manager of FoodCo1 noted, "*we often sell products under the impression of having raw materials as per our system, only to find the stocks missing or expired.*" Similarly, BagCo reported having to verify their inventory against a spreadsheet weekly, a practice shared by ClothingCo3.

Experts suggest Warehouse Management Systems (WMS) to mitigate inventory issues. Supplier 7's WMS solutions enhance warehouse efficiency, while the use of QR codes or RFID tags for quick scanning and verification of items can further streamline operations (AHMAD; ABDULLAH; TALIB, 2020). The implementation of such technologies, like the comprehensive stock management package from Supplier 1, can strengthen inventory management, boost resilience, and maintain market competitiveness for SFs.

Thus, based on the insights from case studies, expert opinions, technology providers, and relevant literature, we can summarize the observations related to the third pillar of Industry 5.0 in the following proposition.

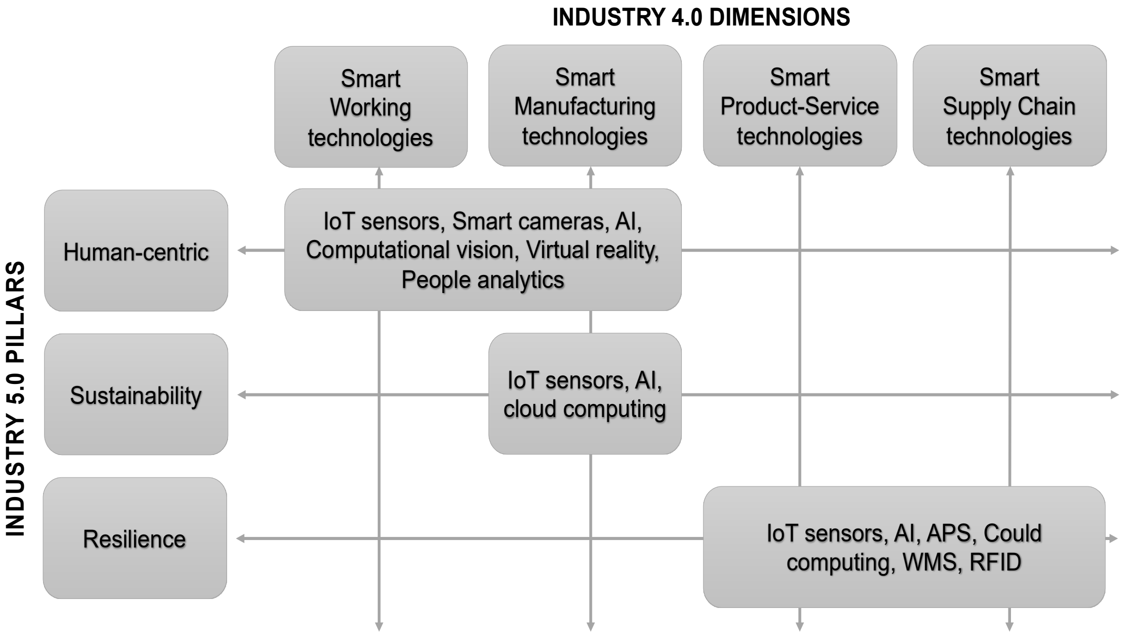
Proposition 3: *Small firms can enhance their business resilience by adopting affordable, user-friendly digital technologies—such as IoT sensors, AI-driven planning and scheduling systems, warehouse management systems, and digital communication platforms—to improve supply chain integration, inventory management, and real-time data sharing with partners. Leveraging these technologies enables small firms to overcome resource limitations, increase visibility and synchronization across their operations, reduce delays, and respond rapidly to market changes and customer needs, thereby aligning with the Industry 5.0 resilience principle.*

6.4.4 Industry 4.0 smart dimensions and the Industry 5.0 pillars

Our previous findings are encapsulated in Figure 26. This figure presents an array of Industry 4.0 technologies that enable SFs to realize the three pillars of Industry 5.0 effectively.

As highlighted in the case studies, the human-centric aspect of Industry 5.0 for SFs is strongly linked to smart working technologies, and to a lesser extent, smart manufacturing technologies. Given financial constraints and the need for flexibility, smaller firms are not necessarily focusing on automation under Industry 4.0, but rather enhancing manual processes through the application of digital technologies (DORNELLES; AYALA; FRANK, 2023). Here, straightforward hardware like IoT sensors and smart cameras, coupled with advanced software applications (AI and visual computing), emerge as key solutions that can be integrated with operational excellence procedures to boost productivity (LEONG *et al.*, 2020). Furthermore, the utilization of virtual reality and people analytics to reduce learning curves allows SFs to become more agile. It is worth noting that the current use of these technologies does not require an in-depth understanding of their inner workings as they are outsourced and designed to be user-friendly software functionalities.

