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RODRIGO GOYANNES GUSMÃO CAIADO

A DECISION SUPPORT FRAMEWORK FOR DIGITALIZATION AND SUSTAINABILITY OF OPERATIONS AND SUPPLY CHAIN MANAGEMENT ALIGNED WITH THE 2030 AGENDA

Thesis presented to the Post Graduation program *Stricto Sensu* in Production Engineering at Universidade Federal Fluminense as partial fulfillment of the requirements for the Doctoral degree (Ph.D.) in Production Engineering.

Area: Systems, Decision Support and Logistics.

Professor Advisor:

Prof. Dr. Osvaldo Luiz Gonçalves Quelhas

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“We are what we repeatedly do. Excellence, then, is not an act,
but a habit.”

(Will Durant)[1].

DURANT, Will. Story of philosophy. Simon and Schuster, 1961.

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ABSTRACT

Industry 4.0 (I4.0) requires rethinking and changing the mindset of how products are manufactured and the services used, leading to a significant structural revolution for operations and supply chain management (OSCM). The adoption of sustainability has also become an essential aspect for industries to sustain themselves in the global market. Although the concept of I4.0 was not popularized in the ratification of Agenda 2030, I4.0 is a watershed in the implementation of the Sustainable Development Goals (SDGs). It can serve as a platform for alignment of the SDGs with the ongoing digital transformation. However, it remains unclear the enablers for sustainable digitalization, the challenges to integrating I4.0 and sustainability in OSCM, the potential I4.0 sustainable technological solutions, and the benefits of this integration, in line with SDGs. Additionally, there is still a lack of a holistic framework that establish links between these enablers, challenges, solutions, and benefits to guide organisations on the journey to sustainable digitalization in OSCM (S-OSCM4.0) and to strategically support their alignment with the SDGs. Therefore, this thesis aims to propose an S-OSCM4.0 framework to help organizations to stay up to date in I4.0 adoption and penetrate sustainability in OSCM in line with Agenda 2030; and to develop a new decision support framework to apply and test the proposed S-OSCM4.0 framework using a series of MCDM analysis to identify the key enablers to be adopted to obtain the benefits, and to select de adequate solution to face these challenges. This thesis employs a multi-method approach structured in three stages. The first stage is theoretical research and will be directed towards the construction of the framework, which covers three steps: systematic review, development of taxonomies and proposition of a conceptual framework. The second and third stages are empirical and consist of the development of the decision support framework. This explorative research study applied a triangulated methodology with qualitative and quantitative data collection mechanisms combining multiple group decision making approaches, such as Fuzzy Delphi, FAHP, FVIKOR, and FDEMATEL, Q-sort, and ELECTRE. The proposed and validated decision support framework focuses on the linkage between ten benefits, ten key enablers, six solutions and 13 challenges; and may be used for different applications. The following contributions can be highlighted as the main distinguishing features of this doctoral thesis: i) expand the literature review of sustainable I4.0; ii) highlight challenges, potential solutions and enablers involving the integration between I4.0 and sustainability in OSCM; iii) identify social and environmental benefits, shaped in Agenda 2030, of the integration of I4.0 and sustainability for OSCM, iv) to propose an S-OSCM4.0 framework with an empirical study approach and treatment of decision support method to increase the applicability of the developed framework, and v) to propose and apply a hybrid multicriteria decision support framework to drive the implementation of S-OSCM4.0. Thus, this study presents theoretical, managerial and political implications to sustainable digitalization, and it is expected that this inspires further investigation and exploration in the areas of sustainable I4.0 and fuzzy group decision making in OSCM. The proposed framework represents a pioneering managerial artefact that integrates taxonomies to guide sustainable development effectively and holistically through an inclusive digital transformation with less impact on the environment and sheds light on the potential of sustainable I4.0 in terms of maximizing company contributions to the SDGs.

Keywords: Industry 4.0; Sustainability; Sustainable Development Goals; Operations and supply chain management (OSCM); Multiple-criteria decision-making (MCDM); Fuzzy logic.

RESUMO

Atualmente, a Indústria 4.0 (I4.0) requer repensar e mudar a mentalidade de como os produtos são fabricados e os serviços usados, levando a uma revolução estrutural significativa para operações e gerenciamento da cadeia de suprimentos (OSCM). A adoção da sustentabilidade também se tornou um aspecto extremamente essencial para que as indústrias se sustentem no mercado global. Embora o conceito de I4.0 não tenha sido popularizado na ratificação da Agenda 2030, I4.0 é um divisor de águas na implementação dos Objetivos de Desenvolvimento Sustentável (ODS) e pode servir como uma plataforma para o alinhamento dos ODS com a transformação digital em curso. No entanto, ainda não está claro quais são os facilitadores para a digitalização sustentável, os desafios para integrar I4.0 e sustentabilidade em OSCM, o potencial de soluções tecnológicas sustentáveis e os benefícios desta integração, em linha com os ODS. Além disso, ainda falta um framework holístico que estabeleça ligações entre esses facilitadores, desafios, soluções e benefícios para orientar as organizações na jornada para a digitalização sustentável em OSCM (S-OSCM4.0) e para apoiar estrategicamente seu alinhamento com o ODS. Portanto, esta tese propõe um framework de S-OSCM4.0 para ajudar as organizações a se manterem atualizadas na adoção do I4.0 e penetrar a sustentabilidade no OSCM em linha com a Agenda 2030; e desenvolve um novo framework de apoio à decisão para aplicar e testar o framework conceitual de S-OSCM4.0 proposto usando uma série de análises de apoio multicritério a decisão (AMD) para identificar os principais facilitadores a serem adotados para obter os benefícios e selecionar a solução adequada para enfrentar esses desafios. Esta tese emprega uma abordagem multi-método estruturada em três estágios. O primeiro estágio é a pesquisa teórica e será direcionada à construção do framework, que compreende três etapas: revisão sistemática; desenvolvimento de taxonomias e proposição do framework. O segundo e a terceiro estágios são empíricos e consistem no desenvolvimento do framework de AMD. Esta pesquisa exploratória aplicou uma triangulação com mecanismos de coleta de dados qualitativos e quantitativos combinando múltiplas abordagens de AMD em grupo, como Fuzzy Delphi, FAHP, FVIKOR e FDEMATEL, Q-sort e ELECTRE. O framework de AMD concentra-se na ligação entre 10 benefícios, 10 facilitadores principais, seis soluções e 13 desafios; e pode ser usado para diferentes aplicações. Portanto, as seguintes contribuições podem ser destacadas: i) ampliar a revisão da literatura sobre sustentabilidade I4.0; ii) destacar desafios, soluções potenciais e facilitadores envolvendo a integração entre I4.0 e sustentabilidade em OSCM; iii) identificar benefícios sociais e ambientais, moldados na Agenda 2030, da integração de I4.0 e sustentabilidade para OSCM, iv) propor um framework de S-OSCM4.0 com uma abordagem de estudo empírico e tratamento de método de apoio à decisão para aumentar a aplicabilidade do framework desenvolvido e v) propor e aplicar um framework híbrido de AMD para conduzir a implementação do S-OSCM4.0. Assim, este estudo apresenta implicações teóricas, gerenciais e políticas para a digitalização sustentável, e espera-se que isso inspire mais investigação e exploração nas áreas de I4.0 sustentável e tomada de decisão em grupo son incerteza em OSCM. O framework proposto representa um artefato gerencial pioneiro que integra taxonomias para orientar o desenvolvimento sustentável de forma eficaz e holística por meio de uma transformação digital inclusiva com menos impacto sobre o meio ambiente e lança luz sobre o potencial do I4.0 sustentável em termos de maximizar as contribuições da empresa para os ODSs.

Palavras-chave: Indústria 4.0; Sustentabilidade; Objetivos de desenvolvimento sustentável (ODS); Gestão de operações e cadeia de suprimentos; Apoio multicritério à decisão (AMD); Lógica difusa.

LIST OF RELATED PUBLICATIONS

I. **Factories for the Future: Towards Sustainable Smart Manufacturing**

Rodrigo Goyannes Gusmão Caiado, and Osvaldo Luiz Gonçalves Quelhas.
Responsible Consumption and Production, 239-250, 2020.
DOI: 10.1007/978-3-319-95726-5_108

II. **A literature-based review on potentials and constraints in the implementation of the sustainable development goals**

Rodrigo Goyannes Gusmão Caiado, Walter Leal Filho, Osvaldo Luiz Gonçalves Quelhas, Daniel Luiz Mattos Nascimento, and Lucas Veiga Ávila.
Journal of Cleaner Production, 198, 1276-1288, 2018.
DOI: 10.1016/j.jclepro.2018.07.102

III. **A taxonomies-based framework towards sustainable Industry 4.0 for operations and supply chain management.**

Rodrigo Goyannes Gusmão Caiado, Luiz Felipe Scavarda, Osvaldo Luiz Gonçalves Quelhas, Bruno Duarte Azevedo, Eduardo Machado
Technological Forecasting & Social Change. **Working paper**, 2021.

IV. **Challenges and benefits of sustainable Industry 4.0 for operations and supply chain management - A framework headed to Agenda 2030.**

Rodrigo Goyannes Gusmão Caiado, Luiz Felipe Scavarda, Bruno Duarte Azevedo, Daniel Nascimento, Osvaldo Luiz Gonçalves Quelhas, 2021.
Sustainability. **Working paper**

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List of Abbreviations

AI	Artificial intelligence
AM	Additive manufacturing
AR	Augmented reality
BDA	Big data analytics
BIM	Building Information Modeling
CPS	Cyber-physical systems
DCV	Dynamic capability View
DL	Deep Learning
HMI	Human-Machine Interface
HPC	High-Performance Computing
I4.0s	Industry 4.0
IIoT	Industrial Internet of Things
IoT	Internet of Things
M2M	Machine-to-Machine
MES	Manufacturing Execution System
ML	Machine Learning
OSCM	Operations and Supply Chain Management
RFID	Radio-frequency identification
SCM	Supply Chain Management
SD	Sustainable Development
SDGs	Sustainable Development Goals
SLR	Systematic Literature Review
TBL	Triple Bottom Line
VR	Virtual Reality
WSN	Wireless Sensor Networks

CONTENTS

1 INTRODUCTION

1.1 Industry 4.0, sustainability and Operations and Supply Chain Management (OSCM)

The fourth industrial revolution, the so-called Industry 4.0 (I4.0), aims to link disruptive technologies to manufacturing systems, tailoring intelligent operations and supply chain management (OSCM) (CAIADO et al., 2021). Kamble, Gunasekaran and Gawankar (2018) state that I4.0 is a range of technologies that allow the development and growth of value chains, leading to a reduction in time with improved quality and increased performance.I4.0 has shown a significant structural theoretical revolution for OSCM (KOH; ORZES; JIA, 2019), which is a vast domain that encompasses several areas of knowledge in the fields of operations management (OM) and supply chain management (SCM) (COUGHLAN et al., 2016). The transition to I4.0 brought to the industry new standards of decentralized and digitalized production (KOH; ORZES; JIA, 2019) and represented a new industrial stage that integrates a set of digital technologies throughout the product's life cycle (FRANK; DALENOGARE; AYALA, 2019), dynamically and autonomously (TORTORELLA et al., 2019; TORTORELLA; FETTERMANN, 2017).

I4.0 is also considered a socio-technical concept in which technological, social and organizational aspects interact (BEIER et al., 2020). Sony e Naik (2020) state that as I4.0 is a socio-technical system, there is a consensus that for an I4.0 to be sustainable, the social and technical elements must be considered together. Additionally, as I4.0 is dealing with the need to produce within environmental constraints (Bonilla et al., 2018), it can be seen as a new vision that can help organizations and society move towards sustainable development (SD) (DE SOUSA JABBOUR et al., 2018). Although the concept of I4.0 was not so popular in the ratification of the Agenda 2030 for SD, I4.0 remains a landmark in the implementation of sustainable development goals (SDGs) through information and communication technologies (ICTs) (NHAMO; NHEMACHENA; NHAMO, 2020). Thus, as Beier et al. (2020), I4.0 can offer a great chance to align the SDGs with the digital transformation underway in industrial development, which in turn also carries the potential to become a threat if sustainability goals are not taken into account during the implementation of I4.0.

I4.0 and sustainability have become the emerging segments for supply chains to improve productivity and develop a more sustainable culture (LUTHRA; MANGLA, 2018). I4.0 has the potential to unlock sustainability in emerging economies (BONILLA et al., 2018a). This is due to the fact that I4.0 may be the last chance for truly sustainable production with greater long-term competitiveness (EROL et al., 2016), integrating greater rationality and sustainability (e.g., optimized use of resources) in manufacturing systems for the production of the future (STOCK et al., 2018). The adoption of sustainability in OSCM is more a concern for manufacturing organizations, as the constantly changing market has insisted that these organizations review their activities to penetrate sustainability effectively through various practices (e.g. lean manufacturing, green manufacturing, circular economy (CE) and I4.0) (YADAV et al., 2020a). In this context, various stakeholders are demanding that the manufacturing sector produces in an economically, environmentally and socially sustainable manner (BONILLA et al., 2018a).

Many countries have also enacted policies related to promoting sustainable OSCM (Matos et al., 2020), such as restricting factory emissions and encouraging renewable energy (MENG et al., 2018). Likewise, the solutions needed to overcome the problems of adopting sustainable SCM also need to be updated according to the constantly changing business environments, and, thus, sustainability is considered a key component of contemporary and socially responsible SCM (CHIAPPETTA JABBOUR et al., 2020a). Also, although OM is crucial to the economy of organizations, due to the pursuit of business impact, it also plays an important role in making sustainable operations related to the environment and society (KOVÁCS et al., 2020). Recent studies have also shown that companies need to accelerate the shift from focus to sustainability and make use of digital technologies (e.g., Internet of Things) to meet organizational goals with greater performance (MANAVALAN; JAYAKRISHNA, 2019; MASTOS et al., 2020).

1.2 Research gaps and questions

Due to advances in technology, OSCM is undergoing significant changes and to maintain the quality of OSCM research, it is essential to be in touch with the latest theoretical and methodological developments, which generally occur in other areas (MELNYK; FLYNN; AWAYSHEH, 2018). However, as Koh, Orzes and Jia (2019) and Caiado et al. (2021), there is still a lack of consideration of research on I4.0 disruptive technologies in OSCM and even less research on what leads I4.0 towards sustainability (STOCK et al., 2018). In addition, previous studies do not clearly show how I4.0 and sustainable OSCM (S-OSCM) are interlinked and how I4.0 leads to sustainability at OSCM (BAG et al., 2018).

Different enablers should be identified and analyzed in this regard. Recent literature has dealt extensively with trends in smart manufacturing (BAG et al., 2018; CHIAPPETTA JABBOUR et al., 2020b; DE SOUSA JABBOUR et al., 2018; GHOBAKHLOO, 2020;

Machado et al., 2020), but the future of the industry depends on some critical factors (e.g., creation of collaborative networks that need effective interoperability approaches and support infrastructures based on open architectures) that still need to be clarified (PANETTO et al., 2019). Enablers, also known as facilitators or drivers, are considered necessary actions to ensure success and competitiveness (LINS; ZOTES; CAIADO, 2019). They can be understood as the key points or conditions that must be met to achieve a change (JULIANELLI et al., 2020), and can also be relevant to prioritise specific valuable resources in resource-constrained environments (DE SOUSA JABBOUR et al., 2018). Therefore, there is a need to distinguish and examine the enablers for integrating I4.0 into supply chains to achieve sustainable SCs, and little discussion is still available regarding the definition of I4.0 enablers to achieve SCs sustainability in the context of an emerging economy (LUTHRA et al., 2020). While it is imperative for companies to recognize all the enablers in I4.0 that can lead to smooth OSCM and achieve sustainability (BAG et al., 2018), it remains unclear what are the enablers for the integration between I4.0 and sustainability in OSCM.

Moreover, while it is essential to understand the underlying dynamics of implementing I4.0, which requires new mindsets to deal with the challenges of digital transformation, there are still few studies focusing on the challenges of implementing I4.0 in companies (MÜLLER; KIEL; VOIGT, 2018). In a complementary way, considering the challenges of I4.0 (e.g., data quality and credibility, unemployment, complexity problems, less human control and greater negative environmental impacts), rigorous research is needed to address the implications of sustainability in intelligent industrial value chain systems based on I4.0 (LUTHRA; MANGLA, 2018). It becomes necessary to identify the crucial factors that obstruct the successful alignment of S-OSCM and I4.0, which have been reported by many studies in the form of barriers, failure factors and challenges (YADAV et al., 2020b). In this vein, it is observed a need to identify the challenges to align sustainability and digital issues towards S-OSCM4.0.

I4.0 solutions are identified as key digital (or disruptive) technologies that enable the development of sustainable supply chain management (SSCM) (MASTOS et al., 2020). However, little is known about the current state of the art on digitally-enabled sustainable OSCM (KOVÁCS et al., 2020). Understanding the current state of knowledge in this area is a relevant priority because I4.0 technologies have the potential to reshape and create more successful OSCM (CHIAPPETTA JABBOUR et al., 2020a). Although previous literature (Li et al. 2020) established the links between digital technologies and the dimensions of sustainability, it is still necessary to enhance the understanding of sustainable technological solutions, which mean solution measures based on I4.0 technologies that can be implemented to favour the achievement of sustainability. According to Yadav et al. (2020b), these solutions will help organisations to remain updated with the advanced technologies and penetrate the sustainability in the SC. Hence, there is also a need to understand what the potential sustainable technological solutions are.

Most studies on the I4.0 digital transformation have focused on the technical aspect of architecture design for integration for the implementation of I4.0 and, as a consequence, the sustainability aspects are not researched comprehensively and possible potentials are not identified (BEIER et al., 2020). Unlike sustainable initiatives, in general, I4.0 technologies do not consider the social and environmental dimensions of sustainability and do not pay attention to the sustainable value of products or the environmental risk of digital transformation processes (LI; DAI; CUI, 2020). Also, while the potential benefits of integrating digital technologies and SCM have been widely reported by both academics and practitioners (CHIAPPETTA JABBOUR et al., 2020b), less is known regarding the current state-of-the-art literature of S-OSCM 4.0 benefits. In this sense, there is a need to investigate the benefits of S-OSCM 4.0 implementation, and even more intense from the triple bottom line (TBL) perspective (KIEL et al., 2017a).

Moreover, although several researchers (BESKE; SEURING, 2014; KHALID et al., 2015) working on sustainability, from generating ideas to delivering the final product to the end user (BASTAS; LIYANAGE, 2018) have proposed frameworks to improve the adoption of sustainability in OSCM, it is significant to note that the current era of the industry is rapidly shifting to digitalization and therefore it has become difficult for organizations to adopt S-OSCM effectively using traditional and sustainability supply chain practices (Yadav et al., 2020a). In addition, the literature (MANAVALAN; JAYAKRISHNA, 2019) suggests that sustainability in OSCM leveraging the fourth industrial revolution has not been previously addressed and, therefore, is considered a gap. Few frameworks in the literature related to the adoption of sustainability in OSCM, focus on the link between challenges or facilitators and solution measures based on I4.0 (BAG et al., 2018; KAMBLE; GUNASEKARAN; GAWANKAR, 2018; YADAV et al., 2020b, 2020c). Bag et al. (2018) proposed a framework of 13 key I4.0 enablers that influence supply chain sustainability. Kamble et al. (2018) proposed a sustainable I4.0 framework comprising of three components: I4.0 technologies, process integration and sustainable outcomes. Manavalan and Jayakrishna (2019) proposed a framework for assessing SSCM from an I4.0 perspective, which contains five enablers that influence the sustainability to meet the requirements of I4.0. Yadav et al. (2020b) have developed a framework that links SSCM challenges with its solution measures. Yadav et al.

(2020a) have developed a framework of I4.0 technologies enablers to improve sustainability adoption across manufacturing organizations of developing nations. However, none of the frameworks available in the literature managed to establish links enablers for sustainable digitalization, the challenges to integrate I4.0 and sustainability in OSCM, the potential I4.0 sustainable technological solutions to generate and obtain the S-OSCM4.0 benefits associated with Agenda 2030. The gaps in the existing literature led to developing the following research questions (RQs):

RQ1: What are the enablers for the S-OSCM4.0?

RQ2: What is the current state of the challenges for S-OSCM4.0?

RQ3: What sustainable technological solutions can be implemented to achieve SD in OSCM?

RQ4: Considering the SDGs, what are the benefits of the integration of I4.0 with sustainability?

RQ5. How to link enablers, challenges, and sustainable technological solutions, to obtain the benefits of S-OSCM4.0 implementation?

Furthermore, considering the dynamism of changes related to the I4.0' era and sustainable needs, the definition and adoption of the right set of enablers (drivers) is complex; it is practically infeasible to address all the possible challenges – obstacles and barriers - simultaneously, being also necessary to understand their relationships (KOUHIZADEH; SABERI; SARKIS, 2021). Thus, the selection of the solutions to tackle these challenges depends on its priorities, as well as, the order of adoption of the key enablers - critical factors - might consider the priority (LUTHRA et al., 2020) of the benefits of the sustainable I4.0 adoption, combining modern technologies as a tool for economic recovery and to shift sustainable production (TORBACKI, 2021), in OSCM. In this vein, multi-criteria decision-making (MCDM) methods may be suitable approaches to aid OSCM organizations (KOUHIZADEH; SABERI; SARKIS, 2021) towards sustainable I4.0 (MACHADO et al., 2021), as they can model the problem and can be used to design a decision support system (QUEZADA et al., 2017).

In addition, most of the studies on sustainability and Industry 4.0 are based on theoretical research and are conducted in a general manner and now, and in the after coronavirus disease 2019 (COVID-19) pandemic period, there is a growing interest in sustainable I4.0, and still a need for a recognized decision support framework that direct the strategic choice of digitalization solutions (TORBACKI, 2021), considering the mutual influence of quantitative and qualitative elements (CHANG; CHANG; LU, 2021).

Moreover, as the disruptive solutions brought by I4.0 and sustainability usually means organizational changes and new ways of handling processes, it is still necessary to develop a methodology to counteract this phenomenon by combining MCDM methods to aid participants of S-OSCM 4.0 organizations to determine the best way to ensure the company's sustainable digitalization, supported by the best implementation strategy, through better decisions and efficient allocation of resources (TORBACKI, 2021).

In this sense, through a study with professionals from an emerging nation context (Brazilian organizations), this thesis also seeks to empirically answer the following questions:

RQ6. What are the key enablers to integrate sustainability and I4.0 in OSCM?

RQ7. What is the criticality order of deploying these enablers to achieve S-OSCM4.0 benefits?

RQ8. What are the necessary enablers to develop sustainable technological solutions?

RQ9. What is the interrelation between these key enablers for S-OSCM4.0?

RQ10. What solutions should be chosen to tackle the prioritized challenges?

These last five questions also represent the test of the proposed S-OSCM4.0 framework from the Brazilian perspective. Despite some previous studies containing examples of the use of hybrid multicriteria decision methods in the context of sustainable Industry 4.0 (TORBACKI, 2021), the gap in this respect is still indisputable. In principle, there are no articles on the subject of the S-OSCM4.0 proposing a decision support framework covering taxonomies of enablers, challenges, solutions and benefits, as well as developing an assessment of the elements of this framework using multiple methods combined with group decision making and fuzzy logic. This thesis also seeks to fill the gap of studies that propose a structured perspective for evaluating sustainable I4.0 through a systematic and process viewpoint (CHANG; CHANG; LU, 2021).

1.3 Research aim, contributions and originality

Within this context, the purpose of this thesis is twofold:

(i) to propose a **framework for the implementation of S-OSCM4.0** by aligning enablers to achieve the sustainable I4.0' benefits, headed to Agenda 2030 (#17 SDGs) and sustainable technological solutions to tackle the challenges for integration of I4.0 and sustainability in OSCM;

(ii) to **develop a new decision support framework** in order to apply and test the proposed S-OSCM4.0 framework using a series of MCDM analyses to identify the right set of factors to be adopted to obtain SD benefits and to select de adequate solution to face these challenges.

This thesis contributes in numerous ways. First, it offers a rigorous and well-defined approach, through a systematic literature review (SLR), to review, analyse, and synthesise and interpret the fragmented literature of I4.0 and sustainability in OSCM. Additionally, it provides a global vision of the OSCM domain, through a holistic and integrated vision of sustainability that explores the sustainable OSCM from the perspective of UN SDGs, and through an inclusive and sustainable digital transformation of the industry, it expands the literature on sustainable I4.0 with particular focus on digitally activated S-OSCM, addressing research practice gaps highlighted before (e.g., paving the way to the transition to more sustainable OSCM practices through I4.0 emerging technologies (MATOS et al., 2020).

Moreover, it is one of the few embryonic studies in the OSCM domain that proposes taxonomies of enablers, challenges, potential technological sustainability solutions and for integrating I4.0 and sustainability, as well as benefits of, which indicates how the I4.0 technologies have the potential to reshape the sustainability of OSCM. The literature available to sustainable I4.0 adoption either focuses on the taxonomy of challenges, benefits, or enablers. For example, de Sousa Jabbour et al. (2018) propose a taxonomy of enablers to boost the integration between I4.0 and environmentally sustainable manufacturing. Luthra and Mangla (2018) provided taxonomies of challenges for effective I4.0 initiatives for supply chain sustainability. It is extremely critical to explore the association between the taxonomies (BASHSHUR et al., 2011), but few studies provide the links between the taxonomies of benefits and challenges (KIEL et al., 2017a), and even fewer studies provide the alignment of the taxonomies of SSCM challenges and I4.0 solution measures (YADAV et al., 2020b). Thus, this research has met the lack of studies of combining multiple taxonomies (enablers, challenges, solutions, and benefits) towards S-OSCM4.0. Finally, it also attempts to establish the causal relationships between the S-OSCM4.0 and the SDGs, providing testable propositions about these relationships.

Furthermore, given the COVID-19 pandemic, this research is particularly relevant and impacting, since the aspect of value to society begins to emerge, the non-understanding of the logic of OSCM puts many lives at risk and digitalization in sustainability represents a fairly open field (KOVÁCS et al., 2020). According to Kovács et al. (2020), Sustainability in OSCM goes beyond mere mission statements and begins to be addressed more seriously, also capturing environmental and social impacts in the supply chain, which gives hope of the potential impact and opportunities offered by this research in emerging economies and at the base-of-the-pyramid., especially in this era of the "*economy of scarcity*" in global supply chains.

In this S-OSCM4.0framework, the concrete implementation of I4.0 technologies and enablers is seen as a platform for the achievement of the SDGs, shaping sustainable operations and supply chains. This will help organizations balance the need for operational excellence in their production and service systems while remaining committed to environmental concerns and social justice.

Finally, this novel decision support framework developed aims to facilitate the sustainable digital transformation (VENÂNCIO et al., 2021), by prioritizing key enablers, indicating their relation to developing sustainable technological solutions, as well as pointing out their causal relations, and identifying the adequate solutions to be implemented to face prioritized challenges. The proposed decision support framework is composed of two stages – construction and application - detailed in Chapter 3, which encompass the combination of multiple methods. Regarding the validation of the S-OSCM4.0 framework, unlike most studies that use a single case study design (GUPTA; KUMAR; WASAN, 2021), this study uses mixed methods approach combining multiple case studies and fuzzy MCDM tools. The presented framework is relatively easy to apply by organizations of other emergent nations and could pave the way for future work to do research involving the use of other fuzzy MCDM methods for S-OSCM 4.0.

To achieve these two principal goals, this thesis is structured into five chapters. After this introduction, Chapter 2 describes the central concepts of this thesis, which are sustainability and I4.0 in OSCM. Chapter 3 describes the adopted research methodology. Chapters 4 details the theoretical and empirical results, including study descriptors, and categorises and analyses four taxonomies (enablers, challenges, solutions, and benefits) found in the literature, as well as the S-OSCM4.0 framework towards Agenda 2030, and the empirically validated decision support framework for S-OSCM4.0, outlining the key enablers, their interrelationship and the adequate set of solutions to overcome the challenges of I4.0-sustainability integration in OSCM. Chapter 5 presents the concluding remarks and potential avenues for future research.

2 BACKGROUND

2.1 Sustainable development

The social, cultural, economic and environmental challenges facing humanity are becoming more urgent, complex and interrelated, and end up increasing the connection between science and society (ARICÓ, 2014). Sustainability is an iterative process that includes multiple perspectives and disciplines (CAIADO et al., 2018; CAIADO; QUELHAS, 2020).

The current concepts of SD are increasingly important, encompassing, in addition to strictly economic concerns, environmental and social development, and impacting people's very survival (KUMI; ARHIN; YEBOAH, 2014). In this context, it is necessary that science serves policy, as well as dealing with requests from the government and multiple stakeholders when they are met with the challenge of achieving sustainable development (ARICÓ, 2014).

The SDGs - successors to the MDG - were agreed in September 2015 in New York, USA, by 193 countries and focused on a highly comprehensive set of development goals (Aitsi-Selmi et al. 2016). The new SDGs and their targets are expected to guide decisions to be made over the next fifteen years and fundamentally influence international policy and available funding for sustainable development, thereby shaping policy efforts futures and the dynamics of natural capital (TERAMA et al., 2015). Furthermore, governments are expected to use these goals to combat extreme poverty and address the challenges that come with ensuring sustainable environmental, social and economic development in their respective communities (CHOI et al., 2016). The SDGs were formulated through an extensive participatory process and passed through high-level panels such as open working groups (OWG), along with numerous consultations, until a negotiated document was finally approved by the heads of state. The heads of state have established five critically important fields, or the “five Ps” of the 2030 Agenda, which are people, planet, prosperity, peace and partnerships (JAYASOORIA, 2016).

According to Stafford-Smith et al. (2016), the SDGs defined an agenda for the SD of all nations that adhered to economic growth, social inclusion and environmental protection. The SDGs represented a top-down approach designed by the political elite based on the goals created during UN summits and conferences in the 1990s (BROLAN et al., 2014). However, according to Sachs (2012), the path to SD should not follow a top-down approach and should follow a compelling problem-solving network that involves universities, companies, NGOs, governments and - most importantly - the young. For the author: “young people are those who will become experts and leaders of a new and profoundly challenging era”.

The SDGs were established through a series of measurable goals and required - at various levels - a great deal of cooperation and effort around the world with regard to monitoring, which unfortunately is rarely possible (GIUPPONI; GAIN, 2016). The SDGs were designed to be qualitatively different from the MDGs in a number of ways in order to be more inclusive of multiple stakeholders at various levels of governance (GELLERS, 2016).

In addition, Stafford-Smith et al. (2016) suggest seven recommendations that countries should commit to:

- Legislative and regulatory incentives for long-term capital also called "patient capital" – investment and capital that measures returns over decades – particularly in low-income countries;
- A partnership approach between countries with less availability of revenue and resources with those with greater availability, in order to co-produce knowledge, technology and processes for sustainability;
- A commitment to embedding systems thinking at all levels of education;
- Integrated SD plans that strengthen ties between fragmented sectors and promote political integrity;
- Political leadership in SD, for example, in the highest branches of government, such as the President/Prime Minister level, as well as in the hierarchy of the Executive Power;
- Indicators for built-in SDGs, supported by "SD Core Variables" as a common reporting standard that encourages or requires agents to work together.

For Stevens and Kanie (2016), the SDGs represent a different approach and, in order to unfold the global governance practices that can contribute to a transformation towards sustainability, it is essential to analyze the decision-making processes and the transformative ideas that are captured in these decisions. Therefore, the potential of SDGs to transform dominant governance approaches to sustainability remains an important issue to be addressed (Stevens and Kanie 2016).

For Sachs (2012), while the SDGs require an unprecedented mobilization of global operational knowledge in various sectors and regions, social media and information technology offer an incomparable opportunity to solve global problems related to the main challenges of DS. This is because more and more people are turning to online collaboration networks, crowdsourcing, group problem solving, and open source solutions facilitated by software and applications.

Challenging scenarios force political decision-makers to employ different combinations of technological change and consumption measures to achieve the desired set of sustainability goals. It is important that they show that marginal improvement will not be enough to achieve a set of goals in sustainable development because to achieve these goals, transformative change is needed (VAN VUUREN et al., 2014).

Cross-sector cooperation, so necessary to achieve synergy on wellness goals, is a distinct challenge. The potential combination of private interests, mechanisms for blaming weaker links, and a lack of transparency mean that these goals can be implemented without balancing the needs of the natural environment with other welfare goals (WAAGE et al., 2015). With regard to resources, the UN system has provided substantial financial support through the Sustainable Development Goals Fund.

However, according to Terama et al. (2015), in an era of growing populations, global consumption and environmental consequences increasingly critical of inaction, it is a global challenge to translate the body of knowledge resulting from the SDGs into political action. Furthermore, according to Munamati, Nhapi e Misi (2016), to substantially contribute to achieving the SDGs, an investment in education must be explicitly considered, given the developed competencies, technical knowledge and skills needed for the development and implementation of policies. It is also important to emphasize research and technology that promote innovative and cost-effective health development.

The assessment of the SDGs is an essential task for the UN and its Member States, and the production and use of quality data is increasingly being recognized as an essential task for the assessment, monitoring and tracking of the SDGs (CHOI et al., 2016).. The biggest challenge today is to ensure economic development that allows the poor to escape poverty without compromising future generations to an even more degraded environment than today (MBOUMBOUE; NJOMO, 2016). Indicator-based assessments are a pragmatic operational solution to support the monitoring of phenomena through a series of static images on the state of social and environmental system variables (GIUPPONI; GAIN, 2016). Furthermore, it is important to communicate your evolutions in a concise and efficient way afterwards. However, the main challenge of monitoring the implementation of the SDGs will be the availability of raw global data comparable in detail and of adequate quality at regular intervals.

From a corporate perspective, the document “SDG Compass” (WBCSD, 2015) recommends that companies should consider the entire value chain - from the supply base and inbound logistics, through production and operations, to distribution, use and end-of-life products - as the starting point for assessing impact and setting priorities. This mapping does not involve a detailed assessment of each SDG at each stage of the value chain but rather a high-level analysis of where negative or positive impacts might be greatest. By aligning with the SDGs, companies can set more meaningful goals, promote shared priorities, and communicate more effectively about their commitment to sustainable development. Thus, the document states that integrating sustainability into organizations has the potential to transform all aspects of your company's core business, including your product and service offering, customer segments, supply chain management, choice and use of materials raw materials, transport and distribution networks and end-of-life of the product.

2.2 Industry 4.0

The term Industry 4.0 (I4.0) was coined in 2011 by a German initiative to develop advanced production systems with the aim of increasing the productivity and efficiency of the national industry (FRANK; DALENOGARE; AYALA, 2019). Also known as the fourth industrial revolution, I4.0 is an emerging concept resulting from technological advances and disruptive developments in the industrial sector (KOH; ORZES; JIA, 2019). The development and implementation of smart manufacturing need to follow three guiding principles - cultivate digital people, introduce agile processes and configure modular technologies to optimize production - to reap benefits such as increasing value creation, reducing production costs, increasing production quality and flexibility, and reducing time to market (SJÖDIN et al., 2018).

Some authors define I4.0 as the trend towards digitalization and automation of the manufacturing environment (OESTERREICH; TEUTEBERG, 2016), and some as a confluence of technologies ranging from a variety of digital technologies (KOH; ORZES; JIA, 2019). According to Weking *et al.* (2019), some authors also define I4.0 as a new stage or paradigm for industrial production, focusing on the results of the transformation process. Thus, there is no consensual definition of the term I4.0.

I4.0 brings innovation in three aspects: horizontal integration that means strengthening cooperation between companies or corporations; vertical integration that refers to the integration between different subsystems in each corporation; and end-to-end integration that allows the combination of design, customers and dynamic production adjustment (MENG et al., 2018). In this context, I4.0 is perceived as a disruptive technological development that acts as a driving force in controlling the entire value chain life cycle (Kamble et al., 2018). It brings innovation to business models in the manufacturing sector (LU, 2017), mainly due to providing a transformational environment, knowledge management and supply chain capacity building, thus being an essential strategy for achieving future competitiveness.

To manage the increasing complexity of OSCM, companies should be innovative and flexible (CAIADO et al., 2021). I4.0 embraces several technologies and associated paradigms that work as enablers for such innovation and flexibility requirements (DE CAROLIS et al., 2017a; LU, 2017). Cyber-physical systems (CPS), in particular, are considered a key technology for I4.0 since they allow data acquisition and processing, machine-to-machine communication (M2M) and human-machine interface (HMI) (WAGNER; HERRMANN; THIEDE, 2017). CPS is responsible for meeting the agile and dynamic production requirements and improving the entire industry's efficiency and effectiveness (LU, 2017). It requires advanced data processing and simulation models, both at the manufacturing process and system operating levels, and a sensor-filled manufacturing system where each process or equipment provides information, along with market research for advanced Big data analysis (LU, 2017). It represents a set of physical devices that interact with virtual cyberspace through a communication network. Each physical device will have its cybernetic part as a digital representation of the real device, culminating in 'digital twin' models (FRANK; DALENOGARE; AYALA, 2019).

Big data analytics (BDA) is a digital technology with three main dimensions, such as volume, variety and velocity (BABICEANU; SEKER, 2016). BDA is a new area of manufacturing that can use insights from other areas of the supply chain and includes business problem cycles, data research, functional team building, project roadmap, data collection and analysis, data modelling and analysis, data visualization, insight generation, integration with IT systems and professional training (BABICEANU; SEKER, 2016). It involves the use of advanced artificial intelligence (AI) data analysis techniques that use machine learning (ML) and deep learning (DL) algorithms in an effort to extract valuable knowledge from large amounts of data. , facilitating decision-making based on data (FRANK; DALENOGARE; AYALA, 2019).

On the other hand, a disadvantage of CPS will be in relation to possible cyber-attacks, common to software and internet-based systems. To combat this manufacturing problem, cybersecurity is a field dedicated to safeguarding the privacy, confidentiality and integrity of digital data stored and/or transmitted in any format through internal networks and/or the Internet (BABICEANU; SEKER, 2016). The term Cybersecurity indicates the huge and unstructured amount of data generated by I4.0 technologies within the organization (BRACCINI; MARGHERITA, 2018). In this way, Blockchain is known as a “trust protocol” as it is a distributed recording technology aimed at decentralization as a security measure. It is a distributed database with a peer-to-peer network, a consensus engine and cryptographic methods (WANG et al. 2016).

The Internet of Things (IoT), described as "*a world of widespread connectivity*", in which the Internet is the hub of connectivity for all smart devices, can create an intelligent network along the value chain in which machines, products and systems (FATORACHIAN; KAZEMI, 2018). IoT is composed of four layers (i.e., sensing, networking, service and interface) (DA XU; HE; LI, 2014) and involves the following technologies: Radio-frequency identification (RFID), Wireless sensor networks (WSN), Middleware, internet-based computing platform and IoT applications (LEE; LEE, 2015).

Clouds, represented by combinations of Internet Service, Web Application and Information Management, are expected to improve decision-making and manufacturing business and the cloud-based business solutions operate in the backbone to support IoT, Manufacturing Execution System (MES) and sensor connectivity (BIBBY; DEHE, 2018). Cloud-manufacturing covers the entire extended life cycle of a product, is considered as a parallel, networked and intelligent manufacturing system (the "cloud manufacturing"), as it receives support from cloud computing, IoT, virtualization, and service-oriented technologies (ZHONG et al., 2017).

Additive manufacture, also known as 3D printing, allows the manufacturing of an often geometrically complex component, composed of a series of layers of material, each of which is printed at the top of the former (i.e., by the deposition of successive layers of the material) (NASCIMENTO *et al.*, 2019). 3D printing technologies offer considerable advantages, such as making lateral movements less risky because products can be manufactured on demand at minimal costs, allowing companies to move easily upstream or downstream to rapidly change the degree of vertical integration (depending on the nature of the innovation considered) and enable business models to become modular and adaptable (RAYNA; STRIUKOVA., 2016).

Augmented reality (AR) consists of enhancing standard human perception with additional, artificially generated sensory inputs, blending natural and digital offerings into a combined and 'augmented' experience that prominently (but not limited to) the visual senses, offering potential to improve productive efficiency, greater flexibility in product development, and team effectiveness through extended live guidance (RAS et al., 2017). Thus, other than virtual reality (VR), AR becomes an introductory vehicle and building block for the digitalization of manufacturing processes. In recent years, Smart Glasses products have emerged that use embedded transparent displays to overlay computer graphics in areas of the field of vision, creating a very convincing super-reality.

Advanced robotics allows systems to mimic human actions and work autonomously (BIBBY; DEHE, 2018) and the use of collaborative robots (cobots) is a key facilitator for the introduction and progress of I4.0 mass customisation (GRAY, 2016). The use of embedded intelligent robots with sensors, dexterity and increased artificial intelligence and machine learning, is one of the main technologies and is vastly improving the productivity of the manufacturing industry, offering a more practical and more productive way than the human would be capable, in some cases (Bibby and Dehe, 2018). While robots and automation were designed to automate operational processes, collaborative robots (cobots) are designed to work with humans, supporting tasks that help increase human flexibility and productivity (FRANK; DALENOGARE; AYALA, 2019) and are capable to communicate with each other and even have the ability to learn (KOH; ORZES; JIA, 2019). Thus, the use of modern robotic systems is a key enabler for the introduction and progress of mass customization of I4.0.

According to Frank, Dalenogare e Ayala (2019), the base technologies are composed of the so-called new ICT, which include IoT, cloud services and BDA, which are considered two technologies (Big data and analytics) by some authors. IoT can create an intelligent network along the value chain in which machines, products and systems can be autonomously connected and controlled (FATORACHIAN; KAZEMI, 2018). Cloud-based business solutions operate on the backbone to support IoT, Manufacturing Execution System (MES) and sensor connectivity (BIBBY; DEHE, 2018). Thus, cloud manufacturing covers the entire extended lifecycle of a product, is considered a parallel, networked, and intelligent manufacturing system (the "manufacturing cloud"), as it is supported by cloud computing, IoT, virtualization and service-oriented technologies (ZHONG et al., 2017). On the other hand, Koh, Orzes e Jia (2019) state that the five main digital technologies discussed in the literature are: IoT, BDA, cloud, 3D printing and robotic systems. Additive manufacturing, also known as 3D printing, allows the fabrication of an often geometrically complex component composed of a series of layers of material, each of which is printed on top of the previous one (i.e., by deposition of successive layers of the material) (NASCIMENTO et al., 2019).

The expected benefits of using I4.0 technologies in industry vary, as they can synergize and interrelate to get better performance in I4.0 (FRANK; DALENOGARE; AYALA, 2019). For example, there can be the interrelationship between IoT, BDA, AR and cloud to integrate and analyze data between sources and companies, which is mainly accomplished through the adoption of industrial communication protocols (e.g., OPC Unified Architecture). Thus, these synergies allow I4.0 to unlock new potential value through new types of business models (MOURTZIS et al., 2019). New business models based on agility and customization and concerns about sustainable and ethical issues are creating interesting opportunities in manufacturing (BRENNAN et al., 2015).

Although disruptive technologies have profound effects on the global manufacturing environment, they seem to be far from having a major impact due to the need to the intensification of capital, knowledge and skills as well as a participatory culture that involves proactive and open communications between management and the team (BRENNAN et al., 2015). I4.0 deployment generated a new manufacturing working environment, changing traditional skills, individual responsibilities, assignments, and relationships, which makes employees survival depends on their degree of adaptability to new job requirements related to: non-technical skills, IT infrastructure, automation technology, data analytics, data security / communications security, development or application of assistance systems, and collaboration software (LICHTBLAU et al., 2015; SONY, 2019). In this sense, learning factories, or islands of learning must be adapted to the new competences required for I4.0 and smart employee adaptability models may be developed to predict the adaptability of employees in workplace changes (SONY, 2019).

Thus, I4.0 is an initiative that aims to innovate production processes in sectors that promise to improve sustainability in organizations (BRACCINI; MARGHERITA, 2018). The purpose of intelligent manufacturing is to maximize factory profits, but from improved measures or methodologies that can be used to modify the production process, these technologies can also be used to eliminate the risk of accidents, increase efficiency or reduce costs. emissions in the production process (MENG et al., 2018).

2.3 Sustainable Industry 4.0

Increasing design complexity, the need for efficient production practices, changing customer requirements and precise quality requirements have resulted in the evolution of manufacturing methods. In this sense, manufacturing processes and technologies have been subject to continuous advances and transformations in the I4.0 concept (SALAH et al., 2019).I4.0 can drive sustainable manufacturing, enabling the development of green products, green manufacturing processes and green supply chain management like never before (DE SOUSA JABBOUR et al., 2018b). To ensure the success of the transformation journey, the transition process to sustainable societies must be properly planned, directed and controlled (BONILLA et al., 2018b).

In addition, I4.0 initiatives can help industries incorporate environmental protection and control initiatives as well as process safety measures into sustainable manufacturing supply chains (LUTHRA; MANGLA, 2018) The authors review, identify and prioritize effective I4.0 concepts for supply chain sustainability in emerging economies, taking into account the perspective of the Indian manufacturing industry. Using the right performance measures (e.g., TBL indicators) in decision-making methods can help policy makers and managers make strategic decisions to propose and target the best disruptive technology solutions for the most critical SDG problems (CAIADO et al., 2018).

Adopting I4.0 can improve economic performance, employing, for example, predictive analytics and maintenance, which eventually help organizations reduce errors and defects across the entire assembly line (BRACCINI; MARGHERITA, 2018). It is also believed that the implementation of lean manufacturing in smart manufacturing environments is a factor of reduction (KAMBLE; GUNASEKARAN; GAWANKAR, 2018) and that Big data - a key technology - can contribute to the development of a circular economy, increasing transparency and feedback-oriented intelligence (DE SOUSA JABBOUR et al., 2018b) radically. In addition, lean tools can be combined with 3D visualization systems (e.g., functionalities of Building Information Modeling - BIM) to continually improve visual management throughout project lifecycles (NASCIMENTO et al., 2019).

The development of smart manufacturing technologies is very influential in the energy sector and facilitates the deployment of sustainable energy, reducing the cost of producing energy devices such as energy collection devices and energy storage devices, or even energy transformation in “smart energy factories” with the help of smart manufacturing technologies (MENG et al., 2018). I4.0, driven by smart devices and an intelligent production system, has the potential to reduce waste, overproduction, circulation of goods and energy consumption (KAMBLE; GUNASEKARAN; GAWANKAR, 2018).The central aspect of the environmental dimension is energy efficiency resulting from the ability to analyze and predict production performance and balance energy consumption with the real needs of the organization (BRACCINI; MARGHERITA, 2018).

In analyzing the implications of the Industrial Internet of Things (IIoT) according to TBL, several case studies based on interviews with experts from leading German manufacturing companies show that to qualify for sustainable value creation industrial, IIoT requires an extension of the TBL established by three other dimensions, that is, technical integration, data and information, and public context (KIEL et al., 2017b). Although I4.0 does not directly contribute to environmental sustainability, it improves these practices by increasing data accuracy in continuous monitoring (BRACCINI; MARGHERITA, 2018). The data produced by the IoT sensors are analyzed with a mathematical model to obtain cost savings and dynamically manage remanufactured resources (BRACCINI; MARGHERITA, 2018). In addition, IIoT can facilitate the reduction of greenhouse gas emissions through data-centric carbon footprint analysis and can be represented by fair assessments of salaries, human learning and employee motivation (KIEL et al., 2017b)

New machine learning (ML) and statistical techniques, such as data mining methods or algorithms, in applications such as high-precision machining and ultrasonic metal welding, aim to increase efficiency and influence integration at the process level, successfully and effectively promoting manufacturing efficiency. Such techniques can be applied to sustainable manufacturing, for example, in the analysis of gasoline residues and emission control, being an effective method to develop a decision-making system or establish a reference for policy makers (MENG et al., 2018).

Visualization technologies, especially virtual reality (e.g., reconfigurable manufacturing system - RMS), were emphasized to train and educate young students in a sustainable way (SALAH et al., 2019). Salah et al. (2019) state that academic institutions need to focus on the design and development of educational programs based on innovative teaching techniques. In addition, wearable technologies such as smart glasses and helmets for use with mobile devices or wearable computing can be used in training to improve safety in hazardous work areas (KAMBLE; GUNASEKARAN; GAWANKAR, 2018). The creation of a safer work environment is a consequence of reducing security incidents and also increase employee morale (BRACCINI; MARGHERITA, 2018).

Additive manufacturing (AM) has the potential to reduce the lifecycle from design to product, significantly reducing resources, including time and energy, is able to convert the material into customized products and services directly, and can be environmentally compatible with traditional small to large manufacturing processes with complex structures (MENG et al., 2018). The use of additive manufacturing according to the principle of traction allows the supply of customized products with reduced lead times, reducing stock levels of raw materials and using capacity more efficiently (KAMBLE; GUNASEKARAN; GAWANKAR, 2018).

Furthermore, in cases where demand is not high, high-performance computing (HPC) in the cloud can also be considered an excellent solution for sustainable manufacturing due to the low energy consumption that causes less energy emissions, but requires that cloud computing be instantly accessible to computing resources and data centres (MENG et al., 2018).

Regarding the 17 SDGs, according to Bonilla et al. (2018), four are closely related to the environmental issues of I4.0 and were selected, namely: SDG No. 7 “clean and accessible energy”, SDG No. 9 “Industry, innovation and infrastructure”, SDG No. 12 “Responsible consumption and production” and ODS No. 13 “climate actions”. The authors reviewed the literature to discuss I4.0's impact and sustainability challenges in four different scenarios: deployment, operation and technologies, SDG integration and compliance, and long-term scenarios. Expected positive and negative impacts were observed related to the basic flows of inputs and production products: raw materials, energy consumption and information and disposal of products and waste.

The socio-technical environment of I4.0 will therefore change the role of workers, who will have more responsibility and personal development, which will require participatory measures of work design and lifelong learning (KAGERMANN; WAHLSTER; HELBIG, 2013). Palma et al. (2017) state that I4.0 will allow employees to act more and more without the need to travel, often working in multiple operations, working in a single specific corporate plant or even working at home. In this sense, the Fourth Industrial Revolution will allow for better working conditions, thus contributing to SDG No. 8, “decent work and economic growth”. Flexible working and demographic conditions will promote a better work-life balance, and smart assistance systems will allow workers to focus more on creative activities rather than routine tasks (KAGERMANN; WAHLSTER; HELBIG, 2013).

On the other hand, I4.0 technologies threaten unskilled and repetitive jobs (e.g., assembly line workers) because they can be performed better and faster by machines and even service jobs (e.g. by possible reduction in outsourcing of business processes) (ANBUMOZHI; KIMURA, 2018). Thus, it is observed that there will be greater demand for jobs that require complex problem-solving skills and greater creativity to innovate at the expense of technical skills.

Furthermore, the dynamic change needed (to combat job loss) in the labour market brought about by the transition to I4.0 will require a transformation of education systems, as workers should expect to have multiple careers instead of just one. It requires a deep commitment to adult education and lifelong learning (ANBUMOZHI; KIMURA, 2018). Thus, the importance of the role of government is realized, whether nationally through policy formulation or regionally through the creation of online education opportunities beyond its borders.

Some other impacts of I4.0 on the sustainability of the value chain are as follows (PALMA et al., 2017): members of the value chain can act and monitor customers and end-users in design, manufacturing and, in the final stage, in tracking product performance to meet individual needs; intelligent products are personalized, can be located at all times and, through the analysis of the current situation, can decide on alternative routes and have the ability to respond flexibly to interruptions and failures, allowing self-sufficiency and autonomous decision-making. In this sense, the digitization of information and systems integration also allows proposing collaborative business models and Factories for the Future's (CAIADO et al., 2018; CAIADO; QUELHAS, 2020) sustainable product design approach focuses on the application of cradle-to-cradle principles.

Therefore, when supported by business and government, I4.0 can act as a promoter of the circular economy and can be used as a tool to achieve recycling at the level and therefore to properly measure and monitor recycling rates (ANBUMOZHI; KIMURA, 2018). For the authors, some digital technologies that can be used to facilitate the circular economy are mobile technology, machine-to-machine communication, cloud computing, social media for businesses, BDA, modular design technology, advanced recycling technology, life technology and material, tracking and return systems, and 3D printing. Thus, among the advantages brought by disruptive technologies for sustainability, there is the possibility of new forms of connection and access to environmentally friendly services; the feasibility of data analysis and artificial intelligence, together with IoT, which will enable a new range of materials management services; the potential for cost reduction, by increasing the degree of automation and efficiency; and the possibility of the greater flexibility that allows companies to react quickly to changes and respond to increasingly individual customer demands (ANBUMOZHI; KIMURA, 2018).

In addition, some potential improvements to the I4.0 environmental accounting initiatives may include better data quality due to greater accuracy, reliability and comparability of reported environmental accounting data, less management discretion in what is measured and how it is measured and reported, and greater data credibility (BURRITT; CHRIST, 2016). Proposing a sustainable smart manufacturing framework can improve the quality of work, energy efficiency and data quality, as well as reduce time to market and provide advanced recycling technology, product lifecycles in closed-loop, safer working environment, data-centric carbon footprint analytics, and effective climate change control and prediction.

Therefore, the integration of I4.0 technologies with sustainable manufacturing offers several benefits, including the improvement of processes and the consumption of materials (optimization of processes and resources), optimized use of a company's machinery park, supported by predictive maintenance (better asset utilization), proper inventory management, increased labor productivity, improved product quality and process using real-time problem solving, perfect understanding of customer demand in terms of quantity (match supply and demand), time reduction (reducing time to market) and new repair possibilities with innovative and after-sales services, which increase uptime (BLUNCK; WERTHMANN, 2017).

For Kamble, Gunasekaran e Gawankar (2018), most, if not all, elements of I4.0 speak directly to some ODS. Given this, sustainable I4.0 has emerged as one of the six future areas of research and research in this space must consider energy sources, climate change, waste and overproduction and how ICT, especially sensing, detection, control and tracking analysis can be applied, which are focus areas that are part of the SDGs (NHAMO; NHEMACHENA; NHAMO, 2020). For the authors (NHAMO; NHEMACHENA; NHAMO, 2020), I4.0 remains closely linked to the well-provided implementation of the SDGs by 2030 and once a baseline has been built, global leaders and other stakeholders in the industry, business, development, civil society and labor will be informed on how best to intervene to prepare the right countries for the I4.0-related paths leading to 2030. Along these lines, ICT indicators are considered a good proxy to assess countries' readiness for I4.0 (NHAMO; NHEMACHENA; NHAMO, 2020). However, given that many countries, particularly those in the developing southern hemisphere, lag behind in terms of ICT readiness due to reasons such as high data costs, which impede access to the Internet, the adoption of I4.0 will be delayed and this slow uptake will result in a slower pace of digital transformation and possible failure to meet the SDGs by 2030 (NHAMO; NHEMACHENA; NHAMO, 2020).

3 RESEARCH METHODOLOGY

This thesis employs a multi-method approach structured in three stages, as shown in Figure 1. The first stage is theoretical research and will be directed towards the construction of the framework, which covers three steps: a systematic review, development of taxonomies and proposition of a conceptual framework to achieve sustainable digitalization according to the SDGs based on the alignment between I4.0 and sustainability in OSCM.

The second and third stages are empirical and consist of the development of the decision support framework. The second stage seeks the opinion of industry professionals to incorporate suggestions, determine the weights of benefits, evaluate the criticality and interrelationship of the key enablers, and to identify the necessary key enablers to build sustainable technological solutions in order to construct the decision support framework. As one of the first empirical efforts to build a new field of knowledge, an exploratory qualitative method is preferred to collect primary data, delving deeply into the experiences of industry experts (TIWARI; KHAN, 2020). In the search for reliable and valid industrial evidence on the subject of interest in this study (NYUMBA et al., 2018), the activities of this stage can be reached through the Delphi method (MURRAY; PIPINO; VAN GIGCH, 1985), panel study (CAIADO et al., 2021; KITZINGER, 1994) and interviews with experts (YIN, 2014). The sampled group must have characteristics of homogeneity and heterogeneity (KITZINGER, 1994) and, therefore, will be composed of industry professionals with different levels of experience in OSCM, sustainability and I4.0. Finally, at the third stage, there is the application of the decision support framework with eight companies to select the adequate solution to address the prioritized challenges to S-OSCM4.0. This stage employs multiple case case analyses, through questionnaires, to explore the convergence and divergence between multiple organizations regarding S-OSCM 4.0 strategies and interests, considering different sizes. Figure 1 also points out an overview of the methods and activities employed to answer the ten research questions and to achieve the objectives of this thesis, which are highlighted in blue.