Figure 26 - Proposition of conceptual framework for the link between Industry 5.0 and Industry 4.0 smart dimensions in the context of SFs



Our study's focus on the sustainability pillar of Industry 5.0 primarily concerned environmental and economic aspects, given that the social dimension was addressed under the human-centric pillar. According to our findings, to achieve sustainability, SFs should emphasize smart manufacturing technologies. These Industry 4.0 base technologies, which are both affordable and adequately meet SFs' needs (FRANK; DALENOGARE; AYALA, 2019), provide visibility into resources, energy, and water consumption. As such, they enable SFs to make data-driven decisions to prevent waste (MADDIKUNTA *et al.*, 2022; TORTORELLA *et* *al.*, 2021). Furthermore, AI applications allow firms to predict maintenance and quality issues, thereby enhancing productivity.

Thirdly, the resilience aspect of Industry 5.0 for SFs is primarily connected to smart supply chain technologies, with a minor relation to smart product-service technologies. Real-time information on supply chain conditions, particularly from key customers and providers, is vital for resilience (GHOBAKHLOO *et al.*, 2022b). This information can be sourced from IoT sensors embedded in smart products (DANA *et al.*, 2022) or RFID tags, but its primary value lies in its use within advanced, integrated software systems such as APS and WMS. The adoption of a data-driven decision-making culture, powered by these technologies, can significantly enhance SFs' competitiveness (DANA *et al.*, 2022; NYAGADZA, 2022).

By analyzing Figure 26, it is possible to observe that some technologies are common to all three pillars of Industry 5.0, while others are specific to individual pillars. Frank et al. (2019) and Meindl et al. (2020) classify Industry 4.0 technologies into base technologies—such as IoT, Cloud, Big Data, and AI—and front-end technologies. These base technologies provide support, allowing specific applications to be implemented within companies. By considering the three pillars of Industry 5.0 within a single framework, unlike previous works that address them separately (ALVES; LIMA; GASPAR, 2023; LU *et al.*, 2022; NAHAVANDI, 2019; SINDHWANI *et al.*, 2022), the analysis suggests that using the same base technology allows SFs to achieve different objectives. For example, IoT can be used to provide visibility into processes, improving the monitoring of employees, energy, and inventory, thereby strengthening the dimensions of Industry 5.0 (GHOBAKHLOO *et al.*, 2022b; JENA; MISHRA; MOHARANA, 2020). Another example is the integration of AI into various management systems with intuitive layouts, which enables the use of advanced technologies in companies that lack specialized labor (SANTOS; SANT'ANNA, 2024). This optimizes resources, which are often limited in SFs, making Industry 5.0 more accessible.

6.5 CONCLUSIONS

Our study aimed to explore how digital technologies can assist SFs in achieving Industry 5.0. Based on our analysis of case studies, we put forward some proposals regarding the contributions of technologies that consider the unique characteristics of SFs. Initially, we examined the four smart dimensions of Industry 4.0 to gain insight into potential technology applications across various industries. We then linked these components to the dimensions of Industry 5.0, adding a comprehensive perspective to the framework proposed by Frank et al.

(2019). Our research sheds light on specific technology applications that SFs should consider meeting the objectives of Industry 5.0, which prioritizes employee-centered manufacturing systems, sustainable principles, and resilient supply chains.

6.5.1 Theoretical Contributions

The relationship between Industry 4.0 technologies and sustainability has been the subject of several studies across diverse industrial and business contexts (EJSMONT; GLADYSZ; KLUCZEK, 2020; INGALDI; ULEWICZ, 2020; KAMBLE; GUNASEKARAN; GAWANKAR, 2018). Yet, during the fourth industrial revolution, sustainability often has taken a backseat to economic considerations. This shifted with the recent advent of Industry 5.0, which emphasizes human elements and resilience as core dimensions, in addition to sustainability (GHOBAKHLOO *et al.*, 2023). Although the influence of Industry 4.0 on SFs has been thoroughly investigated in the past (INGALDI; ULEWICZ, 2020; KHANZODE *et al.*, 2021; KUMAR; SINGH; DWIVEDI, 2020), there remains a significant gap in existing literature concerning the needs of small businesses within the newly emergent Industry 5.0. To address this, our study aims to connect the dimensions of Industry 5.0 and 4.0 with the tangible realities of small enterprises.

Furthermore, while previous studies have typically treated SMEs as a monolithic entity (EWEJE, 2020; NDUBISI; ZHAI; LAI, 2021), our research is novel in its specific focus on small businesses. This distinction is particularly relevant in developing countries (TAMVADA *et al.*, 2022), where the circumstances of small businesses (i.e., firms with up to 99 employees) can markedly differ from those of medium-sized enterprises (i.e., firms with up to 499 employees) (SEBRAE, 2013). Our study emphasizes that the convergence of Industry 4.0 and 5.0 in SFs must account for certain unique constraints, such as limitations on investment, human resources, and time (ALAYON; SÄFSTEN; JOHANSSON, 2022). Nevertheless, we demonstrate that it's both possible and beneficial to implement technologies that enhance financial performance while promoting better working conditions, sustainability, and resilience. Our findings offer fresh insights into practical processes and technologies for achieving Industry 5.0 in small businesses.