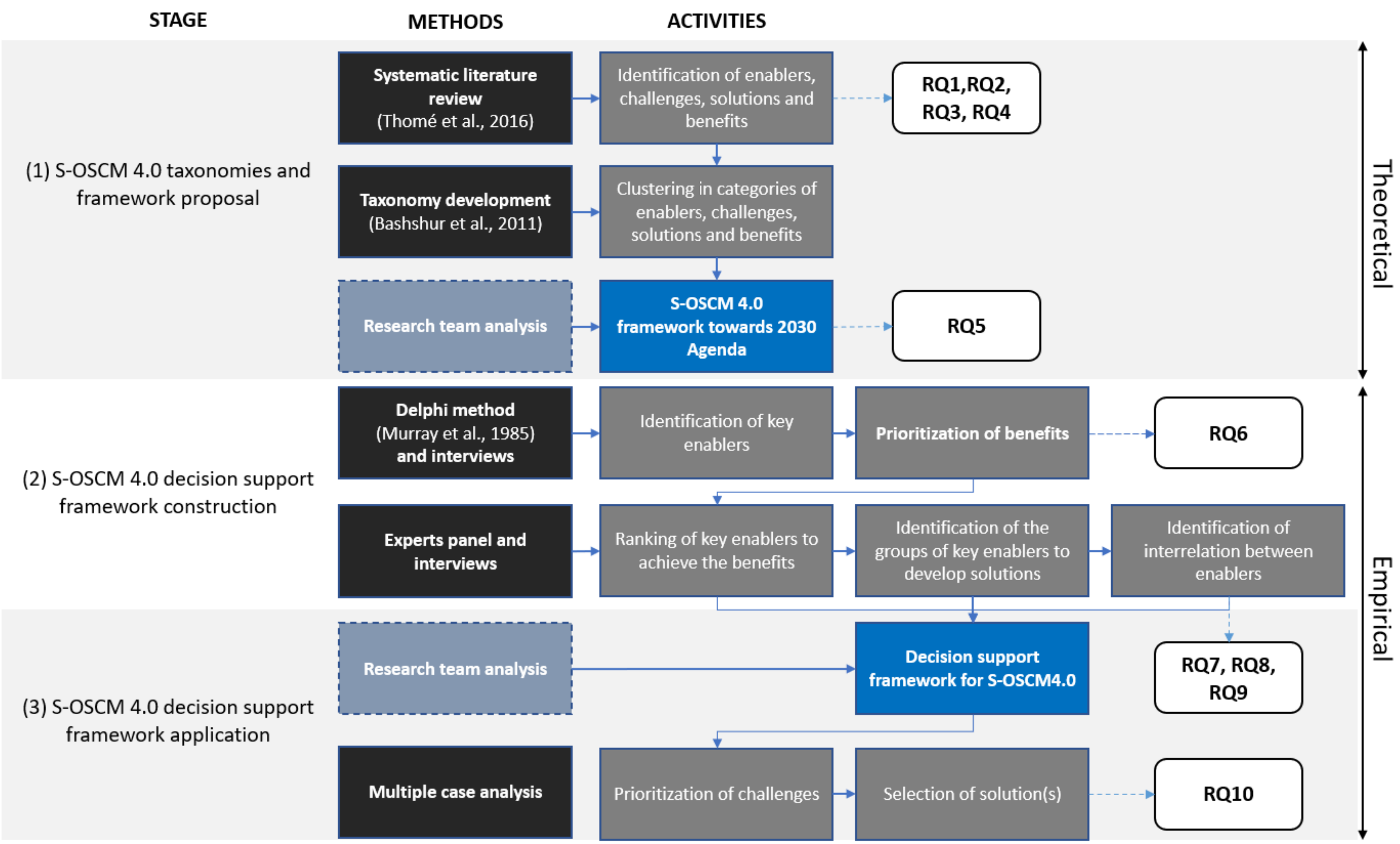

Figure 1. Research methodology

Source: Adapted from (MUÑOZ-LA RIVERA et al., 2020)

The explorative research study applied a triangulated methodology with qualitative and quantitative data collection mechanisms to operationalise the research questions and constructs (YUSUF et al., 2013). As triangulation involves using more than one method to gather data, the data was collected using five mechanisms: (i) a literature review; (ii) Delphi method with 11 practitioners; (iii) panel of experts with 15 practitioners; (iv) two rounds of semi-structured interview with 10 and 15 experts; and (v) questionnaire with multiple cases (eight organizations). It may be observed that the research counts on multiple sources of information, such as content analysis of articles, panels, interview, and questionnaires, and iteration with the constructs developed from the literature, which enables further constructive validity (EISENHARDT, 1989a). The use of multiple sources allows for the support of the constructs, propositions or hypotheses, in other words, the technical use of triangulation helps in the iteration and convergence between various sources of evidence (MIGUEL, 2005). The use of different methods through data triangulation to study the same phenomenon increases the validity of the research results (PSYCHOGIOS; TSIRONIS, 2012).

3.1 Theoretical data collection and analysis

As theoretical data collection, this research adopts a Systematic literature review (SLR) (TRANFIELD; DENYER; SMART, 2003). This SLR adapted the review processes proposed by Thomé et al. (2016) to systematic reviews in OM and follows seven of the following steps: (i) research problem formulation, (ii) literature search, (iii) data collection, (iv) quality assessment, (v) data analysis and synthesis, (vi) interpretation, (vii) presentation of results, (viii) and updating of the review. The problem formulation together with the five RQs and the aims of this review (step 1) is delineated in Chapter 1. As the review is systematic, it will meet the four principles of Briner e Denyer (2012): (a) adopt a systematic procedure or method; (b) present a transparent and explicit method; (c) be replicable and updatable; and (d) summarize and synthesize evidence related to the review issue.

The literature search (step 2) comprises the selection of databases and identification of keywords, which is extremely critical to a comprehensive and unbiased review. According to Thomé et al. (2016), at least two databases should be searched. In this study, the Scopus and Web of Science (WoS) databases were chosen due to their complementarity (MONGEON; PAUL-HUS, 2016). The search is limited to two groups of keywords, which were combined with the Boolean expressions "AND" and “OR”, as shown in the review protocol (see Table 1).

Table 1. Review protocol designed for the SLR process (Adapted from Jasinski et al. (2015))

Steps	Activity	Research questions/Methods
1. Research problem formulation	Review questions	RQ1: What are the enablers for the S-OSCM4.0?
		RQ2: What is the current state of the challenges, along the lines of the SDGs, for integrating I4.0 and sustainability in OSCM?
		RQ3: What sustainable technological solutions can be implemented to achieve SD in OSCM?
		RQ4: Considering the SDGs, what are the benefits of the integration of I4.0 with the sustainability?
		RQ5. How to link enablers, challenges, and sustainable technological solutions, to obtain the benefits of S-OSCM4.0 implementation?
2. Literature search	Searching the literature	**Methods** database searching and backward and forward search
		Databases searched: Scopus and Web of Science
		Keywords for database searching: Search 1: (("Industry 4.0" or "Smart manufacturing") AND ("sustainab*" or "green") AND (“"supply chain" or "SCM")) Search 2: (("Industry 4.0" or "Smart manufacturing") AND (“SDGs or "sustainable development goals"))
3. Data collection	Inclusion criteria	**Population:** Studies presenting adequacy to the scope of the integration of I4.0 and sustainability in OSCM, as well as the combination of digital transformation and sustainable development in manufacturing and SCs, or the interplay between I4.0 and SDGs from the perspective of organizations or industries
		Intervention: No intervention in the research question
		Comparison: No comparison in the research question
		Outcome: Studies that represent, constitute or strengthen any challenge, benefit and enablers to integrate I4.0 and sustainability, or potential sustainability technological solution in OSCM domain
	Exclusion criteria	a) documents that are not published in peer-reviewed journals (e.g. books, conference papers) up to September 2020 b) documents written in a language other than English; c) documents that are not available online; and d) non-adequacy to the scope
4. Quality assessment	Quality check	**Methods:** a trained team was constituted to quality checks and the criteria of Methodi Ordinatio was used.
5. Data analysis and synthesis 6. Interpretation 7. Presentation of results	Data extraction	**Data extraction form with developed categories from relevant studies:** title, authors, year of publication, journal, country of study, gaps, goals, research category (theoretical, empirical or mixed), research approach (qualitative, quantitative or mixed), I4.0 technology focus (based on Caiado et al., 2021), enablers (to integrate I4.0 and sustainablility in OSCM), challenges (to apply I4.0 in OSCM, to apply sustainability in OSCM, and to integrate I4.0 and sustainability in OSCM), potential solutions (e.g. how to use I4.0 technologies towards SD), and Benefits of joining I4.0 and Sustainability.
		Software used for extracting data: Microsoft Excel
	Data synthesis	**Methods:** descriptive analysis (narrative synthesis) and content analysis (developed categories from a detailed examination of all selected studies)
		Presentation methods: tables, matrices and qualitative thematic analysis through iterative cycles to inductively develop taxonomies and a framework.

The conducted research had combined the search terms into title, abstract or keywords, limited to papers in English published in peer-reviewed journals up to September 2020, when they were available (including as in press). The exclusion criteria used for determining evaluation and selection of studies (step 3) were: a) documents that are not published in peer-reviewed journals; b) documents written in a language other than English; c) documents that are not available online; and d) non-adequacy to the scope of the integration of I4.0 and sustainability in OSCM, as well as the combination of digital transformation and sustainable development in manufacturing and SCs, or the interplay between I4.0 and SDGs from the perspective of organizations or industries. This evaluation (step 4) had the participation and analysis of three researchers, thus avoiding subjectivity of interpretation. As in Cunha et al., (2021) a trained team was constituted and involved in all the major steps of the process, to ensure transparency, and the criteria of Methodi Ordinatio was used to ensure the relevance and quality of the base used in the present study. Furthermore, backward and forward search complemented the literature search. The backward consists of evaluating the literature cited by the articles found in the research from the keywords and the forward consists of reviewing the articles that cited those that were filtered by the keywords (THOMÉ; SCAVARDA; SCAVARDA, 2016). Figure 2 describes the process of including and excluding articles during the evaluation and selection of studies, following the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyzes) (MOHER et al., 2009).

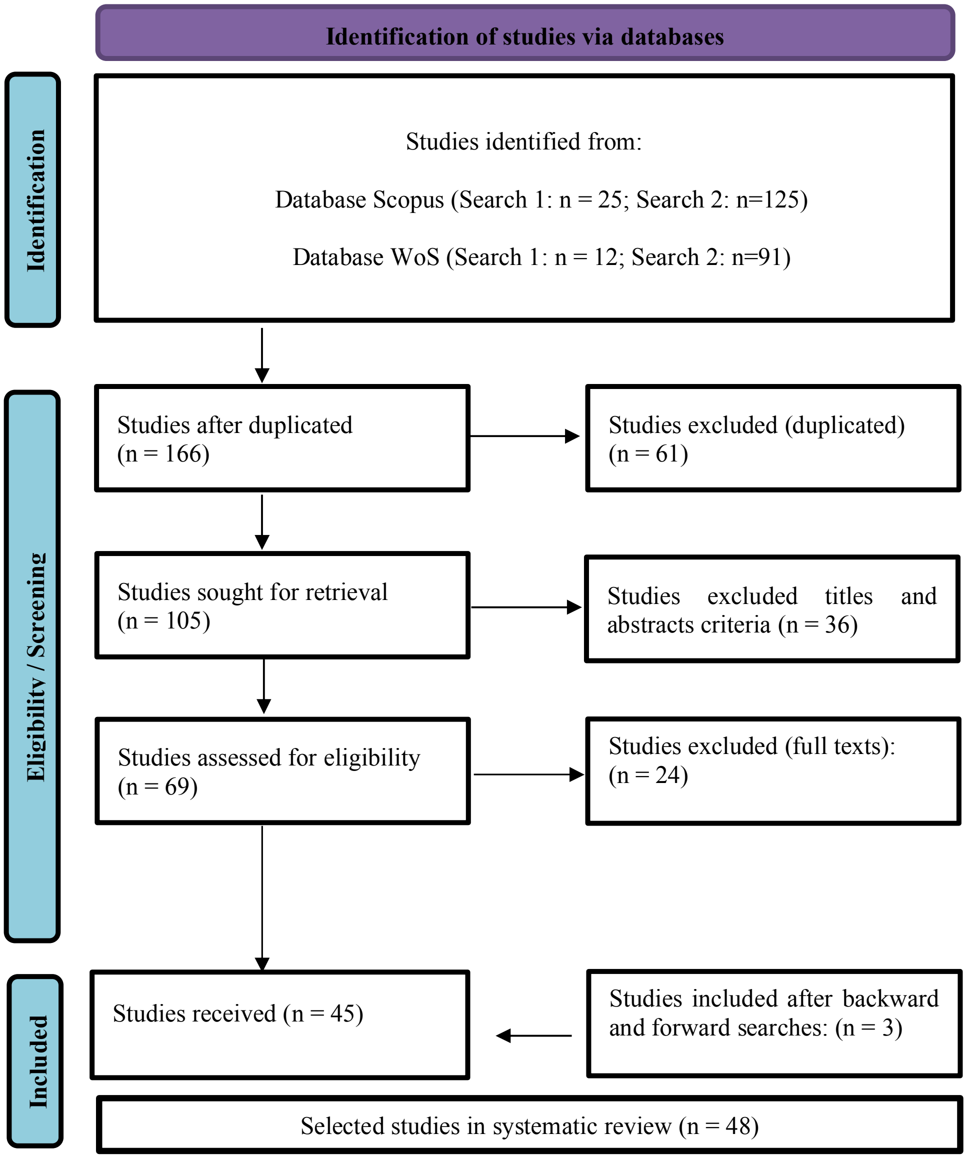

Figure 2. Flowchart of the research methodology. Source: Adapted from Moher et al. (2009).

A total of 48 articles complied with the selection criteria and represented the bibliographic portfolio of this research. Hence, these were all the articles that, to a certain extent, referred to sustainability and I4.0 in OSCM. After identifying the relevant articles, data gathering considered a concept matrix, using Microsoft Excel worksheet, which listed the unit of analysis in lines (articles) and categories (bibliographic characteristics) in columns. Articles were coded according to these categories, and this matrix was used for data analysis, synthesis, and interpretation (steps 5 and 6).

The results were first analyzed using the descriptive analysis, which considered the chronological distribution of the selected articles by research category and research approach, the distribution of studies by I4.0 technology, and the geographical distribution of studies. Then, there was a content analysis guided by Mayring (2004), in which each document from the selected literature was critically evaluated by the authors. Research findings are synthesized into taxonomies and a conceptual framework (TORRACO, 2005), by using content analysis that represents an effective tool for analyzing a sample of research documents in a systematic way (SEURING; GOLD, 2013). Moreover, an iterative taxonomy development approach was used, as a proposal to classify and organize the relevant body of knowledge (e.g., concepts, technologies and applications) (BASHSHUR et al., 2011) belonging to S-OSCM4.0, a new area that requires greater clarity and theoretical understanding of enablers, challenges, solutions and benefits and the relationship of these categories. We also sought to propose a framework based on taxonomies following an inductive approach (EISENHARDT, 1989b; MAYRING, 2004), which also had an iterative process of building, testing, revising, and constantly comparing categories and data, and involved the five researchers in defining the categories and validating the analysis.

To structure taxonomies and their relationship (within the framework), the three steps of taxonomy development of Bashshur et al. (2011) were followed. In the first step, sets of elements are heuristically aggregated in an iterative process with repeated refinements to increase their internal homogeneity and generality to obtain a classification of the categories, which normally contains several exclusive components (or facets). In the second step, we seek to understand the effects of specific compounds or packages, which constitute the various categories and must identify exclusive sets and subsets of enablers, challenges, solutions, and benefits. Thus, taxonomies were structured at two levels, with the classification in packages being the first, or more inclusive, level of generality in S-OSCM4.0 and the second level consists of the specific components and subcomponents of each of these dimensions (categories), and ultimately, the two levels are combined to form a multidimensional taxonomy. Finally, in the third step, the four dimensions of S-OSCM4.0 and the components of each dimension are combined in a single framework to assist the operationalization of sustainable development in operations and supply chains along the lines of Agenda 2030. This last step also seeks to allow an additional specification of the taxonomy-independent variables with an appropriate level of granularity or specificity as extensions of the proposed framework. Thus, the framework represents a managerial artefact that integrates taxonomies to guide sustainable development effectively and holistically through an inclusive digital transformation with less impact on the environment.

3.2 Empirical data collection and analysis

3.2.1 MCDM approaches

The MCDM is an important problem-solving approach involving multiple criteria through quantitative and qualitative analysis (SITORUS; CILLIERS; BRITO-PARADA, 2019). According to Roy (1996), the MCDM can be applied with four types of problems:

I. Choice problem (α): defining the best option or action in a series of alternatives;

II. Classification problem (β): to allocate each of the options in previously established categories, according to common characteristics that you want to group them for decision making;

III. Ordering problem (γ): ranks the alternatives in a descending preference ranking;

IV. Description problem (γ): helps decision-makers to systematically evaluate alternatives, comparison criteria and consequences of their actions.

According to (KAHRAMAN, 2008), MCDM methods can be classified into two categories: multiple attribute decision making (MADM) and multiple objective decision making (MODM). MADM is associated with a discrete and limited space of alternatives, which are ordered according to preference, based on the weights given to each of its attributes. MODM, on the other hand, is normally used for an unlimited and continuous number of alternatives, where the best is the one that meets several previously established restrictions. Regarding the data types used, MCDM can be classified into: Crisp MCDM and fuzzy MCDM methods (FMCDM). In Crisp MCDM methods all available data are precise and known, whereas in Fuzzy MCDM some data used are not clearly defined (KAHRAMAN, 2008).

To solve ranking (ordering) problems, it is common to use additive aggregation methods (CUNHA et al., 2021), seen as compensatory methods in which the evaluation of an alternative considers the trade-offs between the criteria (ALMEIDA, 2013). On the other hand, to solve choice problems is common to use non-compensatory MCDM methods, such as the *ELimination Et Choix Traduisant la REalité* (ELECTRE), a famous outranking method that proceeds with a multiple-criteria aggregation procedure to build multiple outranking relations in order to compare each pair of alternatives in an exploitation process (ROY, 1996). Outranking methods consist of establishing a preference relation on a given set of alternatives in order to indicate a certain degree of dominance among them. These methods are often used to deal with unclear and incomplete information (PENADÉS-PLÀ et al., 2016). In this study, multiple group decision making approaches were employed, such as the Fuzzy Delphi method (FDM), three fuzzy MCDM methods - fuzzy Analytical Hierarchy Process (FAHP), fuzzy *VlseKriterijumska Optimizacija I Kompromisno Resenje* (FVIKOR), and fuzzy Decision-Making Trial and Evaluation Laboratory (FDEMATEL) - Q-Sort, and a non-compensatory MCDM method, ELimination and Choice Expressing REality (ELECTRE). The employment of these methods can be justified by looking at the last five research questions separately and collectively. RQ6 aims to investigate the key enablers to integrate sustainability and I4.0 in OSCM. FDM with 11 practitioners is used to find out the most important enablers to be considered to achieve S-OSCM4.0. FDM combines the Delphi method and fuzzy theory, which mainly focuses on uncertainties and linguistic variables to model the experience and judgment of a group of participants (TSAI et al., 2020). RQ7 aims to evaluate the key enablers with respect to the benefits criteria (i.e., to achieve planet, people and prosperity benefits). First, FAHP, an approach combining traditional AHP and fuzzy theory, through interviews with 10 experts, was adopted to seek the weight value of each SD benefit. FAHP converts the opinions of experts from previous definite values to fuzzy numbers and membership functions (HSU; LEE; KRENG, 2010a). Then, a typical ranking problem can be resolved by a compensatory method. FVIKOR was applied through interviews with 15 experts and is considered an acceptable MCDM tool to handle such an issue, particularly in the fields of SCM and sustainability (ROSTAMZADEH et al., 2015). Note that both AHP and VIKOR were carried out with the aid of the fuzzy set theory because the FAHP and FVIKOR reduce the effect of subjectivity (CUNHA et al., 2021). Concerning RQ8, to identify the necessary enablers to develop sustainable technological solutions, the Q-sort method was used through a panel of 15 practitioners to verify if the enablers (characteristics) were correctly labelled into the categories of solutions (dimensions) (TEN KLOOSTER; VISSER; DE JONG, 2008). Thus, this statistic method was used to assess the validity of constructs using the Cohen's Kappa (COHEN, 1960), and proportional agreement (RUST; COOIL, 1994). RQ9 aims to investigate the interactions among the key enablers for S-OSCM 4.0. The DEMATEL is the best fit tool that can identify the relationships between these factors (YADAV et al., 2020a). This point has also been discussed and validated in many DEMATEL-based research works (MACHADO et al., 2021). Thus, the 15 interviewed experts that participated in FVIKOR also analysed the influence of the key enablers and the FDEMATEL was used to avoid subjectivity. Finally, regarding RQ10, to select the best solution to tackle the challenges to integrate I4.0 and sustainability in OSCM there was a multiple case analysis, with eight organizations, in two stages. First, it was necessary to allocate weights to the different challenges considering its multiple perspectives (Technology, Economic, Environment, Society, and Knowledge & Support); thus, FAHP was applied. Then, a non-compensatory method (ELECTRE I) was used to select the best subset of alternatives. Figure 3 illustrates the decision support framework' construction and application flow involving these six reported methods.

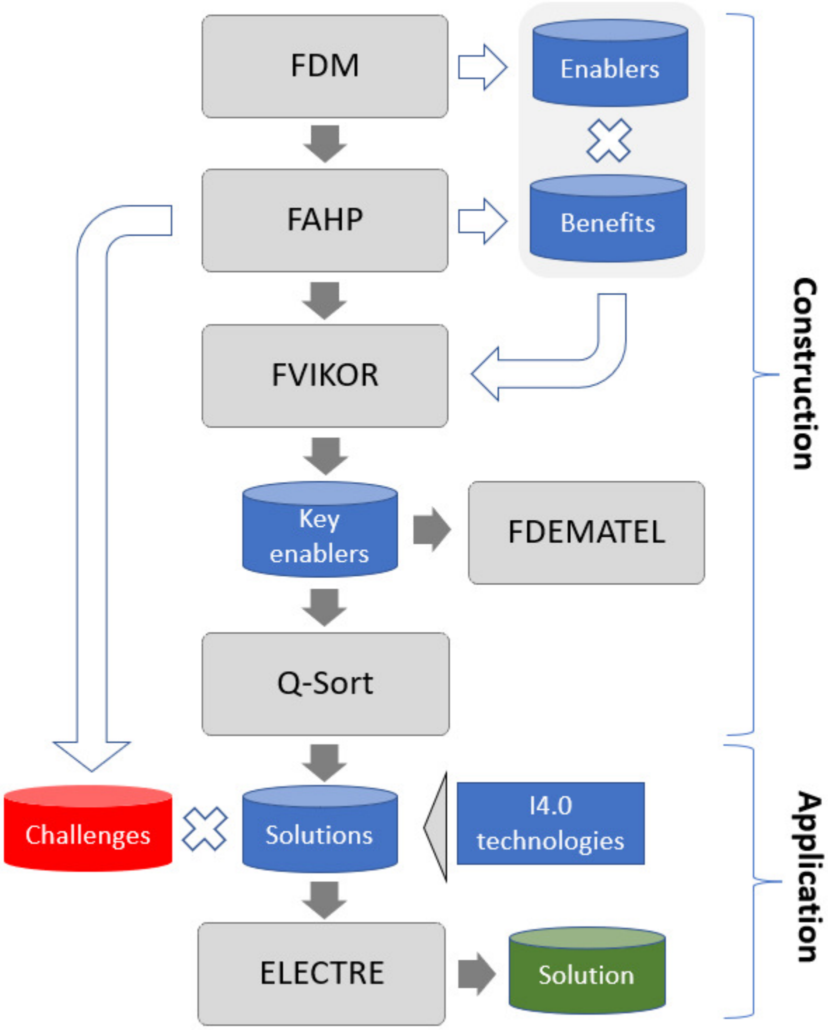

Figure 3. Multiple group decision making approaches

The following sections describe the methods and their steps. These analyses were performed with R software (The R Foundation for Statistical Computing, Vienna, Austria; http://www.r-project.org).

3.2.2 Fuzzy Delphi

In this study was conducted an FDM to group decisions to solve the fuzziness of common understanding of expert opinions (MURRAY; PIPINO; VAN GIGCH, 1985). As previous studies (Hsu et al., 2010), this research applied the triangular membership functions and the fuzzy theory to solving the group decision. According to (TSAI et al., 2020), FDM is a simple and systematic method less complicated and less time-consuming (less rounds than those used in the Delphi method), in which the number of samples (usually between 10 and 15) required is more than 10 participants in order to increase the reliability.

The process of FDM followed eight steps, which were adapted from Hsu et al. (2010) and Chang et al. (2011), as follows:

1. *Collect opinions of decision group*. In this step, K experts are invited to determine the importance of the evaluation criteria (score of each alternate factor's significance) with respect to various criteria, using semantic description method, to allow the respondents to express their assessments and subjective judgments fully, through linguistic variables (Table 2):

Table 2. Linguistic variables for the importance weight of criteria.

Relative Importance	Linguistic variable	Triangular Fuzzy Number
1	Strongly disagree	(0.0,0.0,0.1)
2	Somewhat disagree	(0.0,0.1,0.3)
3	Disagree	(0.1,0.3,0.5)
4	Neutral	(0.3,0.5,0.7)
5	Agree	(0.5,0.7,0.9)
6	Somewhat agree	(0.7,0.9,1.0)
7	Strongly agree	(0.9,1.0,1.0)

2. *Calculate the aggregation weight of experts.* The degrees of importance are defined according to the years of experience reported by each expert in three subjects (Sustainability, Industry 4.0, and OSCM). Then, is calculated the aggregation weight, by getting the sum of percentage for each expert in each subject over the sum of the total years of experience (SÁNCHEZ-LEZAMA; CAVAZOS-

ARROYO, 2014), following the scale of Table 3.

Table 3. Scale of level of experience proposed

Scale	Industry 4.0	Sustainability	OSCM
0	None	None	None
25	1-3 years	Less than 5 years	Less than 5 years
50	4-6 years	5-10 years	5-10 years
75	6-9 years	11-20 years	11-20 years
100	More than 9 years	More than 20 years	More than 20 years

3. *Set up triangular fuzzy numbers*. Calculate the evaluation value of the triangular fuzzy number of each alternate factor given by experts, find out the significance triangular fuzzy number of the alternate factor. Let fuzzy numbers $\tilde{r}_{ij}^{k}$ be the importance of alternative i with respect to criteria j and $\widetilde{w}_{ij}^{k}$ be the jth criteria weight of the kth expert for $i = 1, \dots, m$ $j = 1, \dots, n,$ $k = 1, \dots, K.$

$$\text{And } \tilde{r}_{ij}^{k} = \frac{1}{K}\left[\tilde{r}_{ij}^{1} \oplus \tilde{r}_{ij}^{2} \oplus \cdots \oplus \tilde{r}_{ij}^{k}\right]$$
$$\widetilde{w}_{ij}^{k} = \frac{1}{K}\left[\widetilde{w}_{ij}^{1} \oplus \widetilde{w}_{ij}^{2} \oplus \cdots \oplus \widetilde{w}_{ij}^{k}\right] \qquad \textbf{(1)}$$

Where the operation laws for two triangular fuzzy numbers $\widetilde{m}_j = (m_1, m_2, m_3)$ and $\tilde{n}_j = (n_1, n_2, n_3)$ are as follows:

$$\widetilde{m} \oplus \tilde{n} = (m_1 + n_1, m_2 + n_2, m_3 + n_3),$$
$$\widetilde{m} \otimes \tilde{n} = (m_1 n_1, m_2 n_2, m_3 n_3), \qquad \textbf{(2)}$$
$$a \otimes \widetilde{m} = (am_1, am_2, am_3), \qquad a > 0$$

4. *Use the vertex method.* For each expert, use the vertex method to compute the distance between the average $\tilde{r}_{ij}$ and $\tilde{r}_{ij}^{k}$ and the distance between the average $\widetilde{w}_j$ and $\widetilde{w}_{ij}^{k}$, $k = 1, \dots, K$. This method computes the distance between two fuzzy numbers $\widetilde{m}_j = (m_1, m_2, m_3)$ and $\tilde{n}_j = (n_1, n_2, n_3)$ as follows:

$$d(\widetilde{m}, \tilde{n}) = \sqrt{\frac{1}{3}\left[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2\right]} \qquad \textbf{(3)}$$

5. *Consensus analysis.* According to Cheng and Lin (2002), if the distance between the average and expert's evaluation data is less than the threshold value of 0.2, then all experts are considered to have achieved a consensus. Furthermore, among those m x n ratings of alternatives and n criteria weights, if the percentage of agreement (achieving a group consensus) is greater than 75% (CHANG; HSU; CHANG, 2011), then go to the following step; otherwise, the second round of Delphi is required.

6. *Aggregation.* Aggregate the fuzzy evaluations by

$$\tilde{A} = \begin{bmatrix} \tilde{A}_1 \\ \tilde{A}_2 \\ \vdots \\ \tilde{A}_m \end{bmatrix} \text{ where } \tilde{A}_i = \tilde{r}_{i1} \otimes \tilde{w}_1 \oplus \tilde{r}_{i2} \otimes \tilde{w}_2 \oplus \cdots \oplus \tilde{r}_{in} \otimes \tilde{w}_n \qquad \textbf{(4)}$$

$$i = 1, \cdots, m$$

7. *Defuzzification*. In this step, a simple centre of gravity method was used to defuzzify the fuzzy weight $\tilde{A}_i = (a_{i1}, a_{i2}, a_{i3})$ for each assessing variable (alternate option) to definite value S_j, the followings are obtained:

$$S_j = \frac{1}{3}(a_{i1} + a_{i2} + a_{i3}), \qquad i = 1, \cdots, m \qquad \textbf{(5)}$$

8. *Screen evaluation indexes*: Finally, proper factors can be screened out from numerous factors by setting the threshold α. In this study, the threshold was the average of the S_j of the category of factors. This step can be used to improve the efficiency and quality of questionnaires through more objective evaluation factors that could be screened through the statistical results. (TSAI et al., 2020). The principle of screening is as follows:

If $S_j \geq \alpha$, then No. j is the evaluation index (retain the variable)
If $S_j < \alpha$, then delete No. j factor (remove the variable)

3.2.3 Fuzzy AHP

Analytic Hierarchy Process (AHP) is one of the most used MCDM methods in literature (YANG et al., 2017) due to its attractive resources, such as the possibility to evaluate the consistency of the decision problem. However, this approach has shortcomings related to the use of an unbalanced judgment scale that is often imprecise and subjective (SUN, 2010). These can be improved through the combination of AHP with fuzzy logic (ZADEH, 1965, 1971), known as FAHP. In this study, FAHP was used due to its well-organized approach for determining the criteria weights and for the justification of multi-criteria group decision-making problems using fuzzy set theory (CUNHA et al., 2021). The FAHP was composed by five steps as follows:

1. *Determining the criteria and establishing a hierarchical structure.*

The first step of the FAHP consists in defining the criteria and organizing them in a hierarchical structure, which includes the objective of applying the method, the established criteria and the alternatives that need to be ranked (REZAIE et al., 2014).

2. *Collecting expert judgments in fuzzy parity comparison matrices (PCM).*

The second step consists of establishing the pairwise comparisons between the criteria by decision makers, following the fuzzified Saaty fundamental scale (SAATY, 1980). The evaluation is performed on linguistic variables, which are associated with triangular fuzzy numbers (TFNs), and the evaluations are therefore converted into three parity comparison matrices (PCMs). Table 4 represents each linguistic variable with their respective positive and negative TFNs.

Table 4. Triangular fuzzy numbers

Linguistic variables	Positive TFN	Negative TFN
Same importance	(1,1,1)	(1,1,1)
Intermediate: Same importance - Moderate	(1,2,3)	(1/3,1/2,1)
Moderate importance	(2,3,4)	(1/4,1/3,1/2)
Intermediate: Moderate - Strong	(3,4,5)	(1/5,1/4,1/3)
Strong importance	(4,5,6)	(1/6,1/5,1/4)
Intermediate: Strong - Very Strong	(5,6,7)	(1/7,1/6,1/5)
Very strong importance	(6,7,8)	(1/8,1/7,1/6)
Intermediate: Very Strong - Extreme	(7,8,9)	(1/9,1/8,1/7)
Extreme importance	(9,9,9)	(1/9,1/9,1/9)

Source: Chiou et al. (2012)

The three evaluations are then aggregated into a single PCM, using the geometric mean method proposed by Buckley (1985) as illustrated in:

$$\tilde{a}_{i,j} = (\tilde{a}_{i,j}^{1} \otimes \tilde{a}_{i,j}^{2} \otimes \tilde{a}_{i,j}^{3})^{1/3} \quad \textbf{(6)}$$

3. Calculation of consistency ratio (CR).

In the third step, the consistency of the judgments made is evaluated. To calculate the consistency of the FAHP, the method proposed by Gogus and Boucher (1998) was used, which consists of calculating two CRs, one with the mean values of each TFN (component *m*) and the other with the geometric mean of the smaller and larger values (*l* and *u* components). Firstly, the method consists of forming two new PCMs, one of which we call $\boldsymbol{A^m}$, formed by the mean values of the aggregate matrix and the second we call $\boldsymbol{A^g}$ and will be formed by the geometric mean of the smallest and largest values. The next process follows the Saaty method for crisp numbers, in which for each of the matrices the weight vectors or eigenvectors $w^{\boldsymbol{m}}$ and w^g are calculated, according to:

$$w^m = [w_i^m] \text{ where } \quad w_i^m = 1/n \times \textstyle\sum_{j=1}^{n} \frac{a_{i,j,m}}{\sum_{i=1}^{n} a_{i,j,m}}$$

$$w^g = [w_i^g] \text{ where } \quad w_i^g = 1/n \times \textstyle\sum_{j=1}^{n} \frac{(a_{i,j,u} \times a_{i,j,l})^{1/2}}{\sum_{i=1}^{n} (a_{i,j,u} \times a_{i,j,l})} \quad \textbf{(7)}$$

From the weight vectors, the mean eigenvalue of each of the matrices is calculated, according to:

$$\lambda_{med}^m = 1/n \times \sum_{i=1}^{n} \sum_{j=1}^{n} a_{i,j,m} \times (w_j^m / w_i^m)$$

$$\lambda_{med}^g = 1/n \times \sum_{i=1}^{n} \sum_{j=1}^{n} (a_{i,j,u} \times a_{i,j,l})^{1/2} \times (w_j^g / w_i^g) \quad \textbf{(8)}$$

Following the procedure, the next step is to calculate the consistency indices (CI) from:

$$CI^m = \frac{(\lambda_{med}^m - n)}{(n-1)}$$

$$CI^g = \frac{(\lambda_{med}^g - n)}{(n-1)} \quad \textbf{(9)}$$

Then, to calculate the consistency ratio (CR), the CI is divided by the random index (RI). Gogus and Boucher (1998) developed an RI table as a function of the matrix size, that is, the number of criteria used, illustrated in Table 5.

Table 5. Random índices (RI)

Matrix size	RI^m	RI^g
1	0	0
2	0	0
3	0.4890	0.1796
4	0.7937	0.2627
5	1.0720	0.3597
6	1.1996	0.3818
7	1.2874	0.4090
8	1.3410	0.4164
9	1.3793	0.4348
10	1.4095	0.4455
11	1.4181	0.4536
12	1.4462	0.4776
13	1.4555	0.4691
14	1.4913	0.4804
15	1.4986	0.4880

Source: Adapted from Gogus and Boucher (1998)

4. *Calculation of fuzzy weights*

The fourth step of the FAHP is to define the fuzzy weights of each criterion in the TFN format, which is denoted by (*l,m,u*), where *l* corresponds to the smallest possible value, *m* the most probable value and *u* the largest possible value. For the calculation, the geometric mean method of Buckley (1985) is used, represented by the following equations, where $\tilde{w}_i$ represents the fuzzy weight of criterion i.

$$\tilde{\boldsymbol{r}}_{\boldsymbol{i}} = \left[\tilde{\boldsymbol{a}}_{\boldsymbol{i},\boldsymbol{1}} \otimes \cdots \otimes \tilde{\boldsymbol{a}}_{\boldsymbol{i},\boldsymbol{j}} \otimes \cdots \otimes \tilde{\boldsymbol{a}}_{\boldsymbol{i},\boldsymbol{n}}\right]^{\boldsymbol{1/n}}$$
$$\widetilde{\boldsymbol{w}}_{\boldsymbol{i}} = \tilde{\boldsymbol{r}}_{\boldsymbol{i}} \otimes [\tilde{\boldsymbol{r}}_{\boldsymbol{1}} \oplus \cdots \oplus \tilde{\boldsymbol{r}}_{\boldsymbol{i}} \oplus \cdots \oplus \tilde{\boldsymbol{r}}_{\boldsymbol{n}}]^{-\boldsymbol{1}} \quad \textbf{(10)}$$

5. *PCM defuzzification and calculation of crisp weights*

In the fifth step the fuzzy weights are converted to crisp numbers. For this, the Center of Area (COA) method was used. First, the crisp weights are calculated by the COA method, then, the normalized weights of each criterion are calculated (Kilic et al., 2014).

$$M_i = \frac{lw_i + mw_i + uw_i}{3}$$
$$\widetilde{N}_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \quad \textbf{(11)}$$

3.2.4 Fuzzy VIKOR

This section presents a fuzzy extension of VIKOR that is based on the methodology proposed by Opricovic (2011), which uses triangular fuzzy numbers (TFN) to solve a discrete fuzzy multicriteria problem with non commensurable and conflicting criteria (OPRICOVIC, 2011). Thus, the FMCDM linguistic terms are utilized to calculate that vagueness with ratings. The steps of the procedure proposed are (PAPATHANASIOU; PLOSKAS, 2018):

1. *Identify the Objectives of the Decision Making Process and Define the Problem Scope* In this step, the decision goals and the scope of the problem are defined. In this step the objective is to evaluate the key enablers regarding the criteria.

2. *Arrange the Decision Making Group and Define and Describe a Finite Set of Relevant Attributes.* In this step, a group of decision-makers is formed to identify the criteria and their evaluation scales. In this study, there is three criteria, ten sub-criteria and ten different alternatives.

3. *Identify the Appropriate Linguistic Variables.* In this step, the appropriate linguistic variables for the ratings of alternatives with respect to the criteria are chosen. The decision-makers used TFN linguistic variables shown in Table 6 to evaluate the ratings of alternatives with respect to qualitative criteria.

Table 6. The correspondence of linguistic terms and values. (FVIKOR)

Linguistic variable	Crisp Value	Corresponding TFN value
Very low impact (VL)	4	(0, 1, 3)
Low impact (L)	3	(1, 3, 5)
Medium impact (M)	2	(3, 5, 7)
High impact (H)	1	(5, 7, 9)
Very high impact (VH)	0	(7, 9, 10)

4. *Pull the Decision Makers' Opinions to Get the Aggregated Fuzzy Weight of Criteria and Aggregated Fuzzy Rating of Alternatives, and Construct a Fuzzy Decision Matrix.* The aggregated fuzzy ratings ($\tilde{x}_{ij}$) of alternatives with respect to each criterion can be calculated as:

$$\tilde{\boldsymbol{x}}_{\boldsymbol{ij}} = \left(\boldsymbol{x}_{\boldsymbol{ij1}},\ \boldsymbol{x}_{\boldsymbol{ij2}},\ \boldsymbol{x}_{\boldsymbol{ij3}}\right) \tag{12}$$

Where

$$x_{ij1} = \min_k\{x_{ijk1}\},\ x_{ij2} = \frac{1}{K}\sum_{k=1}^{K} x_{ijk2},\ x_{ij3} = \max_k\{x_{ijk3}\}$$

The problem can be concisely expressed in matrix format as follows:

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \tag{13}$$

And the vector of the criteria as:

$$\tilde{W} = [\tilde{w}_1, \tilde{w}_2, \cdots, \tilde{w}_n] \tag{14}$$

Where $\tilde{x}_{ij}$ and $\tilde{w}_j$, $i = 1,2,\cdots,m,\ \ j = 1,2,\cdots,n$, are linguistic variables according to the third step and can be approximated by TFN:

5. *Defuzzify the Fuzzy Decision Matrix and Fuzzy Weight of Each Criterion into Crisp Values* In this step, there is the Deffuzzification of the fuzzy decision matrix into crisp values using COA defuzzification relation.

6. Determine the Best and the Worst Values of All Criteria Functions. Determine the best $f_j^*$and the worst f_j^- values of all the criteria functions

$$f_j^* = \max_i f_{ij}, f_j^- = \min_i f_{ij}, i = 1, 2, \cdots, m, j = 1, 2, \cdots, n \tag{15}$$

If the jth function is to be maximized (benefit) and

$$f_j^* = \min_i f_{ij}, f_j^- = \max_i f_{ij}, i = 1, 2, \cdots, m, j = 1, 2, \cdots, n \tag{16}$$

If the jth function is to be minimized (cost).

7. Compute the Values Si and Ri. Compute the values *Si* and *Ri* by the relations

$$\begin{gathered} S_i = \sum_{j=1}^{n} w_j \left(f_j^* - f_{ij}\right) / \left(f_j^* - f_j^-\right), i = 1, 2, \cdots, m, j = 1, 2, \cdots, n \\ R_i = \max_j \left[\square_j \left(f_j^* - f_{ij}\right) / \left(f_j^* - f_j^-\right)\right], i = 1, 2, \cdots, m, j = 1, 2, \cdots, n \end{gathered} \tag{17}$$

8. Compute the Values Qi. Compute the values *Qi* by the relation

$$Q_i = v\left(S_i - S^*\right) / \left(S^- - S^*\right) + (1 - v)\left(R_i - R^*\right) / \left(R^- - R^*\right), i = 1, 2, \cdots, m \tag{18}$$

Where $S^* = min_i S_i$; $S^- = max_i S_i$; $R^* = min_i R_i$; $R^- = max_i R_i$; and υ is introduced as a weight for the strategy of the "maximum group utility", whereas $1 - \upsilon$ is the weight of the individual regret.

9. Rank the Alternatives. Rank the alternatives, sorting by the values *S*, *R*, and *Q* in ascending order. The results are three ranking lists.

10. Propose a Compromise Solution Propose as a compromise solution the alternative $[A^{(1)}]$, which is the best ranked by the measure *Q* (minimum) if the following two conditions are satisfied:

C1 - Acceptable advantage:

$$Q\left(A^{(2)}\right) - Q\left(A^{(1)}\right) \geq DQ \tag{19}$$

Where $A^{(2)}$ is the second ranked alternative by the measure Q and $DQ = {}^{1}\!/_{(m-1)}$

C2 - Acceptable stability in decision making:

The alternative $A(1)$ must also be the best ranked by S and/or R. This compromise solution is stable within a decision-making process, which could be the strategy of maximum group utility ($v > 0.5$), or "by consensus" ($v \approx 0.5$), or "with veto" ($v < 0.5$). If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

- Alternatives $A^{(1)}$and $A^{(2)}$ if only the condition C2 is not satisfied, or
- Alternatives $A^{(1)}$, $A^{(2)}$, $\cdots$, $A^{(l)}$ if the condition C1 is not satisfied; $A^{(l)}$ is determined by the relation $QA^{(l)} - QA^{(l)} < DQ$ for the maximum l (the positions of these alternatives are "in closeness").

3.2.5 *Q-Sort*

The Q-sort method is rooted in Q-methodology, and was developed by Stephenson, (1953), as a forced-choice research approach that typically involves the rank-ordering of a set of statements in a near-normal distribution, ranging from agree to disagree (see Figure 4).

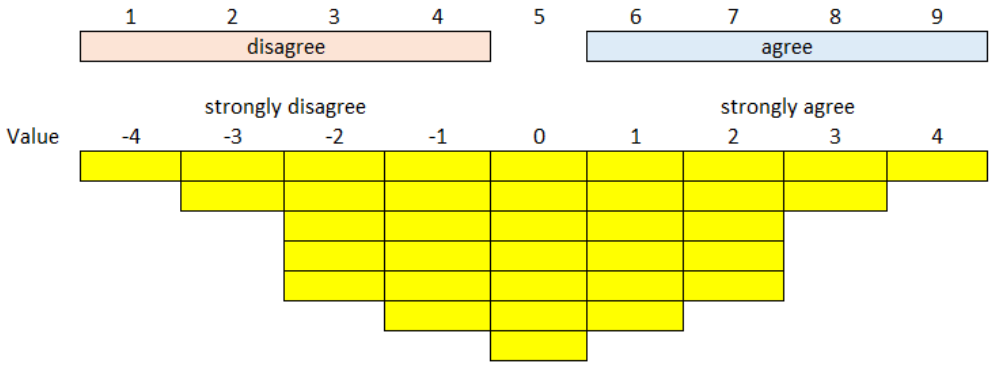

Figure 4. Q-sort distribution

Source: Adapted from ten Klooster et al. (2008)

This method is specifically designed to identify groups of respondents whose overall attitudes are similar and to closely examine the differences with respondents who have other views (BROWN, 1996). As Q-sort studies are designed to sample from a universe of perspectives, it has the practical advantage of requiring relatively small samples of respondents (DENNIS, 1988). The Q-sort method is an important difference between the Q-sort method involves the data analysis, in which the data matrix is inverted, the respondents are the variables that are correlated instead of items (TEN KLOOSTER; VISSER; DE JONG, 2008)

This research adapted the four steps of the Q-sort procedure of ten Klooster et al., (2008), as follow:

1. *Collection of relevant ideas.* In this step there was the collection of opinions concerning the research object based on content analysis of previous research and interviews.
2. *Formulation of the Q-sample.* This step involves the construction and the definition of the statements regarding the description of the elements (e.g.. key enablers) and the categories (e.g. solutions). This statement was randomly numbered as recommended in the procedure.
3. *Respondents assessment using pre-structured Q-sort distribution.* In this step the respondents expressed their perception regarding the placement (sorting) of the key enablers in the groups of solutions, in which each completed sorting task means a Q-sort.
4. *Data analysis of the degree of correspondence between respondents.* This step seeks to assess the degree of agreement of the respondents, in order to identify confounding respondents and non-significant respondents, interpret and explain similarities and differences among the factors. In this thesis, proportion of agreement and Cohen’s kappa were used. The minimum agreement expected in each item should be 75% and the target value for kappa was 0,41 (CABRAL; DHAR, 2019).

3.2.6 *Fuzzy DEMATEL*

DEMATEL has an advantage over other MCDM methods and interpretive structuring modelling (ISM), as it reveals the interrelationships between factors, and prioritizes and separates them into cause-and-effect groups, efficiently presenting the results through matrices and graphs (MACHADO et al., 2021). Although DEMATEL has gained a significant acknowledgement, as it assists in evaluating the causal interactions among decision criteria, it is not effective in practical decision making situations that may involve inconsistency due to human bias and unclear (LUTHRA et al., 2020). In this research, fuzzy set theory has also been embedded with DEMATEL to overcome the inaccuracies and subjectivity of experts' decisions. To quantify the relationship between the key enablers and assess the causal relationship between them using experts input, the FDEMATEL method was applied.

In this research, it was used the same FDEMATEL approach of (MACHADO et al., 2021), using triangular distribution for the scale, and also as a form of aggregation, and the fuzzification considered the responses of the fifteen experts. Thus, FDEMATEL was adopted based on six steps, as follows:

1. *Create the correspondence of linguistic terms and values* (Table 7). Each of the experts uses a linguistic term converted in a number from 0 (zero) to 4 (four) that has a corresponding linguistic value (triangular fuzzy number), as presented on Table 2.

Table 7. The correspondence of linguistic terms and values (FDEMATEL)

Linguistic Term	Crisp Value	Fuzzy Number
Very high influence (VH)	4	(0.75, 1.0, 1.00)
High influence (H)	3	(0.50, 0.75, 1.00)
Low influence (L)	2	(0.25, 0.50, 0.75)
Very low influence (VL)	1	(0.00, 0.25, 0.50)
No influence (No)	0	(0.00, 0.00, 0.25)

2. *Aggregate results and obtain a fuzzy pairwise direct-relation matrix (X).* Expert assessment is added by calculating average scores and forming aggregated direct relationship matrices. When the number of factors is n, the pair comparison matrix, X, is n × n. Each element within this matrix, Xij, represents the level of influence of factor i on a factor j. The influence of each factor on itself that forms the diagonal of the direct relation matrix is nullified. The general matrix of direct pair relationship is presented, following:

$$\tilde{z} = \frac{(\tilde{z}^1 \oplus \tilde{z}^2 \oplus \cdots \oplus \tilde{z}^p)}{p} \tag{20}$$

$$\tilde{Z} = \begin{bmatrix} \tilde{z}_{11} & \tilde{z}_{12} & \cdots & \tilde{z}_{\mathrm{ln}} \\ \tilde{z}_{21} & \tilde{z}_{21} & 0 & \tilde{z}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{z}_{n1} & \tilde{z}_{n2} & \cdots & \tilde{z}_{nn} \end{bmatrix}$$

Relation Fuzzy matrix X by using

$$\tilde{X} = \begin{bmatrix} \tilde{x}_{11} & \tilde{\chi}_{12} & \cdots & \tilde{x}_{\mathrm{ln}} \\ \tilde{x}_{21} & \tilde{x}_{21} & 0 & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{n1} & \tilde{X}_{n2} & \cdots & \tilde{x}_{nn} \end{bmatrix} \tag{21}$$

where:

$$\tilde{x}_{ij} = \frac{\tilde{z}_{ij}}{r} = \left(\frac{l_{ij}}{r}, \frac{m_{ij}}{r}, \frac{n_{ij}}{r}\right)$$
$$r = \max_{k \le i \le n} \left(\textstyle\sum_{j=1}^{n} u_{ij}\right). \tag{22}$$

It is assumed at least one i such that $\sum_{j=1}^{n} u_{ij} < r$.

3. *Normalize the direct-relation matrix and calculate the total relation matrix (T) that determines the relationship between factors where I is the identity matrix:* After computing the above matrices, the total-relation fuzzy matrix $\widetilde{\mathrm{T}}$ is computed. Total-relation fuzzy matrix is defined as:

$$\tilde{T} = \lim_{k \to \infty} \left(\tilde{X}^{1} + \tilde{X}^{2} + \cdots + \tilde{X}^{k}\right) \tag{23}$$

then,

$$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \cdots & \tilde{t}_{\mathrm{ln}} \\ \tilde{t}_{21} & \tilde{t}_{21} & 0 & \tilde{t}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \cdots & \tilde{t}_{nn} \end{bmatrix} \tag{24}$$

In which $\tilde{t}_{ij} = \left(l_{ij}'', m_{ij}'', u_{ij}''\right)$ and

$$\left[l_{ij}''\right] = X_l \times (I - X_1^{-1}), \left[m_{ij}''\right] = X_l \times (I - X_m^{-1}), \left[u_{ij}''\right] = X_l \times (I - X_u^{-1})$$

4. *Determine row and column sums from T:*

Given that *Tij* is the comparison variable of the factor *i* on the factor j in the total relation matrix, *T*, where *i,j* =1, 2, ..., n, the row (*Di*) and column (*Rj*) sum for each row *i* and column *j* are obtained using expressions:

$$D_i = \sum_{j=1}^{n} t_{ij} \quad \forall i$$
$$R_j = \sum_{i=1}^{n} t_{ij} \quad \forall j \tag{25}$$

By producing matrix $\tilde{T}$, then it is calculated $\tilde{D}_i + \tilde{R}_j$ and $\tilde{D}_i - \tilde{R}_j$ in which $\tilde{D}_i$ and $\tilde{R}_j$ are the sum of row and the sum of columns of $\tilde{T}$ respectively. To finalize the procedure, all calculated $\tilde{D}_i + \tilde{R}_j$ and $\tilde{D}_i - Rj$ are defuzified through suitable defuzification method. Then, there would be two sets of numbers: $(\tilde{D}_i + \mathrm{Rj})^{\mathrm{def}}$ which shows how important the strategic objectives are, and $(\tilde{D}_i - \tilde{R}_j)^{\mathrm{def}}$ which shows which strategic objective is cause and which one is effect. Generally, if the value $(\tilde{D}_i - \tilde{R}_j)^{def}$ is positive, the objectives belong to the cause group, and if the value $(\tilde{D}_i - \tilde{R}_j)^{\mathrm{def}}$ is negative, the objectives belong to the effect group.

5. *Determine the overall prominence and net effect values of factors:*

The overall value by which a factor is being influenced and its influence on other factors characterize overall prominence (*P*). The difference between the impact that a factor has on others and the impact received by others characterizes the net effect value (*Ei*). *Pi* and *Ei* can be calculated by the expressions:

$$Pi = \{Di + Rj|i = j\}$$
$$Ei = \{Di - Rj|i = j\} \tag{26}$$

6. *Formulate the DEMATEL cause-effect Diagrams:*

The last step is the graphical representation for each factor (key enablers) of the calculated prominence and net effect values on a two-dimensional axis. *X*-axis is the prominence value; the y-axis is the net effect value. The threshold value θ is defined by the expression:

$$\theta = mean\ (T) + \mathrm{SD}T \tag{27}$$

3.2.7 ELECTRE I

In this study was also applied an outranking method, which is based on pairwise comparisons of the options (alternatives). This means that every option is compared to all other options, and based on the comparisons, final recommendations can be drawn (ISHIZAKA; NEMERY, 2013). *ELimination Et Choix Traduisant la REalite* (ELECTRE) method, presented by Roy for the first time at a conference in 1965 and published on a paper in 1968 (ROY, 1968), evaluates all alternatives using outranking comparisons and eliminates low-attractive alternatives (ALINEZHAD; KHALILI, 2019). This technique belongs to the non-compensatory methods; there is no need for independence of criteria, and the qualitative criteria are converted into the quantitative attributes. ELECTRE methods avoid compensation between criteria (do not tolerate a compensation effect) and any normalization process, which distorts the original data and there is no need to use indifference and preference thresholds, and the performances of the criteria can be expressed in different units (decision-maker wants to avoid defining a common scale) (ISHIZAKA; NEMERY, 2013). On the other hand, ELECTRE methods require various (difficult) technical parameters, which requires that the decision-maker rank (real or fictitious) options that have a clear ranking in order to infer parameters such as the weights of the criteria and the thresholds. The standard procedure for executing the ELECTRE-I approach is defined as follows (ALINEZHAD; KHALILI, 2019; ROY, 1996):

1. *Construct the decision table:* It includes a performance evaluation of all the alternatives (solution measures) regarding the available criteria (challenges). The decision matrix is used in the ELECTRE method as:

$$X = \begin{bmatrix} r_{11} & \cdots & r_{1j} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ r_{i1} & \cdots & r_{ij} & \cdots & r_{in} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mj} & \cdots & r_{mn} \end{bmatrix}_{m\times n} ; \quad i = 1, \ldots, m, \quad j = 1, \ldots, n \tag{28}$$

where r_{ij} is the element of the decision matrix for ith alternative in jth attribute. Furthermore, the decision-maker provides the weight of attributes $[w_1, w_2, \cdots, w_n]$.

2. *Normalize the decision matrix: This step includes the Normalization of the Decision Matrix.*

$$r_{ij}^{*} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^{2}}}; \quad j = 1, \ldots, n \tag{29}$$

where r_{ij} indicates the normalized amount of the decision matrix of ith alternative in jth criteria.

3. *Assign weights to the normalized matrix*: This step includes extraction of weights of challenges obtained through application of FAHP in previous stage. It is utilized as initial inputs for ELECTRE approach.

$$\hat{r}_{ij} = r_{ij}^{*}.w_j; \quad i = 1, \ldots, m, \quad j = 1, \ldots, n \tag{30}$$

where w_j is the weight of the criteria $[w_1, w_2, \cdots, w_n]$.

4. *Determine the Concordance and Discordance sets*: The concordance set $C_{i,k}$ of two alternatives and the complementary subset (discordance set) is described as follows:
   The Concordance set is obtained as:

$$C_{i,k} = \{j | \hat{r}_{ij} \geq \hat{r}_{kj}\}; \quad i, k \in \{1, \ldots, m\} \quad j = 1, \ldots, n \tag{31}$$

The Discordance set is calculated using:

$$d_{i,k} = \{j | \hat{r}_{ij} < \hat{r}_{kj}\} = j - C_{i,k}; \quad i, k \in \{1, \ldots, m\}, \quad j = 1, \ldots, n \tag{32}$$

5. *Construct the Concordance and Discordance matrices*. The relative value of the elements in the concordance matrix is calculated by means of the concordance index, which is the sum of the weights associated with the criteria contained in the concordance set; and the discordance matrix, which express the degree that a certain alternative A_k is worse than a competing alternative A_1.
   The Concordance matrix is indicated as:

$$G_{m\times m} = (g_{ik})_{m\times m}; \quad g_{ik} = \sum_{j\in C_{i,k}} w_j, \quad 0 \le g_{ik} \le 1 \tag{33}$$

Further, the Discordance Matrix is determined by:

$$D_{m\times m} = \left(d'_{ik}\right)_{m\times m}; \quad d'_{ik} = \frac{\max\limits_{j\in d_{i,k}} \left|\hat{r}_{ij} - \hat{r}_{kj}\right|}{\max\limits_{j\in J} \left|\hat{r}_{ij} - \hat{r}_{kj}\right|}, \quad 0 \le d'_{ik} \le 1 \tag{34}$$

6. *Determine the Concordance and Discordance Dominance matrices.* The concordance dominance matrix is constructed by means of a threshold value for the concordance index, and similarly, the discordance dominance matrix G is defined by also using a threshold value.

   The Concordance Dominance matrices is formed as:

$$F_{m\times m} = (f_{ik}); \quad f_{ik} \begin{cases} 0 & if \quad g_{ik} < \bar{g} \\ 1 & if \quad g_{ik} \ge \bar{g} \end{cases}, \quad i,k \in \{1, \ldots, m\} \tag{35}$$

$\tilde{g}$ represents the average of dominant matrix elements, computed as:

$$\bar{g} = \sum_{k=1}^{m} \sum_{i=1}^{m} \frac{g_{ik}}{m(m-1)} \tag{36}$$

The Discordance Dominance matrix is computed by:

$$E_{m\times m} = (e_{ik}); \quad e_{ik} \begin{cases} 1 & if \quad D_{ik} \le \bar{D} \\ 0 & if \quad D_{ik} > \bar{D} \end{cases}, \quad i,k \in \{1, \ldots, m\} \tag{37}$$

$\widetilde{D}$indicates the average of dominated matrix elements, calculated as:

$$\bar{D} = \sum_{k=1}^{m} \sum_{i=1}^{m} \frac{D_{ik}}{m(m-1)} \tag{38}$$

7. *Determine the aggregate Dominance matrix:* The aggregate dominant matrix is formed as:

$$P_{m\times m} = (p_{ik}); \quad p_{ik} = f_{ik}.e_{ik}, \quad i,k \in \{1, \ldots, m\} \tag{39}$$

8. *Eliminate the less favorable alternatives:* From the aggregated dominance matrix one can derive a partial preference ordering of the alternatives. If p_{ik}= 1, then this means that alternative A_k is preferred to alternative A_l by using both the concordance and discordance criteria. The low-attractive alternatives are eliminated in the final ranking of alternatives using the integration dominance matrix and then ranked.