This study also contributes by identifying the challenges that SMEs face when attempting to internalize human-centric, sustainable, and resilient practices. These challenges are even more prominent in developing countries and include labor constraints, inadequate infrastructure, and limitations in investment and credit (ASCÚA, 2021; SILTORI *et al.*, 2021).

Brazil, for example, has one of the highest real interest rates in the world, hindering the investment capacity of SFs (FEIJO, 2024). Additionally, government support tends to be less effective and proactive compared to developed countries such as the USA, Germany, and France, which already have advanced programs to promote digitalization (BEIER *et al.*, 2022; EJSMONT; GLADYSZ; KLUCZEK, 2020; XU; XU; LI, 2018). However, the results suggest that low-cost alternatives are available in the market, making it essential for SMEs to assess their needs and determine which technology is most viable. This reinforces the idea that SMEs do not need to adopt multiple technologies simultaneously but can instead implement one that meets their requirements through a gradual process (SANTOS *et al.*, 2024). Researchers studying Industry 5.0 can build on our analysis of these challenges and technologies, opening up new avenues for future research.

Also, as succinctly captured in Figure 26, our study highlights that SFs striving for Industry 5.0 need not implement all Industry 4.0 technologies. Simple, plug-and-play base technologies can be sufficient for these firms to align with the principles of Industry 5.0 (KAHLE *et al.*, 2020). Our research also clarifies which smart dimensions of Industry 4.0 should be prioritized depending on the specific Industry 5.0 pillar that a firm is aiming to achieve. This helps lay the groundwork for future studies to explore our conceptual framework for different industrial contexts and firm sizes.

6.5.2 Managerial Contributions

Our research carries several practical implications for practitioners. Firstly, while SFs are often overlooked on Industry 4.0 and Industry 5.0, our study shows that despite their size, these firms can indeed prioritize employee well-being, sustainable processes, and resilience. Various affordable and effective digital solutions are available that can enhance productivity and improve management of social, environmental, and resilience dimensions (GHOBAKHLOO *et al.*, 2023; IVANOV, 2022). We encourage managers to explore these technologies by demonstrating current market examples that are cost-effective, easy to implement, and may provide quick returns. Such technologies are accessible to SMEs, illustrating that achieving Industry 5.0 does not require significant investments but rather strategic planning and gradual implementation. Our research underscores the viability of these solutions and their potential to enable SFs to achieve the standards of Industry 5.0. We provide a guide to help small entrepreneurs understand the available technologies that can assist them in reaching Industry 5.0 goals, even in the context of developing countries.

Secondly, our study underscores that technology alone cannot surmount all the challenges associated with Industry 5.0. Entrepreneurs must also foster a digital culture and refine their human resource management practices to facilitate the implementation of Industry 5.0 (LU *et al.*, 2022). This highlights that managerial efforts should consider not only technological investments but also organizational changes, investing in employees, and altering the company culture to foster innovation and digitalization of processes (HEIN-PENSEL *et al.*, 2023). In doing so, it will be possible to minimize implementation barriers and increase the likelihood of success for new technologies (JAMWAL; AGRAWAL; SHARMA, 2023). The human-centric approach of Industry 5.0 is particularly suited to SFs, which traditionally rely on human expertise and manual activities for flexibility - a key competitive differentiator from larger companies (MOEUF *et al.*, 2018). However, to bolster resilience, competitiveness, and to meet consumer demands, developmental efforts should encompass the entire supply chain. It's therefore essential for SFs managers and stakeholders to recognize the importance of coordinated developmental initiatives (KUMAR; SINGH; DWIVEDI, 2020).

It is important to highlight that while our research shows that advances in Industry 4.0 technologies are making their implementation and utilization easier, the technologies alone do not solve the problems. As observed by Marcon et al. (2022b), the implementation of Industry 4.0 technologies must be seen from a sociotechnical perspective consisting of four dimensions: technological, social, environmental, and organizational. This means that technologies are only one important aspect in achieving a successful Industry 4.0 journey. Once implemented, small firms (SFs) will still face challenges in getting the most out of these technologies. For instance, employees must undergo digital literacy training to effectively use the data for decision-making; otherwise, the technology and the data generated by it may be forgotten over time and will not bring any improvement to the firm's performance. Because of this, many authors (e.g., Frank et al., 2024; Pagliosa et al., 2021; Tortorella et al., 2019) have observed that firms mature in lean management and problem-solving strategies are better prepared to extract the most from Industry 4.0 technologies.

Lastly, our study indicates a substantial opportunity for technology providers to cater to SFs by designing products and services tailored to their needs. Small business owners tend to prefer simple, easy-to-use "plug and play" solutions, as well as those offered through a servitized subscription business model, which can help alleviate the challenges they face without requiring large capital investments. (KAHLE *et al.*, 2020; TAMVADA *et al.*, 2022). While SFs may not necessitate a complete suite of advanced technologies, they should prioritize those that offer the most significant impact and align with their specific needs (DUTTA *et al.*, 2020). Additionally, it is crucial to complement these technologies with employee training and process adaptability (ALAYON; SÄFSTEN; JOHANSSON, 2022). Our findings can guide technology providers in developing simpler solutions that require less time and effort to implement while still delivering tangible results. Moreover, it suggests that these companies should invest in a more comprehensive solution for SMEs, addressing not only the technology but also training, implementation, and maintenance (SANTOS *et al.*, 2024). This can increase entrepreneurs' confidence when making investments. Furthermore, with the advent of Industry 5.0, a new ecosystem is emerging for startups to offer customized hardware and software solutions on a global scale (NAHAVANDI, 2019).

6.5.3 Limitations and Future Research

Our study has some limitations and opportunities for future research. We did not examine any companies after suggesting the most appropriate technologies and implementation processes. Success in the future stages of implementation can be a good measure of how well the technologies have been adopted and implemented since Industry 5.0 comprises an interconnected set of technologies and solutions (IVANOV, 2022). Therefore, future studies could analyze the post-implementation stage of the technologies. This would enable researchers to conduct a retrospective analysis and evaluate the integration's success with Industry 5.0 dimensions in the context of SFs, as well as identify potential weaknesses in the implementation. Furthermore, we have not investigated the complementarity of Industry 5.0 with other management approaches such as Lean Manufacturing (LM). However, the dimensions of Industry 5.0 align with the core principles of LM, such as waste reduction and a human-centric approach (ALVES; LIMA; GASPAR, 2023; MADDIKUNTA *et al.*, 2022). Therefore, it would be opportune to explore this correlation, the mutual benefits, and the potential simplification of the implementation process.

The proposed solutions in this study were based on a limited group of SFs, all of which were already participating in an innovation program, indicating their openness to new technologies—an attitude that may not reflect the behavior of most SFs in developing countries. While these insights are valuable, the findings may not be generalizable to a broader population. It is important to note that our propositions are based on case studies and expert insights, suggesting that further empirical evidence would enhance their validity. To address this limitation, expanding the scope of case studies to include different sectors or regions could aid in generalizing the results. Alternatively, complementing the methodology and conducting a survey with a more diverse group of companies could help identify common challenges and potential solutions.

SFs are crucial to the economy and society, providing employment and income. The government and development institutions need to provide support for their success (ALAYON; SÄFSTEN; JOHANSSON, 2022). Future studies can explore government support for SFs in digitization, social and environmental processes, and resilience. By highlighting the potential for collaboration between public authorities and stakeholders, we can further solidify the use of technology in these companies. However, in developing countries, government actions for SFs are often generic and lack clear metrics and objectives (KUNKEL; MATTHESS, 2020). It's important to empirically validate and verify the effectiveness of state and stakeholder collaboration in this process.

7 FINAL CONSIDERATIONS

The literature has extensively explored the integration of I4.0 technologies with sustainability (BIRKEL; MÜLLER; MULLER, 2021; BROZZI *et al.*, 2020; EJSMONT; GLADYSZ; KLUCZEK, 2020; GHOBAKHLOO, 2020; KAMBLE; GUNASEKARAN; GAWANKAR, 2018; STOCK; SELIGER, 2016). Additionally, authors have investigated the influence of I4.0 on SMEs (INGALDI; ULEWICZ, 2020; KHANZODE *et al.*, 2021). However, this study represents the first attempt to bridge I4.0, sustainability, and I5.0 with the realities of SMEs, which are often overlooked in technological advancement and undervalued for their sustainability impact (DENICOLAI; ZUCCHELLA; MAGNANI, 2021). This study thus offers a novel perspective on I4.0 and I5.0 theories, highlighting the interconnection of human-centered, resilient, and sustainable approaches across social, environmental, and economic dimensions. Additionally, it presents these results from a practical perspective, with actions and technologies that can be implemented by SMEs, thereby providing feasibility to the proposed suggestions.

This work comprises five articles focused on specific objectives. Article 1 identifies sustainability functions that can be enhanced through I4.0 digital technologies in SMEs, using a SLR. Article 2 ranks these sustainability functions through Fuzzy DEMATEL, identifying the most prominent and influential. Article 3 identifies the organizational factors that influence the adoption of Industry 4.0 in MSMEs. Articles 4 and 5 delve into practical applications via case studies, exploring necessary technological adaptations and understanding how providers can tailor solutions to meet SMEs' needs, addressing both sustainability and I5.0 pillars.

Article 1 presents an SLR of 42 articles about I4.0, SMEs and Sustainability that met inclusion criteria. Quantitative analysis reveals a growing research focus on developing countries, highlighting the relevance of these themes (KUMAR; SINGH; DWIVEDI, 2020; MASOOD; SONNTAG, 2020; NARA *et al.*, 2021). This review also identified key journals, guiding researchers on where to pursue related topics. In the qualitative phase, 17 sustainability functions were identified, supported by I4.0 in SMEs, including employee skill development, waste generation control, and production organization. Findings illustrate how I4.0 technologies can aid SMEs in achieving each function, with examples like AI and data analysis for HR management, IoT for resource control, and cloud-based WMS for inventory movement control. These analyses indicate that I4.0 technologies provide both economic and sustainability benefits for SMEs. In synthesizing knowledge across all three approaches, the article also highlights research gaps for future exploration.