4 RESULTS AND DISCUSSIONS

4.1 Theoretical findings: Study descriptors, taxonomies and Framework proposal

Addtional details on the thoeretical findings can be obtained in Caiado et al. (2021a) and Caiado et al. (2021b) – working papers.

4.1.1 Study descriptors

In this section, a panoramic perspective on the topic through descriptive analysis is presented. Appendix A provides a summary of the articles reviewed. The SLR process yielded 48 articles that met the eligibility criteria for analysis. The convergence of sustainability and I4.0 in OSCM domain is a topic which has evolved in recent years, and papers' distribution (Figure 5a and 5b) indicates that higher numbers of articles were published over the last four years and the peak was reached in 2020, with 21 articles. The interest in researching the sustainability aspects of the I4.0 in OSCM is increasing in popularity, which is an evolutionary trend compatible with a new research field (MACHADO; WINROTH; RIBEIRO DA SILVA, 2020)

Figure 5a shows the distribution of studies based on the research categories (theoretical, empirical, or mixed) per year of publication. There is a predominance of theoretical studies, but from 2019 onwards there was an increase in mixed research. As a still under-explored, emerging research field, the studies are still going through theoretical approaches (e.g., literature reviews) as the knowledge of concepts of the S-OSCM4.0 still needs to be well consolidated. Then, Fig. 2b presents the chronological distribution of the publications considering the research approach (qualitative, quantitative, or mixed). According to Figure 5b, the most commonly used approach in the analysed articles is the qualitative approach, followed by mixed and quantitative papers. Notably, only 4.17% of the sample adopted just a quantitative approach and from 2020 onwards, there was an increase of studies combining qualitative and quantitative (mixed) approaches, which can also be an indication of the recentness of the subject that, as it acquires maturity, new methodological approaches start to be used (e.g., multiple criteria decision-making methods) and combined.

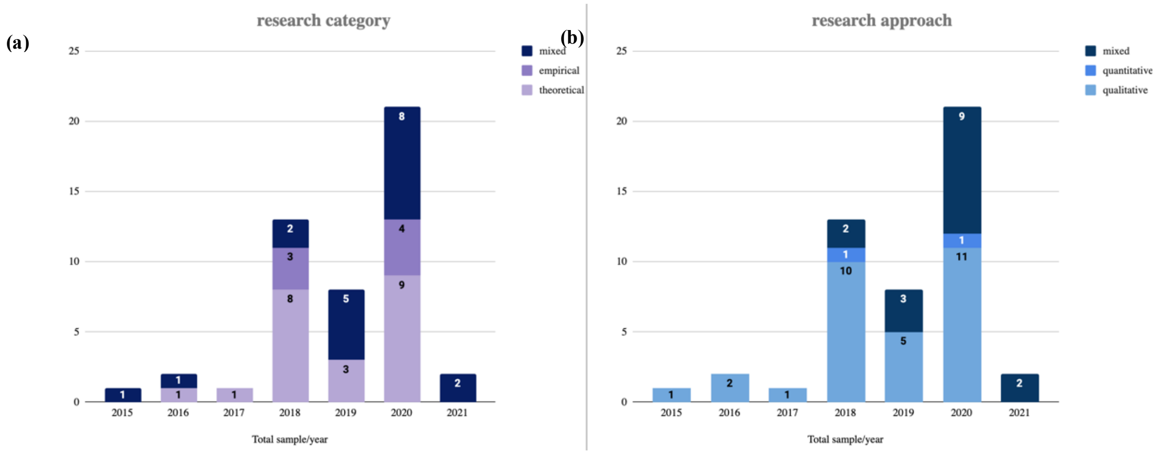

Figure 5. Chronological distribution of articles based on the research category (a) and research approach (b)

In terms of I4.0 technologies to S-OSCM, considering the technologies pointed out in Caiado et al. (2021), Figure 6 shows that over half of the articles (52.08%) involved multiple technologies, in which there is a predominance of base technologies (Internet of things, cloud computing and Big data analytics) (FRANK; DALENOGARE; AYALA, 2019), followed by the general category (39.29%), which means that the paper does not go into detail about one or several technologies and has a more superficial approach to the subject. It should also be noted that among the I4.0 technologies, Big data analytics (BDA) is the technology with the most studies and within the multiple technologies category, this technology has also been widely discussed in the context of sustainability, which reveals growing interest in the BDA for sustainable business management (CHIAPPETTA JABBOUR et al., 2020a).

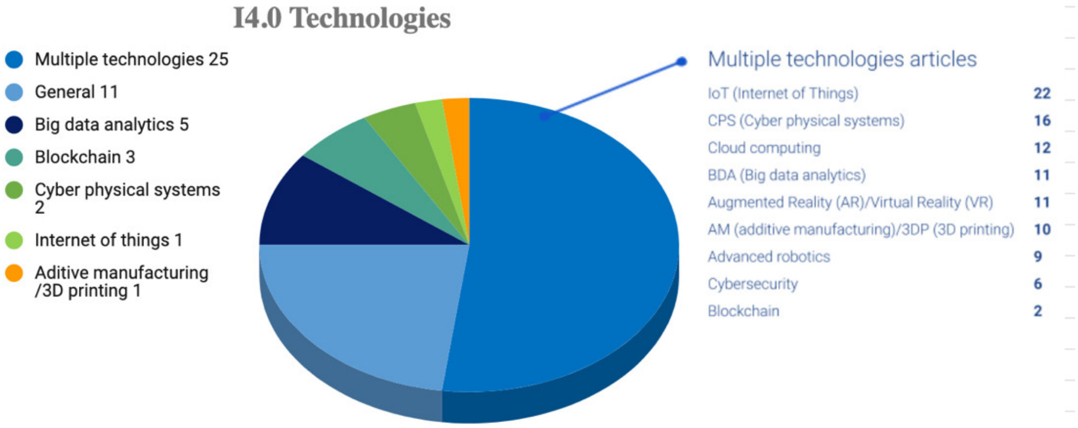

Figure 6. Distribution of studies by I4.0 technology

Figure 7 presents the number of publications by country of affiliation of the authors of the analyzed sample. The principal geographical location of the studies is United Kingdom (11 publications), followed by India (10), United States (8), China (7), Brazil (7) and France (6). It is possible to note that the subject has been studied both by researchers from developing and developing countries, which represents a positive initiative, considering that a sustainable digital transformation is a global need that requires participation and awareness of all regions.

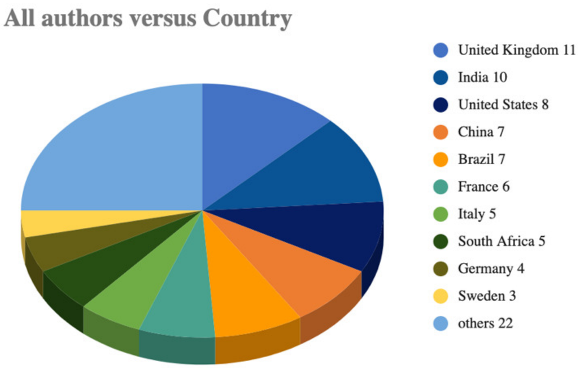

Figure 7. Geographical distribution of studies

4.1.2 Enablers

The enablers were grouped into: Circular & Sustainability, Information & Technology, Innovation, People & Culture, and Supply Chain organization & Processes, and they are discussed next. Appendix B offers the list of papers dealing with each enabler. Figure 8 shows the result of the taxonomy developed for enablers.

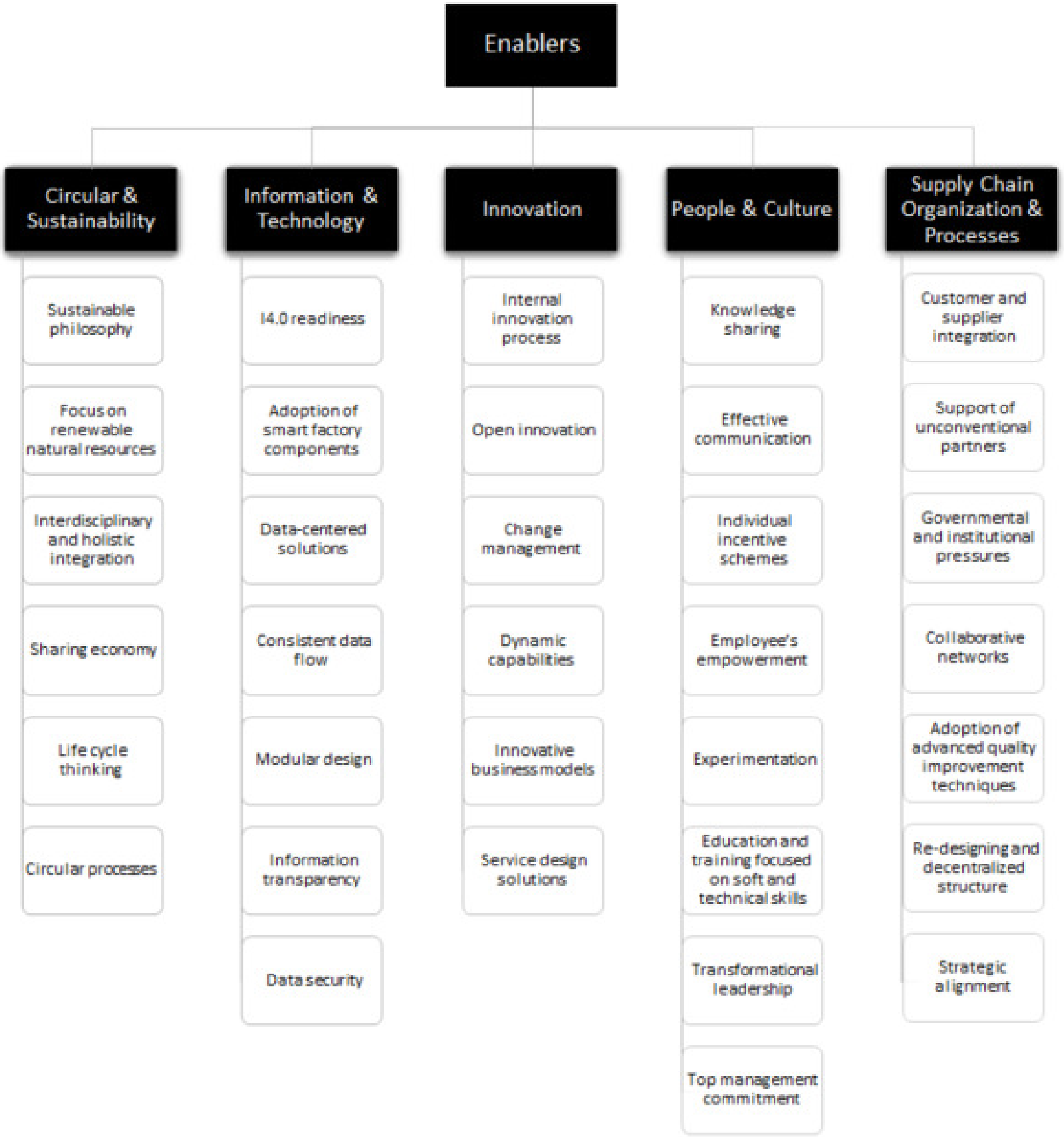

Figure 8. Enablers of S-OSCM4.0

Circular & Sustainability

To create truly sustainable OSCM and reap all the benefits of sustainability, it is necessary for companies to introduce change and innovation beyond the current technical systems, through the **adoption of a sustainable philosophy** that corresponds to their objectives (MAY; STAHL; TAISCH, 2016). Awareness of sustainability concepts among customers will increase their adoption rate (YADAV et al., 2020b). In addition, the adoption of industrial ecology initiatives helps to implement circular economy practices for better sustainability

(YADAV et al., 2020c). This philosophy involves several stages of innovation and corporate culture and must encompass management and employees, to provide a vision and guidance for the direction of companies (MAY; STAHL; TAISCH, 2016). In a complementary way, the focus should be on renewable natural resources as alternatives to non-renewable ones and replacement of the “weak sustainability” model by the rational exploitation of natural resources (OLÁH et al., 2020). If good use is made of I4.0, it can be well integrated with the SDGs, which can result in efficiency and the effective use of non-renewable and renewable resources (BONILLA et al., 2018b).

An **interdisciplinary and holistic integration** is also necessary for a perfect understanding of S-OSCM4.0. The study of sustainability must be approached in a holistic perspective, considering emerging areas, such as the circular economy (MARTÍN-GÓMEZ; AGUAYO-GONZÁLEZ; LUQUE, 2019), as well as the combination of two or more study areas that aims to integrate your insights to build an understanding more comprehensive (interdisciplinarity), and address more complex issues (DRAGONE et al., 2020). Another relevant factor is the potential for sharing, also called the **sharing economy**, which is made possible by digital platforms that allow an easy combination of supply and demand (PHAM et al., 2019). Sustainable business models (e.g., Airbnb, Uber) are successful because they share value and cost assets (BRENNER, 2018). In addition, a **life cycle thinking approach** is required, which means that for each product, all operations (design, production, transport, use and end of life) and material and immaterial inputs and outputs related to its realization are considered (GARCIA-MUIÑA et al., 2018). Thus, thinking in terms of the life cycle of a product or service means thinking about all stages of your life “from the cradle to the grave” (JULIANELLI et al., 2020). The adoption of this thinking offers a systemic view of the production processes, monitoring the consumption of resources, the production of waste and scrap, and emissions into the atmosphere at each stage of the process (GARCIA-MUIÑA et al., 2018).

Another current trend is the sustainable OSCM approach based on the implementation of organizational strategies through **circular processes** (DAÚ et al., 2019). De Sousa Jabbour et al., (2018) state that decision making in relation to sustainable operations management implies a connection between the circular economy (CE) approach and the principles of I4.0. The implementation of circular business models with I4.0 technologies allows the development of local business networks that contribute to the generation of local jobs (NASCIMENTO et al., 2019). The use of sustainable manufacturing techniques, such as closed-cycle supply chains

(PANETTO et al., 2019) and their integration with I4.0 to create a sustainable supply chain seeks to produce a model for the dissemination of sustainable practices through social responsibility (DAÚ et al., 2019). Circular business models using I4.0 technologies can promote a culture of reuse and recycling and motivate the development of techniques for collecting and processing urban waste (NASCIMENTO et al., 2019). For example, the development of advanced production capabilities using 10R-based manufacturing approaches (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, reuse, recycle and recover options) can provide opportunities for cleaner production in the CE-based business (BAG; GUPTA; KUMAR, 2021).

Information & Technology

Bag et al., (2021) states that companies with a high degree of implementation of I4.0 led to a positive development of sustainable practices (e.g., 10R) that have a positive influence on sustainable development results. It is observed that the development of infrastructure for **I4.0 readiness** is considered an essential factor for organizations to improve the results of sustainable development and achieve their objectives in OSCM (BAG; GUPTA; KUMAR, 2021). In addition, the **adoption of smart factory components**, which is considered an indicator based on I4.0, ensures overall sustainability, including economic, environmental and social concerns (YADAV et al., 2020b). Yadav et al. (2020a) also state that the use of intelligent factory components will increase the possibility of success of S-OSCM. In this sense, **networked equipment and computers** are a requirement for horizontal and vertical information connectivity in OSCM (KUSIAK, 2019).

Data-centered solutions (e.g., BDA-centric solutions) can help companies better implement sustainable supply chain practices and can help organizations gain sustainable competitive advantage through opportunities related to business intelligence, value creation and business decisions (RAUT et al., 2019). Data-based analyzes can be used to optimize the use of resources or balance the perspectives of TBL, which is necessary for industrial symbiosis in an eco-industrial park (TSENG et al., 2018). However, it is necessary to be aware that S-OSCM4.0 can be facilitated by the development of other organizational capabilities (CHIAPPETTA JABBOUR et al., 2020b). For example, it becomes vital for organizations to adopt and develop processes using BDA resources to achieve sustainability performance in OSCM (BAG et al., 2020). Management must consider data analysis as a key element in establishing cooperation and collaboration between stakeholders (OLÁH et al., 2020). It is necessary to build a truly data-driven culture not only within companies, but also among members supply chain (CHIAPPETTA JABBOUR et al., 2020b). Therefore, another relevant factor is a **consistent data flow**, as according to Bonilla et al. (2018b), increased integration through the data flow promotes a more flexible structure and exchange of data between all elements. Data flow processes represent a hierarchical structure, in which data collection, integration and analysis are connected (KRISTOFFERSEN et al., 2020). Managing the exponentially growing amount of data is vital to support new requirements for day-to-day operations and requires access to reliable data (GHOBAKHLOO, 2020).

Modular development allows the development of products based on established modules and is also considered an essential concept for sustainability (GU et al., 2018). Configuring technology with a **modular design** can manage the complexity of digital systems, reduces entrapment to specific technologies, makes it possible to deliver each solution step by step, as the training is in progress, and can help with acceptance; and offers opportunities for continuous innovation (SJÖDIN et al., 2018). In addition, scalability is crucial to reduce cost and improve performance, being a key factor in making the I4.0 system commendable and brilliant (MANAVALAN; JAYAKRISHNA, 2019). Thus, modular and scalable business models can be used to obtain financial gains in S-OSCM.

Full transparency and verifiability, greater confidence and security of information are also needed (KOUHIZADEH; SABERI; SARKIS, 2021). **Information transparency** is the key to any social responsibility reporting initiative that is considered a lever to improve internal and external transparency (MAY; STAHL; TAISCH, 2016). Digital technologies such as Blockchain can be used to track sustainability-related indicators (e.g., child labor or the source of resources), and make them available to stakeholders and decision makers (STOCK et al., 2018). In addition, high investments in **data security** specialists are expected, which is important to protect intellectual property and prevent the loss of competitive advantages (BIRKEL et al., 2019). Blockchain technologies are used to distribute data and increase security in OSCM (STOCK et al., 2018).

Innovation

Braccini and Margherita (2018) state that the transition to I4.0 was driven by a purposeful **internal innovation process** that proved to be sustainable according to sustainable principles that guided it. Companies that exhibit greater capacity for innovation can leverage the development of green products to drive greater performance (BAG et al., 2020). Thus, the company's internal potential is most strongly influenced by the potential and commitment of its own employees (STACHOVÁ et al., 2019).

In addition, **open innovation** with sustainability in manufacturing systems is very important and represents a growing issue (SHIM; PARK; CHOI, 2018). Open innovation is a process of interaction between the company and its environment, in order to reach a broader spectrum of knowledge, skills, ideas and solutions (NEGNY et al., 2017). Open innovation allows companies to identify and explore new technological capabilities developed inside and outside the company's boundaries (BRENNER, 2018), despite requiring investments in internal resources (STACHOVÁ et al., 2019).

Change management practices play an important role in promoting the transition process towards the completion of ecofactories (MAY; STAHL; TAISCH, 2016). Readiness for change can affect how work procedures will be achieved and new work skills will be required (DE SOUSA JABBOUR et al., 2018). I4.0 requires the adoption of a new organizational structure, new systems and policies, therefore, to achieve S-OSCM4.0, companies must manage changes strategically and must proactively deal with the attitude of workers and their resistance (BAG et al., 2018).

The **Dynamic capability View** (DCV) theory (TEECE; PISANO; SHUEN, 1997) is an extension of the Resource-based view (GUPTA et al., 2020) that theorizes that a firm earns income by leveraging its unique resources, which in turn give rise to the analysis of learning and knowledge management as the means to create new resources (BRENNER, 2018). Dynamic capabilities play a critical role in a company's sustainability in a complex and volatile environment (BAG et al., 2018). Dynamic innovation will play an important role, as it provides the opportunity to develop new organizations and business models, leading to a greater degree of participation by representatives (MUÑOZ-LA RIVERA et al., 2020). Brenner (2018) states that essentially, resources / skills and dynamic capabilities must be established internally and cannot be simply acquired externally and as a result, detecting, taking advantage and transforming (continuous renewal) are attributes that allow companies to (co) evolve the business environment.

The **adoption of innovative business models** is a facilitator for sustainable I4.0, through the inclusion of sustainability in business models or the development of purely digital business models (digitization, internet and networking technology) (STRANDHAGEN et al., 2017). Innovations of the new business model (e.g., Crowd-Sourced Innovation, Manufacturing as a Service and Product-as-a-Service) can offer significant economic and social sustainability opportunities (GHOBAKHLOO, 2020). New and sustainable business models must guarantee business benefits shared fairly among all stakeholders in the value chain, and they must facilitate innovation, product development, financing, reliability, risk, intellectual property and protection of know-how in a network environment (PRAUSE, 2015). In addition, **service design** (solutions) is considered a sustainable design and successful service design solutions must be connected to an intelligent business model (PRAUSE, 2015).

People & Culture

Knowledge sharing and effective communication are fundamental aspects in the context of industrial work and have a critical role for S-OSCM4.0. Information technology can support the generation of meta-knowledge from those who know what and can generate benefits such as improving team performance (KAASINEN et al., 2019). Information sharing will be the basis for the application of I4.0 technologies in the conduct of environmentally sustainable manufacturing decisions (DE SOUSA JABBOUR et al., 2018). Digital technologies such as virtual reality (VR) or augmented reality (AR) are valid tools to support participatory design in which through the sharing of knowledge one learns from the other, supporting common understanding and collaboration (KAASINEN et al., 2019). In addition, increased productivity and reduced costs can be fully achieved by modern communication technologies (for example, mobile internet and industrial internet) (REN et al., 2019).

Effective communication plays a key role in the development of a collaborative workplace and can improve not only a company's performance level, but also the relationship between different companies in a supply chain (DE SOUSA JABBOUR et al., 2018). The efficiency of communication associated with transparency, surveillance and control generates advantages for S-OSCM 4.0 such as minimizing downtime, waste, defect and risk in the processes (GHOBAKHLOO, 2020).

According to Stock and Seliger (2016), it is necessary to increase extrinsic motivation through the implementation of **individual incentive schemes** based on performance feedback mechanisms within the product's life cycle. Coordination incentive schemes (such as repurchase, quantity discounts, revenue sharing, price discounts, portfolio contracts and combined mechanisms) suggest decentralized coordination that has been considered the basic principle in I4.0, such as the cyber-physical production systems (CPPS) (MA et al., 2020). The amount of incentive to offer users must be accurately calculated with effective business models and sustainability consequences (ESMAEILIAN et al., 2020).

In addition, **employees empowerment** positively affects the sustainable performance of companies (DE SOUSA JABBOUR et al., 2018). The paradigm is changing to adjust the systems to the human operator, with empowerment supported by adaptive human-automation interaction solutions that improve workflow, and thus job satisfaction (KAASINEN et al., 2019). Empowerment is exemplified through a work environment based on managerial practices that allow employees to develop autonomy and responsibility to be innovative and thus develop proactive behaviour (DE SOUSA JABBOUR et al., 2018). Employees can also benefit from the use of personal health technologies (personal monitoring devices and applications, such as wearable motion trackers, heart rate monitors, and health-related mobile apps) to gain strength-building feedback on their well-being in relation to different jobs (KAASINEN et al., 2019). Currently, an open-minded culture is also a key issue and must be considered when adopting new organizational tools and techniques for sustainable management and the transition to I4.0 and environmentally sustainable manufacturing (DE SOUSA JABBOUR et al., 2018). Likewise, **experimentation** can help develop and update ideas for future development and cooperation, and companies must be open to establishing niches as protected spaces for experimenting with new and extraordinary ideas (HAHN, 2020).

Another critical factor in this digital age is **education and training**, in which learning factories seek an action-oriented approach, with participants acquiring skills in a technological learning environment and thus integrating different teaching methods with the aim of bringing the teaching / learning processes of real industrial problems (KAASINEN et al., 2019). The adoption of I4.0 technologies will require adequate training and skill development for OSCM employees and partners, and environmental training is also necessary to enable employees to adopt more advanced sustainable practices (DE SOUSA JABBOUR et al., 2018).

The digital age will require the development of talents, skills and experience in addition to traditional technical skills, such as new technical, analytical and interdisciplinary leadership, to deal with intelligence for decision-making in a connected world in real-time (DRAGONE et al., 2020). Decision-making managers must have certain soft and technical skills and, therefore, a human resources program is crucial in terms of recruiting, educating and maintaining management improvement (OZKAN-OZEN; KAZANCOGLU; KUMAR MANGLA, 2020). Important soft skills include continuous learning, innovative and critical analytical thinking, and technical skill requirements include experience in programming, BDA, robotics and maintenance of intelligent systems (BAG et al., 2020). Additionally, according to Muñoz-La Rivera et al. (2020), some innovative characteristics of the new professional are: adapter, searcher for multiple alternatives, experimenter, knowledge integrator, curious to do and learn, communicator, collaborative and integrative, creative, leader and team manager and focused on the user.

The adoption of I4.0 principles to boost sustainability performance may require a **transformational leadership** style, capable of inspiring followers to neglect their own interests in favor of the organization's good (DE SOUSA JABBOUR et al., 2018). As a result, the leadership style of management can influence the implementation of emerging trends such as the implementation of S-OSCM4.0. In addition, top management has the responsibility to provide organizational opportunities to integrate I4.0 technologies and environmentally sustainable manufacturing into existing production systems (DE SOUSA JABBOUR et al., 2018), so the **commitment of top management** also plays a role vital to the current sustainable digital revolution in OSCM.

Supply Chain Organization & Processes

According to Pham et al. (2019), I4.0 starts with customer requirements and integrates different systems, such as connected technologies. There must be customer and supplier integration for S-OSCM4.0. Companies should extend their use of digital technologies to supply chain processes and establish digital supply chain platforms with upstream suppliers, downstream customers and other partners in order to facilitate supply chain relationships and make the decision-making process more integrated to achieve sustainability (LI; DAI; CUI, 2020).

A sustainable approach offers solutions (given by product integration with ancillary services) capable of satisfying customer needs but using fewer resources and with less environmental and socio-economic impact (GARCIA-MUIÑA et al., 2018). Using digital technologies (e.g., BDA), customers can actively engage in green purchasing practices, cleaner production, eco-labelling and eco-design feedback, which can improve customer satisfaction (RAUT et al., 2019).

In the same way, suppliers can be considered the main input parameter for the effective execution of Sustainable OSCM, therefore; it is essential for suppliers to commit to sustainability parameters (YADAV et al., 2020b), for example by implementing sustainable purchasing practices. The decreasing costs of computing and communications have facilitated collaboration with suppliers and other participants in the market ecosystem, increasing the feasibility for close cooperation with customers or suppliers, using co-creation and open innovation approaches to create value (BRENNER, 2018). Organizations must collaborate with their suppliers for technological integration, environmental criteria and environmental auditing (RAUT et al., 2019). Thus, it is critical for S-OSCM4.0 to maintain constant control of supplier-related activities to establish an uninterrupted sustainable supply chain system (YADAV et al., 2020c), as the supplier's active involvement improves data sharing and encourages companies to achieve greater sustainability goals (RAUT et al., 2019).

The **integration of new unconventional partners** such as Research Institutes & Universities, startups with sustainability solutions, environmental NGOs or investors can also contribute to S-OSCM4.0 (HAHN, 2020). Stakeholders (leaders in the public and private, industrial and academic sectors) must work together to ensure that I4.0 sustainability opportunities are distributed to communities and around the world in the most equal and fair way possible (GHOBAKHLOO, 2020). In addition, government support, through the creation of clear pollution control guidelines (LUTHRA et al., 2020), offers several sustainability support policies for organizations to develop a general sustainable environment (YADAV et al., 2020b). In addition, **institutional and government pressure** can positively stimulate the development of workforce skills (BAG et al., 2020).

Another important factor is the **establishment of collaborative networks**. It is equally important to be involved in proper planning and cooperation with external stakeholders (BAG et al., 2020). The creation of an open development platform involving key industries can allow for such collaboration, including the development of data-based models (collaborative manufacturing networks) (KUSIAK, 2018). Digital infrastructures (of digitally enabled technology) that incorporate supply chain partners can detect and monitor changes in the external environment more efficiently, thus making it a necessary choice for companies to achieve success in sustainable OSCM (LI; DAI; CUI, 2020).