Article 2 presents a quantitative study that ranks the sustainability functions identified in Article 1 using Fuzzy DEMATEL. Experts were consulted to rank functions by influence and prominence. Results indicate that the most prominent and influential functions include Organizing Production Processes, Employee Skill Development, and Simplifying Production Planning and Control. Therefore, investing in I4.0 technologies to support these functions can enable SMEs to amplify the impact of their sustainability initiatives and improve operational efficiency. The authors also observed that Improving Quality Monitoring is the primary function within the effect group. These findings can guide managers in prioritizing I4.0 implementation, starting with high-priority functions to reduce complexity and facilitate future technological and functional integration.

Article 3 employed cluster analysis and ordinal logistic regression to examine the influence of organizational factors on I4.0 adoption in MSMEs. The findings indicate that strategic, technical, and social factors positively influence I4.0 adoption. However, the analysis reveals that only specific factors within these dimensions should be prioritized, as they are the most significant predictors of adoption. Given the limited resources of MSMEs, efforts should primarily focus on Financial Resources, Strategic Vision Competitive Suppliers, and Qualified Employees, as these factors are likely to reduce the complexity of technology implementation. Furthermore, the study highlights that the larger the company size, the higher the probability of I4.0 adoption, as larger companies tend to be better prepared organizationally.

Article 4 utilizes qualitative semi-structured interviews with SME managers and technology providers to explore the practical implementation of I4.0 technologies, with a focus on sustainability and the unique constraints of SMEs in developing countries. The findings indicate that I4.0 technologies can help companies become more sustainable, offering solutions to social, environmental, and economic challenges. Proposals were tailored to address limited investments and workforce constraints, making sustainable I4.0 technology goals more feasible (ASCÚA, 2021). This study outlines a cost-effective, interconnected system of easily implementable technologies that meet managerial needs. Additionally, the study concludes that technology providers should prioritize solutions that are simple to implement and assist SMEs with comprehensive packages that include implementation, training, and maintenance, which can facilitate acceptance.

Article 5 also employs qualitative semi-structured interviews with managers and providers to explore I4.0 technology applications aligned with I5.0's goals: human-centricity, sustainability, and resilience in SFs in developing countries. Initially, the four "smart" dimensions of I4.0 were examined to identify potential technology applications across industries. These components were then linked to the pillars of I5.0, resulting in a framework integrating I4.0's smart dimensions with I5.0's three pillars. This framework can help SFs identify technologies best suited to I5.0 objectives, demonstrating the feasibility of adopting new technologies into SFs' operations. Thus, the study indicates that I4.0 technologies can also be used to achieve the objectives of Industry 5.0, confirming the complementary relationship between the two approaches.

7.1 MANAGERIAL AND THEORETICAL CONTRIBUTIONS

The results show that new digital technologies must be adapted to fit the unique needs of SMEs, which require solutions that are less complex and costly, with greater compatibility and connectivity across multiple devices (MASOOD; SONNTAG, 2020). SMEs often do not need a full suite of advanced technologies; rather, they prefer a select few that align with their vision (MITTAL *et al.*, 2018). This indicates a demand for 'plug-and-play' solutions, which enable rapid implementation and faster returns (KAHLE *et al.*, 2020). Our analysis highlights IoT, cloud computing, big data analytics, and AI as essential I4.0 technologies for sustainability, forming a foundation for various specific applications to achieve sustainability and meet the standards of I5.0, even in the context of developing count (FRANK; DALENOGARE; AYALA, 2019; PANDYA; KUMAR, 2023). Thus, our work emphasizes the viability of these solutions to support SMEs in achieving sustainability and meeting I5.0 standards, even in developing countries, particularly Brazil, where high real interest rates limit investment, causing SMEs to deprioritize digitalization and sustainability efforts. These contributions are summarized in Figure 2.

The results also highlighted the potential to implement technology to address human-centric, sustainable, and resilient concepts without compromising the competitiveness of the company. The advantages of incorporating I4.0 technologies are often indirect, making it challenging for companies to measure economic and financial benefits. These benefits arise through improved information for decision-making, organizational or process changes, enhanced quality, greater predictability, etc. (ASCÚA, 2021). However, this work identifies practical applications where the primary expectations of companies to be profitable and competitive could be respected, considering social and environmental dimensions that go beyond mere byproducts of economic gains (BIRKEL; MÜLLER; MULLER, 2021; DOSSOU *et al.*, 2022). The stability offered by digital operations management provides better working conditions, a safe manufacturing environment for workers, and contributes to reducing resource use (KAMBLE; GUNASEKARAN; GAWANKAR, 2018). This work contributes by highlighting that even with a low level of I4.0 implementation, some low-cost gains seem attainable, allowing for improvements in sustainability (BEIER *et al.*, 2022).