The structure of an organization is the key factor to successfully implement digital technologies, and in its redesign it must accompany a change in jobs and tasks and, therefore, a change in practices and work structure (MURMURA; BRAVI, 2017). A fundamental rethinking of the structure is necessary to ensure that the use of technology focuses on doing the right things, in addition to just doing something the right way (ESMAEILIAN et al., 2020). Thus, an adaptable organizational structure is necessary (BAG et al., 2020), with sustainable design strategies (MACHADO; WINROTH; RIBEIRO DA SILVA, 2020). Stock et al. (2018) claim that **decentralized organizational structures** facilitate and promote partnerships between companies and a reduction in the total amount of waste is expected, e.g., inefficient planning and resulting waste can be minimized. For example, the decentralized organization makes it possible to implement concepts such as Water 4.0, which aims at more efficient and flexible water management through digitalization (OZKAN-OZEN; KAZANCOGLU; KUMAR MANGLA, 2020).

Due to the current turbulent situation in the market and its demand, the organization's operations must be agile (RAUT et al., 2019), reliable through risk management systems to minimize the loss of time due to equipment interruptions and injuries (PINZONE et al., 2020), and have greater capacity for updating, standardization and adaptability of systems (NASCIMENTO et al., 2019). In a complementary way, the integration of I4.0 technologies with environmentally sustainable decisions would be implemented through improvement projects (DE SOUSA JABBOUR et al., 2018). According to Yadav et al. (2020a) the **adoption of advanced quality improvement techniques** is essential. It is essential to continuously monitor the implementation of these practices to ensure that these systems achieve the desired sustainable benefits, for example, energy conservation (LENG et al., 2020). In this sense, tangible and quantitative terms are needed to build and increase reliability among the various stakeholders (OZKAN-OZEN; KAZANCOGLU; KUMAR MANGLA, 2020). The adoption of sustainability performance metrics ensures the tracking of activities and the alignment of sustainability (YADAV et al., 2020b).

As far as strategy is concerned, it is critical to allocate the budget intelligently to different sections of the organization. Smart budget allocation with the use of digital technologies (e.g., Internet of Things - IoT) makes it possible to follow the global progress and helps to distribute the available financial resources effectively among the entire organizational structure, allowing to achieve sustainability (YADAV et al., 2020b). For Ivascu (2020), despite sustainable development, which is a voluntary approach, improving organizational conditions, thus contributing to its competitiveness, interested parties are only interested in this concept as long as they obtain better financial results (increased profit). Finally, De Sousa Jabbour et al. (2018) state that organizations cannot be competitive without total alignment with information technology and the appropriate selection of I4.0 technologies to assist in environmentally sustainable decisions can allow for better **strategic alignment**.

4.1.3 Challenges

The challenges were grouped into technology, economic, society, knowledge & support, and environment and they are discussed next. The name of the categories are based on Moktadir et al. (2018). Appendix C offers the list of papers dealing with each challenge. Figure 9 shows the result of the taxonomy developed for Challenges.

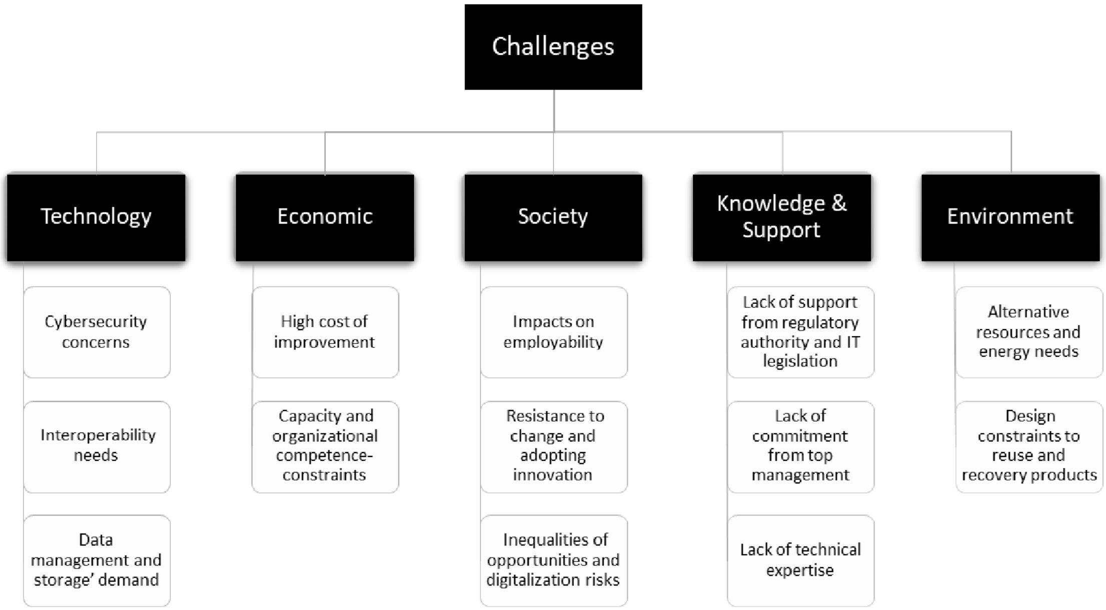

Figure 9. Challenges to S-OSCM4.0

Technology

Cybersecurity concerns are one of the most cited challenges to the implementation of a sustainable I4.0. There is an increase in critical digital data about individuals that can be misused by decision-makers or targeted by cyber-attacks (STOCK et al., 2018). Concerns about inadequate application of IT security standards (BAG et al., 2018), lack of trust when integrating IT systems between supply chain partners (DE SOUSA JABBOUR et al., 2018a), and the reliability of machine-to-machine (M2M) decisions may be questioned (DING, 2018). According to Kamble et al. (2018), data breaches and cyber-attacks through malicious software need to be controlled to improve the trustworthiness and acceptability of the digital systems. As Kouhizadeh et al. (2021), security is as a challenge and a technological barrier to the blockchain technology that impede its application for business purposes.

Given the supply chain complexity (BAG et al., 2020), and considering that every action has to be integrated into both the business model and logistics across the entire supply chain (STRANDHAGEN et al., 2017), many authors present **interoperability needs** as challenges to I4.0 and sustainability. De Sousa Jabbour et al. (2018) bring the low reliability of connectivity between machines and the lack of integration of IT systems between supply chain partners. Luthra and Mangla (2018) discusses the lack of global standards and data sharing protocols, and the lack of integration of technology platforms. Yadav et al. (2020a) go in the same direction and highlight the lack of effective communication with suppliers and the nonexistence of and effective framework for SSCM adoption. Ren et al. (2019) list as challenges the lack of dynamic network infrastructure to link physical and virtual objects, and the centralized management of the heterogeneous lifecycle data. Finally, other authors present other technical issues related to interoperability, such as internet connection and storage requirements (CHIAPPETTA JABBOUR et al., 2020b).

Given its high dependency on data, I4.0 has to overcome the challenge of **data management and storage** to be sustainable (ESMAEILIAN et al., 2020; OZKAN-OZEN; KAZANCOGLU; KUMAR MANGLA, 2020). Many problems still need to be addressed. Luthra and Mangla (2018) listed as challenges the poor existing data quality; the lack of integration of technology platforms; problems related to coordination and collaboration; and the lack of global standards and data sharing protocols. Other authors, such as Leng et al. (2020) and Esmaeilian et al. (2020) stated that data storage is a challenge to blockchain's future applications. Finally, the lack of knowledge about data management between stakeholders (OZKAN-OZEN; KAZANCOGLU; KUMAR MANGLA, 2020) and the ineffective management of data acquired during historical product design and development processes (REN et al., 2019), are also cited.

Economic

The **high costs of improvement** involved in I4.0 and sustainability are the biggest economic challenge presented in literature. The investment needed and the capital expenditures underlying the I4.0 technologies are quite intense, especially for manufacturing companies located in the context of emerging economies (NASCIMENTO et al., 2019). To worsen the situation, there is a lack of funding for technological up-gradation (BAG et al., 2018), products whose demand level does not justify the high fixed costs of the I4.0 assembly line (BRACCINI; MARGHERITA, 2018) and a lack of interest in investing money for sustainability given its long and uncertain amortization (BIRKEL et al., 2019). Ultimately, the challenge is to align an understanding of the requirements of competitiveness with those that represent long-term sustainability (PINZONE et al., 2020).

Another challenge for companies refers to their **capacity constraints, and organizational, competence - constraints** (MAY; STAHL; TAISCH, 2016). Ineffective linkage of sustainability with existing process structure, ineffective supplier selection strategies, ineffective performance measurement system, may hinder the integration between I4.0 and sustainability (YADAV et al., 2020c). Birkel et al. (2019) presents many risks related to this theme, such as the decision in what to invest and when; the changing of business models that may lead to losing the core competencies; customer demands/acceptance; lack of understanding about data-driven business models; and new competitors.

Society

Employability is a challenge associated to Society. A smart factory can hinder the opportunity for a labour-intensive workforce, which can lead to social problems in local communities (DING, 2018). There are many social risks involved, such as job losses, shifts of competencies, automation, reduction of process steps (BIRKEL et al., 2019). Indeed, managing human resources to fit in the I4.0 setup is a large challenge for top management (BAG; GUPTA; KUMAR, 2021). In this sense, the physical and psychological wellbeing of the workers, aging, and diversity need to be considered (PINZONE et al., 2020). **Resistance to change and adopting innovation** may also be a challenge for society. I4.0 requires policy, infrastructure, societal and environmental changes (BAG et al., 2020). These changes may face a lack of management commitment and support (KOUHIZADEH; SABERI; SARKIS, 2021); the resistance of culture change (YADAV et al., 2020c), including employee and mid-level management resistance (BAG et al., 2020); and cultural differences with the supply chain partners (KOUHIZADEH; SABERI; SARKIS, 2021). May et al. (2016) called them as behavioural barriers that demand the managers to have a strong involvement (YADAV et al., 2020b).

Inequalities of opportunities and digitalization risks were also pointed as a challenge for society. Given the high investments required to implement I4.0 (OZKAN-OZEN; KAZANCOGLU; KUMAR MANGLA, 2020), megacorporations in more developed countries can benefit from the pioneer advantage, increasing wealth disparities in the global consumer market (GHOBAKHLOO, 2020). In this sense, digitalization may increase global inequalities (HAHN, 2020). Hahn (2020) also highlights that the ability to develop countries to catch up does not only include building adequate technological infrastructure and increasing local knowledge and capabilities through education and training. Access to technological interfaces, and knowledge, which enable and empower countries and local communities to integrate and ultimately contribute to the development of the technology and their community, is also necessary.

Knowledge & Support

The **lack of support from regulatory authority and an absence of strong IT legislation** are also a challenge for sustainable I4.0 application. The absence of IT security standards and policies may affect both the customer and suppliers in the supply chain network (BAG et al., 2018). Furthermore, regulatory, and procedural barriers hinder the adoption of SSCM (NASCIMENTO et al., 2019). In addition to legal aspects concerning working time regulations and data protection, Birkel et al. (2019) also presents political risks, like insufficient infrastructure (Broadband internet; Mobile network) to I4.0. Leng et al. (2020) concluded that the current standards and rules are a limitation for blockchain application; therefore, governments may need to formulate policies to either encourage or demand that producers use blockchain systems to improve their environmental sustainability.

The **lack of commitment from top management** is another challenge for I4.0 and sustainability application/integration. Luthra and Mangla (2018) identified this problem as one of the top six challenges to I4.0 initiatives for a sustainable supply chain in the Indian context. There is a lack of management approval for a big investment in newer technologies (BAG et al., 2018), which might be linked to the lack of understanding of the importance of Industry 4.0 at top management levels (KHANZODE et al., 2020). Ozkan-Ozen et al. (2020) also mentioned the lack of middle and lower-level managers' support and involvement in promoting 'greener' products.

The **lack of technical expertise** about I4.0 technologies is another great challenge presented in the literature. There is a need for staff training and education Oláh et al. (2020), given that society has a lack of qualified and skilled labour to adapt to I4.0 technologies and sustainability (OZKAN-OZEN; KAZANCOGLU; KUMAR MANGLA, 2020). Birkel et al. (2019) cite as barriers internal resistance and corporate culture from older employees, which Khanzode et al., (2020) called as hesitation to convert to new systems; new requirements for training; mental stress and permanent availability; and missing social interaction at the same time interdisciplinary thinking is needed.

Environment

One significant challenge associated to the environment regards to **alternative resources and energy needs**. The rate of exploitation of natural resources should not exceed the rate of regeneration (BONILLA et al., 2018b); however, Industry 4.0 has focused mainly on production and achieving the highest profits (OLÁH et al., 2020). The increase in production rates linked to I4.0 led to higher resource and energy consumption, as well as high pollution concerns (GHOBAKHLOO, 2020); deforestation; health-related diseases; and ground and water service contamination. Industry 4.0 still has a high consumption of resources, raw materials, information, and energy, which is environmentally unsustainable (OLÁH et al., 2020). Esmaeilian et al. (2020) stated that energy consumption is a major limitation for blockchain, which is aligned with Raut et al. (2019), who affirmed that energy consumption and material quantity on BDA have a negative impact on environmental sustainability.

One of the biggest challenges linked to customized products (a benefit of I4.0) is that the more individualized products become, the harder it is for another company or person to reuse those products (BIRKEL et al., 2019). Thus, the **design constraints to reuse and recovery products** is a critical challenge. As presented in Nascimento et al. (2019), fast-speed innovation can make reuse impossible. Furthermore, there is low management support in usage of I4.0 technologies for "design for reuse" philosophy (OZKAN-OZEN; KAZANCOGLU; KUMAR MANGLA, 2020). Therefore, waste might be increased, and recycling might become more difficult (BIRKEL et al., 2019). In addition, the effective management of the knowledge acquired during historical product design and development processes is challenging (REN et al., 2019). This situation is aggravated considering the absence of reverse logistics facilities and internal bureaucracy in creating a circular logic in the supply chain (YADAV et al., 2020c). Finally, there are some technical limitations. For instance, Nascimento et al. (2019) stated that 3D printing may not provide the surface characteristics specified in the component design or even material properties, which may demand other processes to be performed.

4.1.4 Sustainable technological solutions

Sustainable technological solutions can be defined in this study as the interdisciplinary efforts that can positively contribute to sustainability through the development of digital technologies (CAIADO et al., 2021) to deal with multifaceted and contested issues and tradeoffs, having a positive impact in reducing the environmental footprint (DRAGONE et al., 2020). These solutions were grouped into smart energy, smart maintenance, smart products, smart mobility, smart analytics, and smart contracts. Appendix D offers the list of papers dealing with each solution and the link of each one with I4.0 technologies.

Smart Energy

Technological solutions aimed at **smart energy** facilitate the integration of electrical networks and renewable energy sources (GHOBAKHLOO, 2020) and can support production efficiently in terms of energy and resources (BAI et al., 2020). When connecting smart grids to the organization, renewable energy resources are used more frequently and their use can lead to a greater share of renewable energy resources as input to manufacturing systems (STOCK et al., 2018). In addition, IoT technologies for the product lifecycle can enable real-time exchange of information with reliability, allow the acquisition of energy consumption data in real time and analysis at the machine and production line level for improve energy-conscious decision-making and can monitor and map the storage area in real time and suggest usage strategies for the company (MACHADO; WINROTH; RIBEIRO DA SILVA, 2020). Through virtualization (e.g., VR / AR Technologies), it becomes possible to design and test new plants before configuring them (BONILLA et al., 2018b), and improvements in the plant can be supported to reduce energy consumption and to optimize and add value to operations, simulating all activities throughout the supply chain (BAI et al., 2020). IoT, BDA and cloud provide rigid and flexible infrastructure to address energy and resource efficiency in production activities (BAI et al., 2020). If well designed, decentralized intelligence, through the use of high quality Blockchain and BDA, can lead to sustainable and energy-saving systems (LENG et al., 2020).

Smart Maintenance

Technological solutions aimed at **smart maintenance** involve reducing the risk of operation (BAI et al., 2020) and keeping the human workforce safer (GHOBAKHLOO, 2020). Wearable technologies, such as smart glasses and helmets, can be used with mobile devices or wearable computing to improve safety in hazardous work areas with safety training and risk maps (KAMBLE; GUNASEKARAN; GAWANKAR, 2018). The life cycle of the equipment can be substantially extended and the equipment can be reused in new life cycles, so organizations can extend the life of the equipment by studying the environmentally friendly characteristics of sustainable product manufacturing (MANAVALAN; JAYAKRISHNA, 2019). The CPS functionalities can also be used to optimize the operations of existing systems, raising their real performance to the level of maximum performance (GHOBAKHLOO, 2020) and improving and innovating existing systems (PINZONE et al., 2020), increasing its maximum performance changing and redefining tasks and jobs (REN et al., 2019). CPS offers a more accessible, secure, fast and productive learning experience, and high-resolution simulation models in connection with real-time data collection and processing are now available as prototypes for new plant management and control (GHOBAKHLOO, 2020). IoT and BDA enable the monitoring and preventive maintenance of machines and robots, as well as continuous communication throughout the supply chain, and increase production efficiency and flexibility, reduce waste and minimize the carbon footprint for each product (CHIAPPETTA JABBOUR et al., 2020b). Smart cameras; smart sensors; and smart wearables can detect and report any human or machine behavior that could pose a security risk (GHOBAKHLOO, 2020). BDA and CPS can be used for predictive and remote maintenance and promote real-time monitoring (BONILLA et al., 2018b). Blockchain vehicle identity (VID) can facilitate vehicle maintenance (ESMAEILIAN et al., 2020). Incorporating blockchain into IIoT solutions can help predict and prevent manufacturing equipment failures and can be used to capture the activities of the product's manufacturing process and improve reputation among different functions in manufacturing asset management (LENG et al., 2020).

Smart Products

Technological solutions aimed at **smart products** can be applied to save material (BONILLA et al., 2018b), enable a variety of end-of-life practices (STOCK et al., 2018), allow production with almost no waste (ESMAEILIAN et al., 2020) and facilitate the development of new environmentally friendly products (GHOBAKHLOO, 2020). Cloud technology can bring greater efficiency in the use of materials, reduced use of toxic materials and less impact on effluents and waste (GHOBAKHLOO, 2020). For example, the use of additive manufacturing by means of 3D printers can achieve the possibility of metal forming and does not require cooling of the cooling / lubricant process, and thus less residual water is generated (MAY; STAHL; TAISCH, 2016). In addition, when combined with rapid manufacturing, it can support individualized production (STRANDHAGEN et al., 2017).

Nanotechnologies can contribute to the development of bioplastics and lightweight bio-based composites, thus contributing to the reduction of fuel consumption, CO2 emissions from vehicles and the use of petroleum-derived plastics, relating to economic sustainability and environmental (BAI et al., 2020). In addition, in relation to social sustainability, it can also improve the livelihoods of farmers (BAI et al., 2020). The alignment of IoT, cloud and BDA allow for an improved management of the information flow and facilitates the development of green products and innovation in ecological design (LI; DAI; CUI, 2020). The Internet of Service and the Internet of People offer and facilitate the development of the Product-as-a-Service (PaaS[2]) business model (GHOBAKHLOO, 2020), which is reshaping the concept of ownership, reducing the importance of valuable assets and facilitating accessibility of goods at the time of need (BONILLA et al., 2018b).

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[2] Product-as-a-Service (PaaS) is a business model that allows customers to purchase a desired result rather than the equipment that delivers that result.

Smart Mobility

Technological solutions aimed at **smart mobility** can optimize CO2 emissions from incoming and outgoing logistics, as well as intra-company transport as part of the logistics organization (STOCK et al., 2018), and can contribute to the traceability of minerals (rare) used in this industry also regarding the autonomous disassembly of electronic equipment for recycling / reusing its components (BAI et al., 2020). In addition, drones can allow personalized deliveries to a new level, and autonomous transport and production have a potential contribution to the advancement of organic farming and precision farming for fiber crops (STRANDHAGEN et al., 2017). The fifth generation of mobile technology (5G) can enable smart urban mobility and increased productivity (BAI et al., 2020). The IoT can be used to track the location of the shipment and the speed of the vehicle and so that users are alerted for delays in deliveries (MANAVALAN; JAYAKRISHNA, 2019). The IoT can be implemented to monitor the condition of equipment from a remote location and can perform data collection and exchange remotely and automatically (MAY; STAHL; TAISCH, 2016). Such solutions can facilitate the sharing of manufacturing, transportation, and other resources, allowing the identification and tracking of individual products throughout their life cycle (KUSIAK, 2018). The interaction between hardware and software, using embedded systems and wireless technologies, is currently spreading in highly flexible manufacturing environments (PRAUSE, 2015). RFID tags and sensors embedded in products collect all data about a product's life cycle and monitor the condition of components for reuse, recycling, and remanufacturing (MANAVALAN; JAYAKRISHNA, 2019). Thus, BDA and IoT can anticipate, and shape potential customer demands and improve manufacturing, logistics and distribution efficiencies (KAMBLE; GUNASEKARAN; GAWANKAR, 2018). Blockchain can be used for vehicle communication, traffic management, reducing carbon emissions and sharing data from autonomous cars, among other applications (ESMAEILIAN et al., 2020).

Smart Analytics

Technological solutions involving **smart analytics** allow devices and machines to develop learning capacities and act in response to different situations, thus being able to determine the customer's next need and ensure a useful structure for sharing information with the supplier (RAUT et al., 2019). Thus, cooperation, involvement and coordination between supply chain partners (for example, customers, suppliers) is guaranteed in the implementation of sustainable practices (for example, carbon footprint reduction, waste emissions and pollution control) (BONILLA et al., 2018b). A robust internal business process is also guaranteed with infiltration of sustainability objectives in the organization, increasing the company's reliability and performance (and productivity) through better visualization and efficient decision-making (REN et al., 2019).

Smart analytics brings potential advantages to OSCM, such as improved supply chain planning and demand forecasting, identification of consumption patterns and supply chain bottlenecks, reduction of risks and uncertainties, knowledge generation, KPI optimization, predication and feedback for product and process design (BAG et al., 2020; GHOBAKHLOO, 2020). For example, data-centric carbon footprint analyzes contribute to reducing greenhouse gas emissions, and managers can extract significant patterns from employee data and learning patterns from each employee (DUBEY et al., 2019). Such solutions provide the service of remote operational data storage in real time and on-demand access to data displayed in a cloud (BAI et al., 2020) and create an agile manufacturing ecosystem (GHOBAKHLOO, 2020; LI; DAI; CUI, 2020), which allows rapid reaction and adaptation capabilities in response to changes and environmental uncertainties (STRANDHAGEN et al., 2017). It is of great importance in the development of environmental sustainability, with the long-term objective of reducing the effects of climate change, in addition to promoting green behavior among consumers and decreasing the operational costs of systems (BONILLA et al., 2018b). They also allow managers to build complex models of a manufacturing network using a data-based approach and provide multiple services and products more quickly with improved reliability (ESMAEILIAN et al., 2020).

In addition, it can be used to distribute data and to increase security in supply chains and manufacturing processes (LENG et al., 2020), which are characteristics that can be used to track sustainability-related indicators (STOCK et al., 2018). IoT can be used with other technologies, such as GPS, soil sensors and meteorological data in the field of precision agriculture to integrate data and analysis with crop science to enable scientific agricultural decisions (BAI et al., 2020). IoT and Blockchain can improve communication between stakeholders, contribute to sustainability and total resource management, increase efficiency in data sharing and contribute to the decentralized structure (OZKAN-OZEN; KAZANCOGLU; KUMAR MANGLA, 2020). Blockchain technology can serve as a bridge to connect IoT technologies with BDA, in order to guarantee the sharing of real data with members of the supply chain (CHIAPPETTA JABBOUR et al., 2020b). In addition, an integrated blockchain system with digital tracking sensors provides accurate and tamper-proof data for product end-of-life support decisions (LENG et al., 2020).

Smart Contracts

Finally, technological solutions involving **smart contracts** could also be particularly important to S-OSCM4.0. High quality blockchain and BDA can now be encoded in smart contracts executed on agents who can make decisions that represent the participants (LENG et al., 2020). Contract-based integration is the basis for intelligent cross-linking of supply chain entities from the point of view of I4.0 (STOCK; SELIGER, 2016). Thus, a cost-sharing contract is beneficial from the point of view of both the consumer and the ecologist. In addition, both the manufacturer and the retailer participate in the cost-sharing agreement, as the contract improves the participants 'profitability, so that the participants' individual rationality constraints are satisfied. Through coordination contracts, the value delivered to end customers is greater, while entities in the supply chain also benefit (GHOSH et al., 2020).

4.1.5 Benefits

The benefits are aligned with Agenda 2030, which is considered a plan of action for people, planet and prosperity. Appendix E offers the list of papers dealing with each benefit and the link of each one to the SDGs and specific targets. Figure 10 shows the result of the taxonomy developed for Benefits.

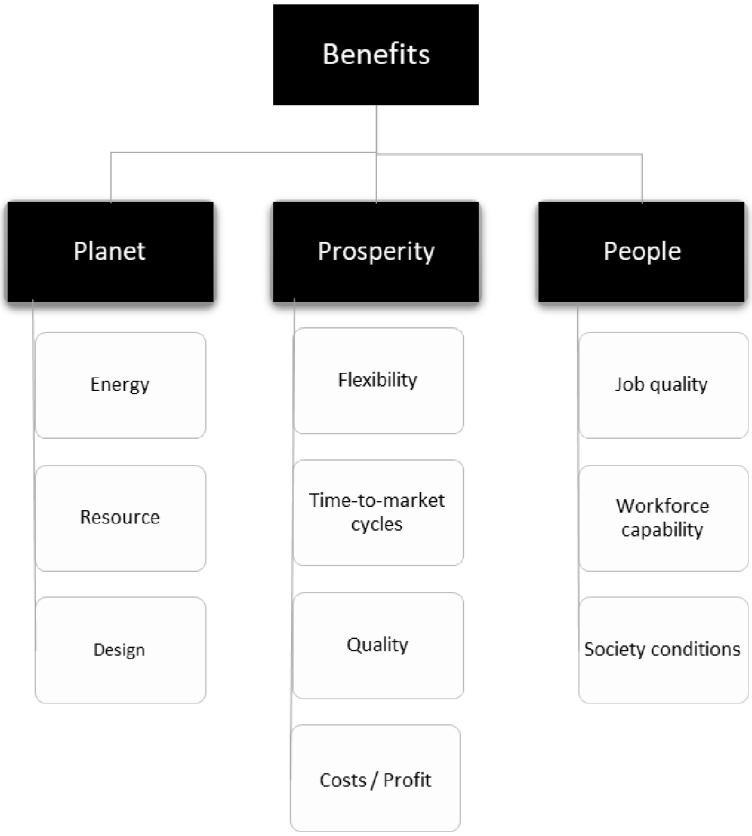

Figure 10. Benefits of S-OSCM4.0

Planet

The adoption of I4.0, with smart production systems, has the potential to reduce **energy** consumption of the companies (KAMBLE; GUNASEKARAN; DHONE, 2020). By using real time data from production systems and supply chain partners, less and more intelligent energy consumption will occur (DE SOUSA JABBOUR et al., 2018). As an example, unused electricity from wind power plants can be intelligently distributed at night and used industrially (STOCK et al., 2018). Additionally, a company's energy consumption can also be reduced through using process simulations (BIRKEL et al., 2019; LUTHRA et al., 2020), by sharing renewable energy surplus with other plants (MACHADO; WINROTH; RIBEIRO DA SILVA, 2020), and by improving throughput times, and capacity utilization (STOCK et al., 2018).

Similar to energy reduction, I4.0 adoption can lead to less consumption of **resources**. Virtualization and the use of intelligent devices in a smart production system, enables to reduce the production of waste (BAG et al., 2020; GHOBAKHLOO, 2020); and overproduction (MACHADO; WINROTH; RIBEIRO DA SILVA, 2020; STOCK et al., 2018). Dynamically configurable production processes improve the material efficiency of production, which diminishes the quantity of materials used (STOCK et al., 2018). I4.0 can also increase the share of reused, remanufactured and recycled materials (BAG et al., 2020). As some examples, blockchain facilitates recycling behavior by incentivizing individuals to participate in deposit-based recycling programs (ESMAEILIAN et al., 2020), Additive manufacturing (AM) makes possible the use of waste to generate new value-added products (NASCIMENTO et al., 2019).

I4.0 initiatives have also the potential of unlocking supply chain sustainability by developing green products (LUTHRA; MANGLA, 2018), through a more sustainable **design**. Digital technologies can provide efficient solutions for green product design and production and service processes (LI; DAI; CUI, 2020). These new processes can favor easy disassembly for recycling (RAUT et al., 2019). Furthermore, it is possible to design products with extended life spans, by applying the 5Rs strategy (reduce, repair, re-use, recycle, and remanufacture) (DE SOUSA JABBOUR et al., 2018).