For SME managers, this study underscores the essential role of commitment and support from top management in improving performance through the adoption of new technologies (CHEGE; WANG, 2020). Such support is fundamental to initiating transformative change (DEY *et al.*, 2023; HARIASTUTI *et al.*, 2022; KHANZODE *et al.*, 2021). Furthermore, the study reveals that technology alone cannot resolve all sustainability-related challenges. A common misconception among companies is that technological investments will automatically generate positive performance outcomes (CIMINI *et al.*, 2021). It is necessary for organizations to foster cultural and behavioral changes alongside technology implementation (ESTENSORO *et al.*, 2021; LU *et al.*, 2022; SHUKLA; SHANKAR, 2023). The study highlighted a positive relationship between organizational factors and higher levels of Industry 4.0 adoption in MSMEs. It suggests that companies should prioritize improvements in Financial Resources, Strategic Vision, Competitive Suppliers, and Qualified Employees to minimize the complexity of technology implementation (WONG; KEE, 2022). The organizational factors examined are practical for MSMEs to implement, as they are within the companies' control, use accessible language, and have clear, achievable objectives. Finally, the results indicate specific sustainability functions that should be prioritized in terms of attention, effort, and investment, particularly as they hold high impact and influence over others. This approach enables companies to follow a clear implementation pathway, identifying areas for improvement and directing focused efforts, thereby avoiding frustration with simultaneous actions that may not yield immediate results (BETTIOL *et al.*, 2023).

For technology suppliers, this study highlights the importance of adapting technologies and sales processes to better align with SME needs. SMEs often lack the necessary knowledge about new technologies and their applications, making them less likely to invest in or implement these innovations (YU; SCHWEISFURTH, 2020). Thus, traditional marketing approaches may not be effective, and suppliers must work to raise SME awareness of the benefits and relevance of these tools (KAARTINEN; PIESKA; VAHASOYRINKI, 2017). This underscores the need for providers to develop and offer simpler solutions tailored specifically to SMEs. Additionally, investing in technical support services is essential to address the skill gaps that often hinder I4.0 adoption among SMEs, especially in developing countries (JAYASHREE *et al.*, 2022). Our findings offer guidance for technology providers on creating accessible solutions that require minimal time and effort to implement but still deliver impactful results, as well as prioritizing areas that should be the focus of their service offerings.

Finally, this study contributes to highlighting the main challenges faced by SMEs in implementing sustainable practices, I5.0 pillars, and adopting new technologies. We identify several barriers reported by managers of the studied SMEs, many of which are supported by existing literature (INGALDI; ULEWICZ, 2020; KHANZODE *et al.*, 2021; MOEUF *et al.*, 2020) and propose alternatives using technologies so that companies are not excluded from sustainable development.

7.2 LIMITATIONS AND FUTURE RESEARCH

The study has some limitations, particularly regarding the SLR methodology. The databases used may constrain the number of articles found, as the study was limited to the use of WoS and Scopus. While these databases are comprehensive and reputable, they cover only a fraction of scientific publications. Additionally, the research was confined to peer-reviewed journal articles, ensuring high quality. However, it omitted, for instance, conference papers, book chapters, and articles in other languages, which could also contain valuable information (BIRKEL; MÜLLER; MULLER, 2021; EJSMONT; GLADYSZ; KLUCZEK, 2020). Therefore, future work may expand the scope of this research to include new articles.

In the quantitative studies, the DEMATEL method faces certain limitations, particularly its dependence on expert evaluations, which can introduce a level of subjectivity (MACHADO *et al.*, 2021; VINODH; WANKHEDE, 2020). To mitigate this, sensitivity analysis was incorporated to enhance the methodological robustness of the proposed system (KUMAR; REHMAN; PHANDEN, 2022). Additionally, fuzzy set theory (ZADEH, 1965) was utilized to address uncertainties within expert judgments. As a result, managers should keep these limitations in mind when applying the findings to business decisions. Future research could examine alternative approaches and evaluate the advantages of integrating various MCDM methods. In the study that employed ordinal logistic regression, the limited sample size potentially restricts the generalizability of the findings. Additionally, the study did not specify how companies can develop the organizational factors influencing I4.0 adoption, only identifying which factors are relevant. Thus, future research could focus on methodologies that assist MSMEs in improving their organizational readiness to be better prepared for I4.0.

About the case studies, their scope was limited to analyzing the potential of technologies, examining how they could contribute to human-centric approaches, sustainability, and resilience in SMEs. However, the real impact of these implementations was not verified. These analyses were conducted with propositions derived from case studies and insights from selected experts, indicating that further empirical evidence would enhance the robustness of these propositions. Therefore, future studies could concentrate on analyzing the post-implementation stage of these technologies to conduct a retrospective analysis and assess the success of their integration with sustainability in the context of SMEs.