Prosperity

The advent of Industry 4.0 favors the introduction and the widespread application of new business model innovations such as Crowd-Sourced Innovation (CSI), Manufacturing as a Service (MaaS), and PaaS (GHOBAKHLOO, 2020). In this sense, process efficiency and data exchange between robots, increased the level of innovation (IVASCU, 2020). Furthermore, employee development improves the level of knowledge and increases the capability and support of employees to develop green projects (BAG et al., 2020; PINZONE et al., 2020), which shortens innovations (BAI et al., 2020; PRAUSE, 2015). I4.0 implantation can lead to reduced set-up times, shorter lead times, reduced labor and material costs, which increases production **flexibility** (BAI et al., 2020; PINZONE et al., 2020). Data analytics, machine learning, and artificial intelligence enable the digitalization and interconnection of industrial processes intended by Industry 4.0 (MÜLLER; KIEL; VOIGT, 2018). IoT and AI-based production increase the efficiency and flexibility of production (GHOBAKHLOO, 2020). Cloud manufacturing enable flexible small scale production systems with local production networks that are integrated on demand (MAY; STAHL; TAISCH, 2016). AM allows for the production of multiple parts simultaneously in the same build, making it possible to produce locally an entire product (MURMURA; BRAVI, 2017).

I4.0 can also be a driver for shortening **time-to-market cycles** (PRAUSE, 2015). For instance, Murmura and Bravi (2017) states that due to 3D printing companies in the wood-furniture industry are free to explore their imagination, which bring in a shorter time on the market products with more complex shapes. In addition, BDA can assist in decisions regarding perceiving and predicting market demands, sourcing, supply chain network design, product design and development, which provides a faster response to market and faster-decision-making (CHIAPPETTA JABBOUR et al., 2020b; REN et al., 2019).

Braccini and Margherita (2018) found that I4.0 leads to increased production efficiency and higher **quality** products. This statement is confirmed by many authors, as Birkel et al. (2019) and Murmura and Bravi (2017). The latest presenting the 3D printings as an enabler for this new reality. According to Oláh et al. (2020), robotic-assisted production, big-data-driven quality control, and quality assurance teams to analyze proactively, will allow all business processes that might involve inefficiencies to be eliminated. Digitally enabled infrastructure and multiple data sources, can create a differentiated competitive advantage, by producing customized products, and increasing their perceived values (LI; DAI; CUI, 2020).

Finally, **costs** decreasing **/ profit** improvements is one of the most cited benefits of adopting digital technologies. Ren et al. (2019) estimated that the combination of BDA and lean management could worth tens billions dollars in improved profits for large manufacturers. Digitizing manufacturing and smarter machines may offer numerous advantages related to cost reduction, such as: increasing manufacturing productivity and improving resource efficiency (GHOBAKHLOO, 2020; LI; DAI; CUI, 2020; PINZONE et al., 2020); decreasing inventory and logistics costs (BIRKEL et al., 2019); reducing operators or man power and saving energy (VARELA et al., 2019). Moreover, BDA allow manufacturers to prepare spare parts for the right machine at the right time with the right quantity, optimizing the fuel use efficiency and the real-time route of spare parts transportation for suppliers (REN et al., 2019).

People

For many authors I4.0 can improve working conditions, environment in the companies and, thus, **job quality**. Digitalization and the emergence of labour-saving technologies (e.g., intelligent robots, autonomous vehicles, and cloud solutions) will eliminate great part of lower-skilled jobs while creating many job opportunities in various areas such as automation engineering, control system design, machine learning, and software engineering (GHOBAKHLOO, 2020). In many cases, there will be a reduction of monotonous work (MÜLLER; KIEL; VOIGT, 2018), and employees will be able to work from their homes, which ensures flexibility and a reduction in pollution (OLÁH et al., 2020). Finally, process automation can lead to safer conditions in the work environment (BAI et al., 2020; KAMBLE; GUNASEKARAN; GAWANKAR, 2018).

According to Mastos et al. (2020), IoT technologies are better accepted when users have been trained and the workforce have been informed about the expected benefits of the solution. In this sense, it is expected that I4.0 will improve **workforce capability**, through a more effective education of workers (STOCK et al., 2018)(BAI et al., 2020), and more training courses (VARELA et al., 2019). As Bag et al. (2020), employee development increases the level of knowledge and improve the capability and support of workers in green product projects.

The competitive advantage obtained by adopting I.4.0 leads to increased social sustainability by defending the employment levels, producing new job employment opportunities, and paying more taxes on the value delivered (BRACCINI; MARGHERITA, 2018). To Varela et al. (2019) I.4.0 can improve **society conditions**, creating employment opportunities for disabled and elderly employees (MACHADO; WINROTH; RIBEIRO DA SILVA, 2020). In addition, open source-based applications of 3D printing could contribute to a sustainable development in rural areas with low economic profiles, as it overcome the spatial gap to markets of spare parts, consumer products or tools (MURMURA; BRAVI, 2017).

4.1.6 S-OSCM4.0 framework towards Agenda 2030

This section presents the framework comprising the four taxonomies, and how they relate to the purposes of the integration of sustainability and I4.0 in OSCM, taking the discussion on the link between S-OSCM4.0 and Agenda 2030 into account.

Based on the SLR, this thesis proposes a S-OSCM4.0 framework comprising of four main components viz., enablers, challenges, sustainable technological solutions, and benefits (see **Figure 11**), which are linked to strongly assist the practitioners to improve SSCM adoption rate (YADAV et al., 2020b), while also digitalizing their operations. This framework can be used as a guideline to sustainable digitalization in OSCM, and to align the organizational activities towards Agenda 2030. This taxonomies-based framework has a holistic and interdisciplinary view and suggests that the enablers should be properly managed, and the challenges should be overcome in order to use the I4.0 technologies to build sustainable technology solutions, fully integrating sustainability and I4.0 in six focal areas of OSCM, to obtain the SD benefits of this integration in line with SDGs.

To guide an organisation on the journey to S-OSCM4.0, managers should implement this framework in four steps: (i) manage and integrate the enablers into OSCM; (ii) face the challenges of the sustainability-I4.0 integration and work on them; (iii) build sustainable technological solutions combining multiple I4.0 technologies; and (iv) use enablers and solutions to obtain SD’ benefits. The first step concerns the management of the 34 enablers as a list of good practices that plays a critical role and that should be followed to increase the integration of I4.0 and sustainability. These five categories - Circular & Sustainability, Information & Technology, Innovation, People & Culture, and Supply Chain Organization & Processes – of enablers are important predictors of S-OSCM4.0 maturity, with a better understanding and performance of these enablers in an organization, relevant factors can be manipulated to improve S-OSCM4.0 integration. Then, the second step consists of identifying the existence of some of the 13 challenges in the five categories (technology, economic, society, knowledge and support, and environment), facing them with the correct implementation of enablers to overcome potential restrictions to the integration of I4.0 and sustainability in OSCM. In the third step, sustainable technological solutions are built in six Smart categories (energy, maintenance, products, mobility, analytics, and contracts) using I4.0 technologies for S-OSCM. Finally, the fourth step concerns the leverage of enablers and solutions to achieve planet, people, and prosperity benefits, also increasing the positive impact over SDGs.

Thus, this framework can strategically support organizations in aligning their priorities with the SDGs (WBCSD, 2015) and in managing their contribution regarding the 10 benefits of S-OSCM4.0. As an example of the implementation of this four-step framework, organizations that wish to obtain (prioritize) a reduction in energy consumption (KAMBLE; GUNASEKARAN; DHONE, 2020) (benefit to the Planet) must adequately manage, and in an integrated manner, the Circular and Sustainability enablers (sustainable philosophy, focus on renewable natural resources, interdisciplinary and holistic integration, sharing economy, life cycle thinking, and circular processes) so that the exploitation of the natural resource is not exceeded (BONILLA et al., 2018b) and can make use of solutions with multiple technologies (e.g., IoT, BDA and cloud) in order to get a flexible infrastructure that enables more energy efficiency (smart energy) (BAI et al., 2020). Additionally, if an organization wants to focus on improve workforce capability (STOCK et al., 2018) (benefit to People), there must be an integrated management of People & Culture enablers (knowledge sharing, effective communication, individual incentive schemes, employee's empowerment, experimentation, education, and focused training on soft and technical skills, transformational leadership and top management commitment) to overcome Knowledge and Support’ challenges such as the lack of technical expertise (OZKAN-OZEN; KAZANCOGLU; KUMAR MANGLA, 2020), and can make use of solutions combining wearable technologies (KAMBLE; GUNASEKARAN; GAWANKAR, 2018) that facilitate safety training (smart maintenance).

Although, the enablers and sustainable technological solutions play a key role to potentialize the S-OSCM4.0, it is expected that the enablers be fully integrated in OSCM to ease the I4.0 and sustainability adoption, in an integrated way; and the digital technologies must also be combined under socio-environmental demands and not only with an economic focus.

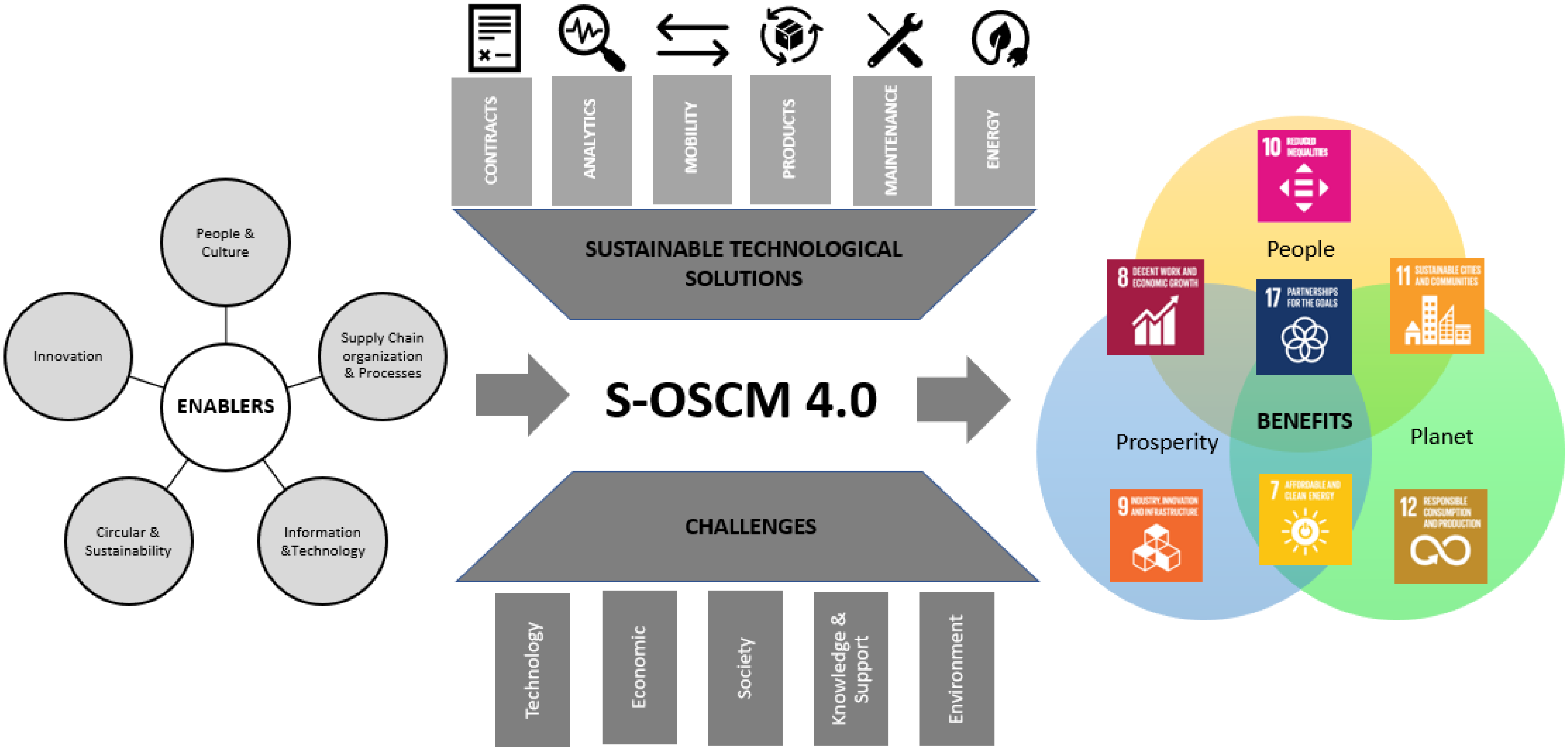

Figure 11. S-OSCM4.0 taxonomies-based framework towards Agenda 2030

5.1.7 Implications to Agenda 2030

The present study also highlights seven research propositions (RPs) on the topic of S-OSCM4.0 as ready-made hypotheses for testing through empirical research. The propositions of this work are:

- RP1: Organizations with S-OSCM4.0 can positively contribute to reliable and modern energy services and to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology (SDG#7);
- RP2: Organizations with S-OSCM4.0 can positively contribute to sustainable economic growth by supporting productive activities and decent job creation (SDG#8);
- RP3: Organizations with S-OSCM4.0 can positively contribute to promote inclusive and sustainable industrialization, by fostering innovation through increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes (SDG#9);
- RP4: Organizations with S-OSCM4.0 can positively contribute to reduce inequality, by empowering and promoting the socio-economic inclusion of all, and ensuring equal opportunities (SDG#10);
- RP5: Organizations with S-OSCM4.0 can positively contribute to more inclusive, safe, resilient and sustainable cities, through accessible, sustainable and smart transport systems (SDG#11);
- RP6: Organizations with S-OSCM4.0 can positively contribute to strengthen the technological capacity to move towards more sustainable consumption and production patterns, by reducing waste generation through prevention, reduction, recycling and reuse (SDG#12);
- RP7: Organizations with S-OSCM4.0 can positively contribute to promote multi-stakeholder partnerships that mobilize and share knowledge, expertise, technology and financial resources, to support the achievement of the SD (SDG#17);

By providing these seven research propositions for future studies on S-OSCM4.0 (from RP1 to RP7), this work aims to pave the way towards a better understanding of how organizations can synergistically use enablers and sustainable technological solutions to overcome challenges of I4.0-Sustainability integration in OSCM and unlock SD benefits headed to Agenda 2030.

4.2 Empirical findings: prioritization, interrelationships, ranking and selection

4.2.1 Key enablers to integrate sustainability and I4.0 in OSCM

In terms of experience level in OSCM, I4.0 and sustainability, it is observed that all Delphi experts have some level of experience in the three subjects. Table 8 indicates that of the eleven experts, four have greater weight as they either have more than ten years' experience in OSCM or sustainability or have more than five years' experience in Industry 4.0, which is a more recent topic and is currently completing a decade. Most respondents also belong to managerial positions.

Table 8. Score of experience of experts

	Score of experience				
Expert	OSCM	Sustainability	Industry 4.0	Degree of importance (%)	Aggregation weight
e1	25	25	25	0.2500	0.0345
e2	50	50	50	0.5000	0.0690
e3	100	75	50	0.7500	0.1034
e4	25	25	25	0.2500	0.0345
e5	50	25	25	0.3333	0.0460
e6	25	25	75	0.4167	0.0575
e7	75	75	75	0.7500	0.1034
e8	75	75	75	0.7500	0.1034
e9	75	25	50	0.5000	0.0690
e10	50	100	100	0.8333	0.1149
e11	25	25	25	0.2500	0.0345
			Total	5.5833	1

As shown in Table 8, first the degree of importance of the specialists was calculated based on the average of the experience scores, then the aggregate weight was calculated in order to normalize the weight of each specialist. This calculation was based on Sánchez-lezama and Cavazos-arroyo (2014). Then, the group consensus was estimated, based on the frequency of agreement, and the distance between two fuzzy numbers was calculated by measuring the deviation between the mean fuzzy assessment data and the experts' assessment data (Vertex method). Six enablers present a level of agreement below 75%, which were: "Data-centered solutions", "Modular design", "Information transparency", "Open innovation", "Change management", "Governmental and institutional pressures". Based on Table 9, it is observed that

15 of the 34 enablers (approximately 44%) presented distance above 0.2 and therefore were considered acceptable, among them: "sharing economy", "circular processes", "customer and supplier integration", " Support of unconventional partners", and "adoption of advanced quality improvement techniques". It can be seen from Table 9 that the factors "Data-centered solutions", "Modular design", "Information transparency", "Open innovation", "Change management", and "Governmental and institutional pressures" were eliminated by the two FDM conditions (vertex method and percentage of agreement). During the assessment, some respondents also pointed out that there were specific factors that could be part of more general ones, such as the case of “open innovation” that was removed, but could be part of the "innovative business models" that was retained.

Based on the previously proposed taxonomy of enablers, the 34 enablers were clustered in five categories: "Circular and sustainability" (CS), "Information and technology" (IT), "Innovation"(I), "People and culture" (PC), and "Supply chain organization and processes" (SOP). Those enablers which showed a real score higher than the threshold value of the category $(S_j > \alpha)$ after defuzzification were retained and the remainder discarded, as follows:

1) CS: of the seven variables, two were retained, “Focus on renewable natural resources”, having the highest score, with 0.0797, followed by “Sustainable philosoph”, with a score of 0.0776.

2) IT: of the six variables, retained, “Data security”, having the highest score, with 0.0861, followed by “Consistent data flow”, with a score of 0.0708.

3) I: of the six variables, retained, “Internal innovation process”, having the highest score, with 0.0772, followed by “Innovative business models”, with a score of 0.0768.

4) SOP: of the eight variables, retained, “Effective communication”, having the highest score, with 0.0822, followed by “Top management commitment”, with a score of 0.0820.

5) PC: of the seven variables, retained, “Strategic alignment, having the highest score, with 0.0802, followed by “Collaborative networks”, with a score of 0.0730.

The 10 relatively important factors resulting from the examination process are shown in Table 10. A description of the variables selected from each category is given in Table 11 and corresponds to the latent variables considered from the S-OSCM4.0 framework. Thus, the use of the FDM helps to solve the uncertainty o an accurate expert distinction in the examination of the key enablers during the procedure, ensuring a better quality of the analysis.

Table 9. Expert consensus about enablers to S-OSCM 4.0

Items	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	Average/item	Average	Agreement
CS1	0.1823	0.0514	0.1823	0.2101	0.1823	0.0514	0.2101	0.0514	0.2101	0.1823	0.2101	0.1567	0.1889	accept
CS2	0.1334	0.0417	0.0417	0.1334	0.1334	0.2586	0.1334	0.2586	0.1334	0.1334	0.2586	0.1509		accept
CS3	0.1519	0.1519	0.1519	0.1519	0.2401	0.1033	0.2401	0.1033	0.1519	0.2401	0.1519	0.1671		accept
CS4	0.4277	0.1343	0.4277	0.1238	0.1238	0.1238	0.1238	0.1343	0.2579	0.2579	0.1238	0.2053		reject
CS5	0.1455	0.1085	0.1455	0.1455	0.1455	0.1455	0.1455	0.1085	0.4056	0.1455	0.4056	0.1860		accept
CS6	0.1121	0.1121	0.1461	0.2804	0.1121	0.1461	0.2804	0.1461	0.4051	0.1461	0.4051	0.2083		reject
CS7	0.2246	0.0843	0.0843	0.0843	0.1692	0.0843	0.0843	0.0843	0.0843	0.1692	0.4666	0.1472		accept
IT1	0.3255	0.3600	0.0688	0.0688	0.0688	0.0688	0.1912	0.1912	0.3255	0.3600	0.0688	0.1907		accept
IT2	0.0750	0.2502	0.2502	0.4294	0.2502	0.4294	0.0750	0.3013	0.5534	0.2502	0.3013	0.2878		reject
IT3	0.1296	0.4216	0.1236	0.2688	0.1236	0.1236	0.1296	0.1296	0.1236	0.1296	0.1296	0.1666		accept
IT4	0.2714	0.2714	0.4123	0.2797	0.2714	0.0464	0.0464	0.0464	0.2797	0.2714	0.0464	0.2039		reject
IT5	0.3050	0.3050	0.3770	0.0458	0.3770	0.0458	0.0458	0.2461	0.3050	0.3050	0.2461	0.2367		reject
IT6	0.0417	0.1111	0.0417	0.0417	0.1111	0.0417	0.0417	0.0417	0.0417	0.0417	0.1111	0.0606		accept
I1	0.1936	0.1982	0.1936	0.1936	0.1982	0.0710	0.1982	0.0710	0.1936	0.1936	0.4892	0.1994		accept
I2	0.2929	0.1033	0.1033	0.1635	0.2929	0.1635	0.3889	0.3889	0.2929	0.3889	0.1635	0.2493		reject
I3	1.0788	0.0757	0.3794	0.0757	0.0757	0.3794	0.2989	0.2570	0.3794	0.2989	0.2570	0.3233		reject
I4	0.6855	0.0962	0.0962	0.2998	0.0962	0.0962	0.0962	0.0962	0.2998	0.2998	0.2998	0.2238		reject
I5	0.2067	0.1850	0.2067	0.0778	0.1850	0.0778	0.0778	0.1850	0.2067	0.2067	0.4777	0.1903		accept
I6	0.4211	0.1271	0.1271	0.2647	0.1271	0.1306	0.1271	0.1306	0.2647	0.2647	0.1271	0.1920		accept
PC1	0.1251	0.0375	0.2683	0.0375	0.1251	0.1251	0.2683	0.0375	0.1251	0.1251	0.0375	0.1193		accept
PC2	0.0375	0.0375	0.1176	0.0375	0.0375	0.1176	0.0375	0.0375	0.1176	0.1176	0.2783	0.0885		accept
PC3	0.2804	0.1121	0.2804	0.1121	0.1121	0.1461	0.1461	0.1461	0.4051	0.1461	0.4051	0.2083		reject
PC4	0.2093	0.1830	0.2093	0.2093	0.2093	0.0845	0.0845	0.0845	0.4731	0.0845	0.4731	0.2095		reject
PC5	0.0768	0.0768	0.0768	0.1796	0.0768	0.1796	0.0768	0.1796	0.1796	0.3160	0.6759	0.1904		accept
PC6	0.1958	0.1974	0.1974	0.1974	0.0591	0.1958	0.0591	0.0591	0.1958	0.0591	0.1974	0.1467		accept
PC7	0.5346	0.0430	0.1488	0.1488	0.1488	0.1488	0.2431	0.1488	0.0430	0.0430	0.0430	0.1540		accept
PC8	0.0845	0.3073	0.0845	0.0750	0.0845	0.0845	0.3073	0.0845	0.0845	0.0845	0.0845	0.1241		accept
SOP1	0.1206	0.1206	0.1586	0.2807	0.2807	0.1206	1.1773	0.1586	0.2807	0.1586	0.1586	0.2741		reject
SOP2	1.0369	0.0694	0.0694	0.0694	0.2461	0.0694	0.0694	0.3050	0.3050	0.3050	0.0694	0.2377		reject
SOP3	0.5380	0.3182	0.0762	0.3182	0.0762	0.0762	0.2330	0.3182	0.2330	0.2330	0.0762	0.2270		reject
SOP4	0.1723	0.0798	0.0798	0.0798	0.2229	0.0798	0.1723	0.0798	0.1723	0.1723	0.0798	0.1264		accept
SOP5	0.2544	0.2544	0.1389	0.2544	0.1389	0.1263	0.1389	0.1263	0.2544	0.4277	0.4277	0.2311		reject
SOP6	0.2900	0.2900	0.1037	0.1037	0.1581	0.1037	0.3937	0.1581	0.2900	0.1037	0.3937	0.2171		reject
SOP7	0.0845	0.0750	0.0845	0.0845	0.0845	0.0845	0.3073	0.0845	0.0845	0.3073	0.0845	0.1241		accept

Table 10. Evaluation of enablers after FDM screening (11 experts)

			Agreement (d ≤ 0.2)	Expert Consensus (more than 75%)	Sj	Sequence	Key enabler	Alphas (threshold)
Circular and sustainability	Sustainable philosophy	CS1	accept	accept	0.0776	2	key	0.0755
	Focus on renewable natural resources	CS2	accept	accept	0.0797	1	key	
	Interdisciplinary and holistic integration	CS3	accept	accept	0.0751	3	-	
	Sharing economy	CS4	reject	accept	0.0716	6	-	
	Life cycle thinking	CS5	accept	accept	0.0709	7	-	
	Circular processes	CS6	reject	accept	0.0730	5	-	
	I4.0 readiness	CS7	accept	accept	0.0745	4	-	
Information and technology	Adoption of smart factory components	IT1	accept	accept	0.0666	3	-	0.0700
	Data-centered solutions	IT2	reject	reject	0.0581	6	-	
	Consistent data flow	IT3	accept	accept	0.0708	2	key	
	Modular design	IT4	reject	reject	0.0627	5	-	
	Information transparency	IT5	reject	reject	0.0643	4	-	
	Data security	IT6	accept	accept	0.0861	1	key	
Innovation	Internal innovation process	I1	accept	accept	0.0772	1	key	0.0755
	Open innovation	I2	reject	reject	0.0632	6	-	
	Change management	I3	reject	reject	0.0657	5	-	
	Dynamic capabilities	I4	reject	accept	0.0700	4	-	
	Innovative business models	I5	accept	accept	0.0768	2	key	
	Service design solutions	I6	accept	accept	0.0729	3	-	
People and culture	Knowledge sharing	PC1	accept	accept	0.0785	4	-	0.0800
	Effective communication	PC2	accept	accept	0.0822	1	key	
	Individual incentive schemes	PC3	reject	accept	0.0730	7	-	
	Employee’s empowerment	PC4	reject	accept	0.0755	6	-	
	Experimentation	PC5	accept	accept	0.0708	8	-	
	Education and training focused on soft and technical skills	PC6	accept	accept	0.0759	5	-	
	Transformational leadership	PC7	accept	accept	0.0793	3	-	
	Top management commitment	PC8	accept	accept	0.0820	2	key	
Supply chain organization and processes	Customer and supplier integration	SOP1	reject	accept	0.0672	5	-	0.0700
	Support of unconventional partners	SOP2	reject	accept	0.0655	6	-	
	Governmental and institutional pressures	SOP3	reject	reject	0.0593	7	-	
	Collaborative networks	SOP4	accept	accept	0.0730	2	key	
	Adoption of advanced quality improvement techniques	SOP5	reject	accept	0.0698	3	-	
	Re-designing and decentralized structure	SOP6	reject	accept	0.0687	4	-	
	Strategic alignment	SOP7	accept	accept	0.0802	1	key	

Table 11. Key enablers

ID	Key enablers	Description
E1	Sustainable philosophy	This philosophy involves several stages of innovation and corporate culture and must encompass management and employees, to provide a vision and guidance for the direction of companies. Awareness of sustainability concepts among customers will increase their adoption rate. In addition, the adoption of industrial ecology initiatives helps to implement circular economy practices for better sustainability.
E2	Focus on renewable natural resources	The focus should be on renewable natural resources as alternatives to non-renewable ones and the replacement of the "weak sustainability" model by the rational exploitation of natural resources. If good use is made of I4.0, it can be well integrated with the SDGs, which can result in efficiency and the effective use of non-renewable and renewable resources
E3	Consistent data flow	Data flow processes represent a hierarchical structure in which data collection, integration and analysis are connected. It increases integration and promotes a more flexible structure and exchange of data between all elements.
E4	Data security	The process of protecting data from unauthorized access and data corruption throughout its lifecycle. High investments in data security specialists is important to protect intellectual property and prevent the loss of competitive advantages. For example, blockchain technologies are used to distribute data and increase security in OSCM.
E5	Internal innovation process	Companies that exhibit greater capacity for innovation through innovation labs, R&D units and intrapreneurs. Company's internal potential is most strongly influenced by the potential and commitment of its own employees with futuristic ideas.
E6	Innovative business models	The adoption of innovative business models is a facilitator for sustainable I4.0, through the inclusion of sustainability in business models or the development of purely digital business models (digitization, internet and networking technology). Innovations of the new business model (e.g., Crowd-Sourced Innovation, Manufacturing as a Service, Product-as-a-Service, Open innovation) can offer significant economic and social sustainability opportunities. New and sustainable business models must guarantee business benefits shared fairly among all stakeholders in the value chain, and they must facilitate innovation, product development, financing, reliability, risk, intellectual property and protection of know-how in a network environment.
E7	Effective communication	Effective communication plays a key role in the development of a collaborative workplace and can improve not only a company's performance level, but also the relationship between different companies in a supply chain. The efficiency of communication associated with transparency, surveillance and control generates advantages for S-OSCM 4.0 such as minimizing downtime, waste, defect and risk in the processes.
E8	Top management commitment	Top management has the responsibility to provide organizational opportunities to integrate I4.0 technologies and environmentally sustainable manufacturing into existing production systems, so the commitment of top management also plays a role vital to the current sustainable digital revolution in OSCM.
E9	Collaborative networks	A network consisting of a variety of entities that are largely autonomous, geographically distributed, and heterogeneous in terms of their operating environment and culture, but that collaborate to achieve compatible goals. It is equally important to be involved in proper planning and cooperation with external stakeholders. The creation of an open development platform involving key industries can allow for such collaboration, including the development of data-based models (collaborative manufacturing networks). Digital infrastructures (of digitally enabled technology) that incorporate supply chain partners can detect and monitor changes in the external environment more efficiently, thus making it a necessary choice for companies to achieve success in sustainable OSCM.
E10	Strategic alignment	Process that ensures an organization's structure, use of resources (and culture) support its strategy. Organizations cannot be competitive without total alignment with information technology and the appropriate selection of I4.0 technologies to assist in environmentally sustainable decisions can allow for better strategic alignment. For example, As far as strategy is concerned, it is critical to allocate the budget intelligently to different sections of the organization. Smart budget allocation with the use of digital technologies (e.g., Internet of Things - IoT) makes it possible to follow the global progress and helps to distribute the available financial resources effectively among the entire organizational structure, allowing to achieve sustainability.