The proposed solutions in this study were based on a limited group of SMEs. While this provides valuable insights, the findings may not be generalizable to a larger population. To address this, conducting a survey with a more diverse group of companies can help identify common challenges and proposed solutions. Further research can expand upon our findings by conducting larger-scale studies involving a wider range of SMEs to validate and enhance the proposed framework. Additionally, the paper focuses on cases from Brazil. To better generalize and confirm the results, authors should expand the analysis to other developing countries where digitalization and sustainability approaches may differ (JAYASHREE *et al.*, 2021a).

This study focused on investigating manufacturing SMEs, and service-oriented SMEs were not analyzed. While the literature has laid a foundation for investigating Industry 4.0 technologies in manufacturing SMEs, there is still a need for research in service-oriented SMEs (PANDYA; KUMAR, 2023). This gap can be further explored in future studies.

Finally, it was observed that SMEs play a strategic role in the development of countries, given their economic importance (ASCÚA, 2021; COSTA MELO *et al.*, 2023a). However, government actions that can assist SMEs in implementing technology and sustainability were not investigated. The literature offers limited insight into the concrete efforts undertaken and the potential measures that governments can implement to attain the desired objective of having digitized, sustainable, and competitive SMEs (KHANZODE *et al.*, 2021; KUMAR; SINGH; DWIVEDI, 2020). Thus, future research can verify the effectiveness of state collaboration in this process.

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9 APPENDIX A

Appendix A functioned as the data collection instrument to **Article 2**. The first section of the questionnaire included informed consent, study objectives, and procedural details, with respondents being advised that there were no right or wrong answers to minimize bias. The second section captured expert profiles, while the third section focused on correlating sustainability functions. The aim was for respondents to rank the sustainability functions, indicating which are most prominent and influential among them.

Questionnaire – Sustainability Functions

Part 1 – Research Presentation

You are invited to volunteer in a research study. This document, called the Informed Consent Form, aims to ensure your rights as a participant, and you may keep a copy if you wish. If you have any questions before or even after indicating your electronic agreement, you may clarify them with the researchers during the research, either in person or online. Your identity will not be used.

Objectives: The primary justification for conducting this research is to identify which sustainability functions are priorities and exert the most influence on the sustainability/digitalization trajectory of small and medium-sized enterprises (SMEs) in the industrial sector. The sustainability functions that can be supported by Industry 4.0 technologies will be presented to you, and you should indicate the intensity of each item in relation to its respective importance/influence on the sustainability trajectory of SMEs.

Procedures: Initially, check the first option stating that you wish to participate as a volunteer. Then, enter your details and your email if you would like to receive statistically processed results and a final report of the research. Finally, please correlate the degree of influence of the sustainability functions based on your knowledge and experience. In Part 3, assess the intensity of the sustainability functions that can be supported by Industry 4.0 technologies in terms of importance and influence on SMEs. There are no right or wrong answers; evaluate according to your experience.

Do you agree to participate as a volunteer in this research? ( ) Yes
( ) No

Please enter your email address if you would like to receive the results of this research:

____

Part 2 – Respondent Profile

How many years of experience do you have with or in SMEs? ___________________

What is your knowledge/experience with Industry 4.0 technologies?

- None
- Up to 2 years
- 3 to 5 years

- More than 5 years

What is your knowledge/experience with sustainability?

- None
- Up to 2 years
- 3 to 5 years
- More than 5 years

Part 3 – Research Questionnaire

In the survey questions, you must compare two sustainability functions at a time (i.e., in pairs). The comparison scale should be used according to Table 27.

Table 27 - Legend used in the influence study

Code	Legend
VH	Very High Influence
H	High Influence
L	Low Influence
VL	Very Low Influence
NO	No influence

For example: If you are comparing the function in the row (SF1) "Employee Skills Development" with the function in the column (SF2) "Recruitment, Selection, and Career Planning," then a value of **VL** means that function SF1 has a *very low influence* on function SF2. Below is Table 28 for completion.

Table 28 - Sustainability functions that can be supported by Industry 4.0 technologies in manufacturing SMEs

	Functions in column j																	
		SF1	SF2	SF3	SF4	SF5	SF6	SF7	SF8	SF9	SF10	SF11	SF12	SF13	SF14	SF15	SF16	SF17
	SF1	0																
	SF2		0															
	SF3			0														
	SF4				0													
	SF5					0												
	SF6						0											
	SF7							0										
Functions in row x	SF8								0									
	SF9									0								
	SF10										0							
	SF11											0						
	SF12												0					
	SF13													0				
	SF14														0			
	SF15															0		
	SF16																0	

	SF17																	0
	* Do not fill in any entries in boxes marked with 0.																	

Table 29 presents the legend of sustainability functions for completing Table 28.

Table 29 - Description of sustainability functions that can be supported by Industry 4.0 technologies in SMEs

Dimension	Code	Sustainability Function
Social	SF1	Employee skill development
	SF2	Recruitment, Selection, and Career Planning
	SF3	Improving Work Ergonomics - Posture, Movements, Physical Effort
	SF4	Improving Work Ergonomics - Environmental Analysis
	SF5	Minimizing Effort, Stress, and Monotony
	SF6	Enhancing Workplace Safety
	SF7	Improving Company-Customer Relationship
Environmental	SF8	Reducing Energy Consumption and Waste
	SF9	Reducing Water Consumption and Waste
	SF10	Controlling Waste Generation
Economic	SF11	Organizing Production Processes
	SF12	Organizing Warehouse
	SF13	Simplifying Production Planning and Control
	SF14	Optimizing Supply Chain Connectivity
	SF15	Optimization of Maintenance Processes
	SF16	Improve Quality Monitoring
	SF17	Enhancing Product Quality

10 APPENDIX B

Appendix B served as a data collection instrument to **Article 4**. The semi-structured questionnaire comprises questions addressing sustainability challenges across three dimensions - social, environmental, and economic. It aims to identify the obstacles faced by companies and the practices and tools they employ in pursuit of sustainability.

1. Do you face energy management challenges in your company?
   a) How do you manage this? Do you have metrics? Do you use any technology?
2. Do you encounter resource utilization challenges (such as water) in your company?
   a) How do you handle this? Do you have metrics? Do you use any technology?
3. Are there challenges regarding input and raw material consumption in your company?
   a) Do you experience significant waste? Is this a problem for you?
   b) How do you address this? Do you have metrics? Do you use any technology?
4. How does your company innovate in internal processes to boost productivity and cut costs?
5. What are the main challenges in production processes? Inventory management? Organizational processes?
6. What are the challenges in the relationship/integration with suppliers and clients?
7. How is the acceptance of technology usage among your employees?
8. What challenges do your employees face in carrying out their duties regarding ergonomics?
   a. How do you manage this? Do you use any technology?
9. How does the company contribute to the comfort and well-being of its employees?

11 APPENDIX C

Appendix C presents a literature review of articles examining Industry 5.0 to **Article 5**, highlighting a research gap to be addressed (Table 30). This review shows that many studies often overlook the needs and potential of small firms, especially in developing countries. This analysis reinforces the need to explore how to integrate I5.0 into small firms.

Table 30 - Literature review of articles examining Industry 5.0

Title	Authors	Main Results
Actions and approaches for enabling Industry 5.0-drive	Ghobakhloo et al., 2022a	Identified and prioritized 11 drivers for Industry 5.0 within a strategic roadmap, with the first being governmental support and public policies, and the second being resource capacity.
Can industry 5.0 revolutionize the wave of resilience and social value creation? A multi-criteria framework to analyze enablers	Sindhwani et al., 2022	Prioritized enabling technologies to achieve Industry 5.0 objectives in social and resilience domains, with a focus on bionics and IoT.
Disruptive Technologies and Operations Management in the Industry 4.0 Era and Beyond	Choi et al., 2022	Discussed the pros and cons associated with the use of disruptive technologies and uncovered potential human–machine conflict areas. They presented the results in a two-level, multi-step framework to illustrate how policymakers can achieve human–machine reconciliation.
Identifying industry 5.0 contributions to sustainable development: A strategy roadmap for delivering sustainability values	Ghobakhloo et al., 2022b	Identified Industry 5.0 functions to achieve sustainability values and prioritized them to establish implementation priorities.
Industry 4.0 and Industry 5.0—Inception, conception and perception	Xu et al., 2021	Identified the main differences between Industry 4.0 and Industry 5.0, and how companies should approach the challenges of the transition.
Industry 5.0—A Human-Centric Solution	Nahavandi, 2019	Discussed the infrastructure adaptation needs for implementing Industry 5.0, including its technological potential involving collaboration between robots and humans.
Industry 5.0: Prospect and retrospect	Leng et al., 2022	Correlated enablers for Industry 5.0 with potential applications and implementation pathways, while introducing the main challenges.
Industry 5.0: A survey on enabling technologies and potential applications	Maddikunta et al., 2022	Identified the key technologies and their applications necessary to achieve Industry 5.0 goals in sectors such as Healthcare and Supply Chain, along with the main challenges for implementation.

Is Industry 5.0 a Human-Centred Approach? A Systematic Review	Alves et al., 2023	Presented the concept and potential of I5.0 with a primary focus on the human element, emphasizing the need to adapt technologies to ensure the human is at the center of the system.
Maturity assessment for Industry 5.0: A review of existing maturity models	Hein-Pensel et al., 2023	Examined existing maturity models and identified that none are human-centric as required by Industry 5.0, nor adaptable for SMEs. On the contrary, these models tend to be holistic, generic, and not very instructive.
Outlook on human-centric manufacturing towards Industry 5.0	Lu et al., 2022	Presented a framework consolidating the concepts, needs, and enabling technologies necessary to achieve human-centric manufacturing, indicating that such a scenario is possible to attain.
The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human-centricity perspectives	Ivanov, 2022	Presented a framework for Industry 5.0, based on its principles and applicability across societal levels, networks, and within plant operations, from the perspectives of operations and supply chain management.