Then, in order to evaluate the criticality of deploying these 10 key factors (section 5.2.2), there was also the need to prioritize the ten sustainable development benefits accomplished by the S-OSCM4.0 implementation. The sample of interviewed experts that prioritize the benefits was composed of ten managers with more than five years in sustainability and more than three years of experience with I4.0 technologies. To resolve the clarity and vagueness of human thinking (compared with AHP), FAHP was used by adopting the column geometric mean method (Buckley's method). FAHP involves steps of establishing fuzzy linguistics, defuzzification, and normalization. The resulting integrated fuzzy-weighted decision matrices are shown in Table 12. All CR (CRm and CRg) values were lower than 0.1; thus, all the judgments are considered consistent, which represents the accuracy of the results of the group of the respondents interviewed.

Table 12. Integrated Fuzzy Comparison Matrix

Benefits criteria CRm = 0.0059 CRg = 0.0172

	Planet			Prosperity			People		
Planet	1	1	1	1.4142	1.5518	1.6986	0.9895	1.1455	1.3195
Prosperity	0.5887	0.6444	0.7071	1	1	1	0.8123	0.9266	1.0718
People	0.7579	0.8730	1.0106	0.9330	1.0792	1.2311	1	1	1

Planet subcriteria CRm = 0.0005 CRg = 0.0009

	Energy consumption			Resource consumption			Sustainable design		
Energy comsumption	1	1	1	1.0481	1.2457	1.4461	1.0065	1.1455	1.2973
Resource consumption	0.6915	0.8027	0.9541	1	1	1	0.8360	0.9827	1.1487
Sustainable design	0.7708	0.8730	0.9936	0.8706	1.0176	1.1962	1	1	1

Prosperity subcriteria CRm = 0.0103 CRg = 0.0346

	Flexibility			Time-to-market cycles			Quality			Profit		
Flexibility	1	1	1	0.8604	0.9650	1.1161	0.5676	0.7192	0.9441	0.6871	0.8513	1.0592
Time-to-market cycles	0.8960	1.0363	1.1623	1	1	1	0.8027	0.9650	1.1962	1.0414	1.2148	1.4461
Quality	1.0592	1.3904	1.7617	0.8360	1.0363	1.2457	1	1	1	1.5337	1.7035	1.9082
Profit	0.9441	1.1746	1.4555	0.6915	0.8232	0.9603	0.5241	0.5870	0.6520	1	1	1

People subcriteria CRm = 0.0117 CRg = 0.0263

	Job quality			Workforce capability			Society conditions		
Job quality	1	1	1	0.8015	0.9158	1.0845	0.6186	0.7108	0.8459
Workforce capability	0.9221	1.0920	1.2477	1	1	1	0.4562	0.5630	0.7364
Society conditions	1.1822	1.4069	1.6166	1.3580	1.7761	2.1919	1	1	1

Table 13 indicate that the experts were most concerned with the Planet benefits. The maximum weight obtained by combining global priority is Planet aspect (0.399) through FAHP, secondly is the People aspect (0.323) and Prosperity aspect (0.278). Within the "Planet" dimension, experts were most concerned with Energy comsumption. Within the "People" dimension, the Society conditions was the most important. Within the "Prosperity" dimension, experts were most concerned with Quality.

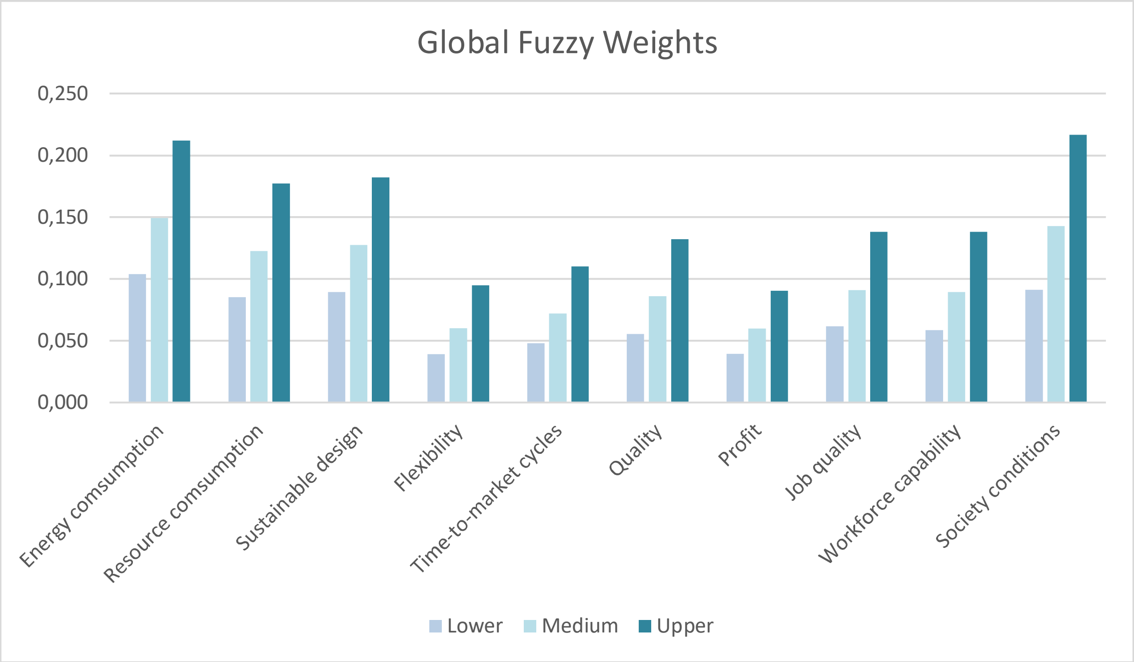

Figure 12. Global fuzzy weights

The results illustrated in Figure 12 indicate that the sequence of the four benefits with the highest weights of all the SD benefits of S-OSCM4.0 were Energy consumption, Society conditions, Sustainable design, and Resource consumption. The total weights for these four benefits were 0.5405. The least important items among the factors considered by experts when prioritizing benefits were "Quality", "Time-to-market cycles", "Flexibility", and "Profit". The total weight for these four aspects was 0.2847.

Table 13. Evaluation of benefits weights using FAHP with ten experts (Buckley's method)

Dimensions	Weight	Fuzzy Weights			Benefits	Fuzzy Weights (local)			Local weight	Fuzzy Weights (global)			Global weight
Planet	0.3988	0.3394	0.3993	0.4688	Energy consumption	0.3063	0.3739	0.4523	0.3726	0.1039	0.1493	0.2121	0.1486
					Resource consumption	0.2506	0.3069	0.3781	0.3078	0.0851	0.1225	0.1773	0.1228
					Sustainable design	0.2634	0.3193	0.3885	0.3195	0.0894	0.1275	0.1821	0.1274
Prosperity	0.2779	0.2373	0.2776	0.3266	Flexibility	0.1645	0.2167	0.2907	0.2240	0.0390	0.0601	0.0950	0.0622
					Time-to-market cycles	0.2011	0.2595	0.3368	0.2658	0.0477	0.0720	0.1100	0.0739
					Quality	0.2333	0.3093	0.4046	0.3158	0.0554	0.0859	0.1321	0.0878
					Profit	0.1653	0.2145	0.2763	0.2187	0.0392	0.0595	0.0903	0.0608
People	0.3233	0.2703	0.3231	0.3853	Job quality	0.2282	0.2819	0.3583	0.2837	0.0617	0.0911	0.1381	0.0917
					Workforce capability	0.2160	0.2766	0.3585	0.2781	0.0584	0.0894	0.1381	0.0899
					Society conditions	0.3376	0.4414	0.5622	0.4382	0.0913	0.1426	0.2166	0.1417

4.2.2 Criticality of deploying enablers towards S-OSCM4.0 benefits in organizations

After applying FAHP to determine the weights for the benefits that are the criteria and subcriteria, this study also took into account the uncertainty to explore the level of impact of the key enablers to achieve the benefits. Thus, in this section, a hybrid FMCDM method - combining fuzzy weights of FAHP and the performance of the ten key enablers in relation to the benefits through FVIKOR – was proposed, as illustrated in Figure 13. This application had the participation of five more experts in addition to the ten who participated in the interviews in the previous round, totalling a panel of 15 respondents. This proposed hybrid method can allow decision analysts to better understand the entire assessment process and provide a more accurate and systematic decision support tool (SUN, 2010).

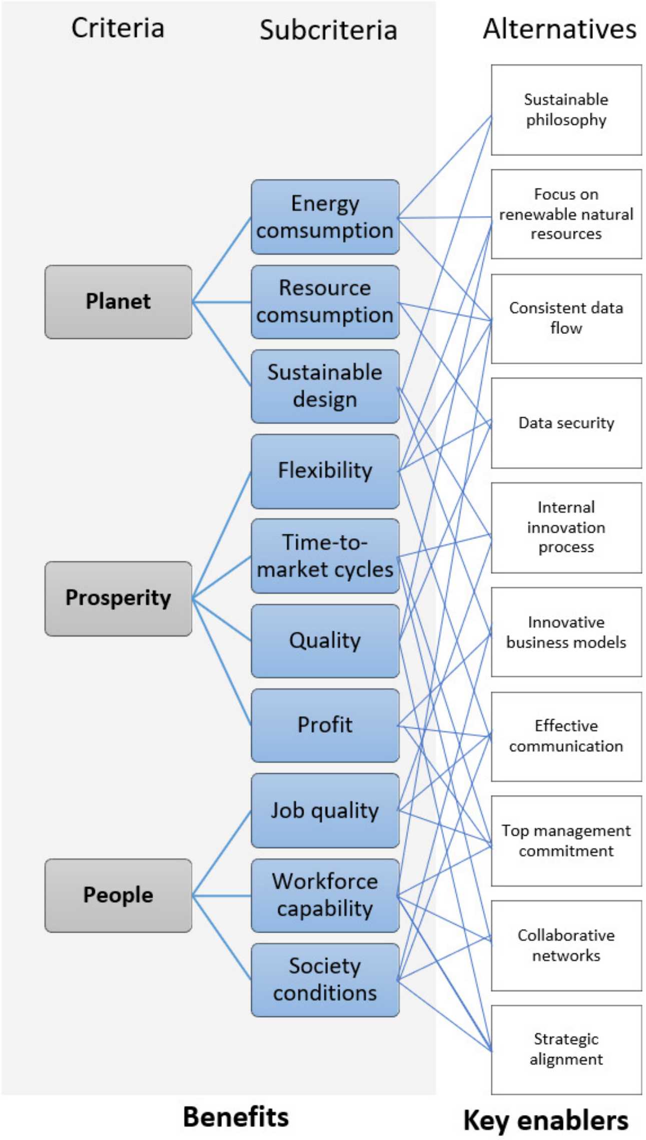

Figure 13. Hierarchy of benefits x key enablers

The integration of Fuzzy set theory (ZADEH, 1965) with VIKOR, a compensatory MCDM method that focuses on ranking and sorting a set of alternatives against various decision criteria, aims to resolve the lack of precision in the evaluation (OPRICOVIC, 2011) of the key enablers against the benefits weighted previously. Unlike TOPSIS, VIKOR introduces the ranking index based on the particular measure of closeness to the ideal solution and uses linear normalization to eliminate units of criterion functions (CUNHA et al., 2021). The most considerable advantage of the VIKOR technique consists of its capacity in obtaining a "*compromise solution with the maximum group utility of a majority whilst maintaining a minimum of an individual regret for the opponent*" (OPRICOVIC; TZENG, 2004). Table 14 exemplifies the assessment of one of the fifteen decision-makers.

Table 14. Criticality of key enablers (one expert's ratings is given as an example).

			Energy consumption	Resource consumption	Sustainable design	Flexibility	Time-to-market cycles	Quality	Profit	Job quality	Workforce capability	Society conditions
Key Enablers x Benefits			B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
CS1	Sustainable philosophy	E1	VH	VH	VH	M	H	H	H	M	H	H
CS2	Focus on renewable natural resources	E2	H	H	H	M	H	H	H	H	VH	VH
IT3	Consistent data flow	E3	M	M	L	H	VH	VH	H	L	H	L
IT6	Data security	E4	L	M	M	VH	H	H	VH	M	M	M
I1	Internal innovation process	E5	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH
I5	Innovative business models	E6	VH	VH	VH	M	H	M	VH	M	H	M
PC2	Effective communication	E7	H	H	H	VH	M	H	H	H	H	M
PC8	Top management commitment	E8	M	H	H	M	VH	M	VH	H	H	M
SOP4	Collaborative networks	E9	L	M	M	M	M	M	L	L	M	M
SOP7	Strategic alignment	E10	M	M	M	H	VH	VH	VH	M	H	M

Table 15 presents the aggregated fuzzy values of experts rates and subjective importance weights obtained through this Fuzzy Multi-Criteria Decision Making methodology.

Table 15. Integrated Matrix (FAHP-FVIKOR) and the best and the worst fuzzy values

Fuzzy Weight	W1			W2			W3			W4			W5			W6			W7			W8			W9			W10		
	0.1039	0.1493	0.2121	0.0851	0.1225	0.1773	0.0894	0.1275	0.1821	0.039	0.0601	0.095	0.0477	0.072	0.11	0.0554	0.0859	0.1321	0.0392	0.0595	0.0903	0.0617	0.0911	0.1381	0.0584	0.0894	0.1381	0.0913	0.1426	0.2166
	B1			B2			B3			B4			B5			B6			B7			B8			B9			B10		
A1	4.8667	6.7333	8.3333	4.9333	6.8667	8.4667	5.5333	7.4000	8.8000	3.3333	5.1333	7.1333	3.6000	5.2667	7.2667	4.0667	5.9333	7.8000	4.6000	6.4667	8.2000	4.0667	5.9333	7.7333	3.7333	5.5333	7.4667	4.0000	5.8000	7.6000
A2	4.6667	6.6000	8.2667	5.4667	7.4000	8.8667	5.2000	7.1333	8.7333	3.2667	4.8667	6.7333	3.4000	5.0000	6.9333	3.7333	5.5333	7.5333	4.4667	6.4667	8.2667	4.1333	5.9333	7.7333	3.4000	5.1333	7.0000	4.2000	5.9333	7.6667
A3	3.0667	4.8667	6.8667	3.0000	4.7333	6.7333	2.6000	4.2000	6.2000	3.2000	5.0000	7.0000	4.5333	6.4667	8.2667	4.8000	6.7333	8.5333	4.6667	6.6000	8.4000	4.3333	6.2000	8.0000	4.4000	6.3333	8.3333	3.0667	4.6000	6.5333
A4	2.8667	4.3333	6.2000	3.0667	4.7333	6.6667	2.5333	4.2000	6.2000	3.9333	5.8000	7.6000	4.2667	6.2000	8.0667	3.6667	5.4000	7.4000	5.1333	7.1333	8.7333	3.9333	5.8000	7.6667	3.2000	4.8667	6.8000	3.6667	5.4000	7.2000
A5	4.0000	5.8000	7.6000	4.3333	6.2000	7.9333	4.4000	6.3333	8.0667	4.8667	6.7333	8.4667	4.4667	6.4667	8.4000	4.8667	6.8667	8.6667	5.1333	7.1333	8.9333	5.3333	7.2667	8.9333	5.0667	7.0000	8.6667	3.5333	5.2667	7.1333
A6	4.2667	6.0667	7.8667	4.6667	6.6000	8.2667	4.4000	6.3333	8.0667	4.9333	6.8667	8.6000	4.4000	6.3333	8.2000	4.8667	6.7333	8.3333	5.3333	7.2667	8.8667	4.8000	6.7333	8.4667	4.8667	6.7333	8.4667	3.4000	5.1333	7.1333
A7	2.8000	4.3333	6.2667	3.4667	5.2667	7.2000	3.2667	5.0000	6.9333	3.6667	5.4000	7.3333	4.3333	6.2000	8.0667	5.1333	7.1333	8.8000	4.4667	6.3333	8.1333	5.0000	7.0000	8.8000	4.2667	6.2000	8.0667	4.2667	6.2000	8.0000
A8	4.6667	6.4667	8.1333	5.0000	6.8667	8.6000	4.7333	6.7333	8.4667	4.3333	6.3333	8.2000	5.0667	7.0000	8.7333	4.6667	6.6000	8.4000	5.0667	7.0000	8.6667	5.5333	7.5333	9.1333	4.8000	6.7333	8.4667	3.8667	5.6667	7.4667
A9	3.3333	5.0000	6.9333	3.6667	5.4000	7.3333	3.7333	5.5333	7.3333	4.2000	6.0667	7.8667	4.0667	5.9333	7.7333	4.2667	6.2000	8.0667	4.1333	5.9333	7.8000	4.7333	6.6000	8.4667	4.4000	6.2000	7.9333	4.4667	6.3333	8.1333
A10	4.4667	6.3333	8.0000	4.2000	6.0667	7.8000	4.8667	6.8667	8.6667	5.4000	7.4000	9.0667	6.0667	8.0667	9.4667	6.0000	7.9333	9.3333	6.0667	8.0667	9.5333	5.6000	7.5333	9.0667	5.4667	7.4000	9.0000	4.3333	6.2000	8.0000
MAX	4.867	6.733	8.333	5.467	7.400	8.867	5.533	7.400	8.800	5.400	7.400	9.067	6.067	8.067	9.467	6.000	7.933	9.333	6.067	8.067	9.533	5.600	7.533	9.133	5.467	7.400	9.000	4.467	6.333	8.133
MIN	2.800	4.333	6.200	3.000	4.733	6.667	2.533	4.200	6.200	3.200	4.867	6.733	3.400	5.000	6.933	3.667	5.400	7.400	4.133	5.933	7.800	3.933	5.800	7.667	3.200	4.867	6.800	3.067	4.600	6.533
Fuzzy Best Value F+	4.867	6.733	8.333	5.467	7.400	8.867	5.533	7.400	8.800	5.400	7.400	9.067	6.067	8.067	9.467	6.000	7.933	9.333	6.067	8.067	9.533	5.600	7.533	9.133	5.467	7.400	9.000	4.467	6.333	8.133
Fuzzy Worst Value F-	2.800	4.333	6.200	3.000	4.733	6.667	2.533	4.200	6.200	3.200	4.867	6.733	3.400	5.000	6.933	3.667	5.400	7.400	4.133	5.933	7.800	3.933	5.800	7.667	3.200	4.867	6.800	3.067	4.600	6.533

Then, Table 16 presents the fuzzified results, which include the maximum group utility (*Si*, “majority”), the minimum of the individual regret (*Ri*) of the “opponent”, and the strategy parameter (*Qi*). This study used the constant value as $v = 0{,}5$, which implies *consensus* among decision-makers, decreasing the discrepancy among decision-makers (TIAN et al., 2019).

Table 16. The fuzzy values of S, R and Q for each key enabler (FVIKOR)

Alternatives	$\tilde{S}_j$,			$\tilde{R}_j$,			$\tilde{Q}_j$i		
Sustainable philosophy	-0.3112	0.1873	1.1878	-0.0094	0.0332	0.1767	-0.7203	0.0642	0.8536
Focus on renewable natural resources	-0.3039	0.1996	1.2014	-0.0068	0.0364	0.1682	-0.7128	0.0742	0.8397
Consistent data flow	-0.2297	0.3377	1.3845	-0.0095	0.0651	0.2166	-0.6978	0.1720	0.9909
Data security	-0.2025	0.3685	1.4172	-0.0095	0.0651	0.2095	-0.6903	0.1805	0.9854
Internal innovation process	-0.3287	0.1651	1.1586	-0.0183	0.0300	0.1967	-0.7436	0.0514	0.8869
Innovative business models	-0.3265	0.1675	1.1597	-0.0168	0.0338	0.2024	-0.7398	0.0598	0.8991
Effective communication	-0.2702	0.2636	1.2870	-0.0129	0.0648	0.2121	-0.7160	0.1507	0.9546
Top management commitment	-0.3567	0.1165	1.0935	-0.0186	0.0202	0.1824	-0.7520	0.0175	0.8393
Collaborative networks	-0.2788	0.2501	1.2643	-0.0126	0.0468	0.1917	-0.7178	0.1097	0.9059
Strategic alignment	-0.3866	0.0532	1.0007	-0.0244	0.0278	0.1625	-0.7722	0.0158	0.7722

Crisp values (by defuzzification) of $\tilde{S}_j$, $\tilde{R}_j$, $\tilde{Q}_j$, j = 1, 2, …, J are presented in Table 17. Ranking by crisp values are $\{A\}_S = A10, A8, A5, A6, A1, A2, A9, A7, A3, A4$; $\{A\}_R = A10, A8, A2, A1, A5, A6, A9, A7, A4, A3$; $\{A\}_Q = A10, A8, A5, A1, A2, A6, A9, A7, A3, A4$. Thus, considering DQ = 0.1111, the compromise solution is $A10$, which is: Strategic alignment, satisfying the two conditions (acceptable advantage and stability in decision making).

Table 17. The defuzzified values of S, R and Q for each key enabler

Alternatives		Crisp Si		Crisp Ri		Crisp Qi	
Sustainable philosophy	**A1**	0.3547	**5**	0.0668	**4**	0.0659	**4**
Focus on renewable natural resources	**A2**	0.3657	**6**	0.0659	**3**	0.0670	**5**
Consistent data flow	**A3**	0.4975	**9**	0.0907	**10**	0.1550	**9**
Data security	**A4**	0.5277	**10**	0.0884	**9**	0.1585	**10**
Internal innovation process	**A5**	0.3317	**3**	0.0694	**5**	0.0649	**3**
Innovative business models	**A6**	0.3335	**4**	0.0731	**6**	0.0730	**6**
Effective communication	**A7**	0.4268	**8**	0.0880	**8**	0.1298	**8**
Top management commitment	**A8**	0.2844	**2**	0.0613	**2**	0.0350	**2**
Collaborative networks	**A9**	0.4119	**7**	0.0753	**7**	0.0992	**7**
Strategic alignment	**A10**	0.2224	**1**	0.0553	**1**	0.0053	**1**

4.2.3 Necessary key enablers to develop sustainable technological solutions

This section presents the results of the Q-sort method used to understand the level of adherence of the key enablers with sustainable technological solutions. The fifteen experts who participated in the panel of experts (to rate the impact of the key enablers to achieve the benefits) also answered a questionnaire. After retrieving the responses, the questionnaire analysis was divided into six parts related to the categories of key enablers since there are six potential groups (described in Table 18) for the key enablers. Each round was evaluated through proportional agreement and Cohen's kappa.

Table 18. Sustainable technological solutions

Solution	Description
Smart Contracts	This solution concerns the use of high quality blockchain, BDA and cloud to contract-based integration, which is the basis for intelligent cross-linking of supply chain entities, and to provide a cost-sharing agreements that could improve the participants 'profitability and increase the value delivered to end customers and society
Smart Analytics	This solution could involve the use of IoT, BDA, Cloud and Blockchain to improve supply chain planning, communication and demand forecasting considering data-centric carbon footprint analyzes, identification of customer consumption or employee data and learning patterns and supply chain bottlenecks, reduction of risks and uncertainties, knowledge generation, KPI optimization and prediction, and feedback for product and process design. Such solutions also provide the service of remote operational data storage in real time on-demand access and create an agile ecosystem, being also important to reduce effects of climate change, in addition to promoting green behavior and build complex models to provide multiple services and products more quickly with improved reliability.
Smart Mobility	This solution could involve the use of IoT, BDA, Advanced robotics and blockchain for vehicle communication, traffic management, reducing carbon emissions and sharing data from autonomous cars, autonomous transport and production, to track the the location of the shipment and the speed of the vehicle and so that users are alerted for delays in deliveries, to monitor the condition of equipment from a remote location or of components for reuse, recycling, and remanufacturing. Thus it can optimize CO2 emissions from incoming and outgoing logistics, as well as intra-company transport.
Smart Products	This solution could involve the use of IoT, BDA, cloud and AM (e.g., 3D printing) to save material, enable a variety of end-of-life practices, allow production with almost no waste, and facilitate the development of new environmentally friendly products. For example nanotechnologies can contribute to the development of bioplastics and lightweight bio based composites, thus contributing to the reduction of fuel consumption. In addition, when aligned with new business models, as Product-as-a-Service, it can also reduce the importance of valuable assets and facilitate the accessibility of goods at the time of need.
Smart Maintenance	This solution could involve the use of IoT, CPS, VR/AR, Advanced robotics and Blockchain in order to reduce the risk of operation and keeping the human workforce safer. For example wearable technologies, smart cameras and sensors could be used to improve safety in hazardous work areas with safety training and risk maps. By studying the environmentally friendly characteristics of sustainable product, organizations can predict and prevent equipment's failures to extend their life cycle. Thus, it could offer a more accessible, secure, fast and productive learning experience.
Smart Energy	This solution could involve the use of IoT, BDA, Cloud, VR/AR, Advanced robotics and Blockchain to facilitate the integration of electrical networks and renewable energy sources through real-time exchange of information, and can lead to sustainable and energy-saving systems. For example, IoT can allow the acquisition of energy consumption data in real time for improve energy-conscious decision-making. Through virtualization it becomes possible to design and test new plants before configuring them, to reduce energy consumption and to optimize and add value to operations, simulating all activities throughout the supply chain.

As shown in Table 19, the minimum agreement expected in each item should be 60% (EKINCI; RILEY, 2001; LOCKWOOD; PYUN, 2020). If the item did not reach upper this level, it was desconsidered for the category. In this research, the average kappas from the questionnaire, considering more than two raters (CONGER, 1980), and the weighted kappas, which considers off-diagonal elements as well, respectively were: 0.46 and 0.59 (Contracts part), 0.50 and 0.76 (Analytics part), 1 and 0.81 (Mobility part), 0.51 and 0.51 (Products part), and 0.51 and 0.41 (Maintenance part). Thus, all the kappa values were superior to the target value for kappa, indicating at least moderate or substantial agreement.

Table 19. Frequency of agreements of items in its potential group

	Contracts		Analytics		Mobility		Products		Maintenance		Energy	
	A (%)	Quant.	A (%)	Quant.	A (%)	Quant.	A (%)	Quant.	A (%)	Quant.	A (%)	Quant.
E1	40%	6	53%	8	60%	9	80%	12	80%	12	87%	13
E2	33%	5	60%	9	67%	10	80%	12	67%	10	87%	13
E3	80%	12	87%	13	73%	11	73%	11	67%	10	60%	9
E4	87%	13	80%	12	67%	10	93%	14	93%	14	60%	9
E5	60%	9	93%	14	47%	7	87%	13	93%	14	73%	11
E6	67%	10	80%	12	60%	9	73%	11	93%	14	67%	10
E7	80%	12	73%	11	67%	10	60%	9	67%	10	47%	7
E8	80%	12	60%	9	67%	10	80%	12	73%	11	53%	8
E9	60%	9	67%	10	73%	11	60%	9	87%	13	67%	10
E10	87%	13	87%	13	80%	12	87%	13	93%	14	80%	12

Finally, Table 20 indicates the necessary key enablers that should be combined with I4.0 technologies presented in Appendix D to build each sustainable technological solution. For example, to build Smart Analytics it is necessary the following key enablers: Consistent data flow, Data security, Internal innovation process, Innovative business models, and Strategic alignment. In this study, Q-sort ensures the Face validity, indicating which key enablers (indicators) seem to be reasonable measures of the Solutions (construct) (BHATTACHERJEE, 2012).

Table 20. Necessary key enablers to develop sustainable technological solutions

Key enabler			SMART -					
			Contracts	Analytics	Mobility	Products	Maintenance	Energy
CS1	Sustainable philosophy	E1				●	●	●
CS2	Focus on renewable natural resources	E2			●	●		●
IT3	Consistent data flow	E3	●	●	●			
IT6	Data security	E4	●	●	●	●	●	
I1	Internal innovation process	E5		●		●	●	●
I5	Innovative business models	E6		●			●	●
PC2	Effective communication	E7	●		●			
PC8	Top management commitment	E8	●		●	●		
SOP4	Collaborative networks	E9			●		●	
SOP7	Strategic alignment	E10	●	●	●	●	●	●

4.2.4 Interrelation between key enablers for S-OSCM4.0

In this section, an empirical analysis is conducted to examine the influential strength of the identified key enablers and to build an interrelationship diagram. FDEMATEL was used to analyse the influential strength (cause-effect interrelationship) between the ten enablers, which can help organizations to effectively adopt I4.0 for sustainable OSCM. Fifteen experts (managers) from different companies as well as reputed academic institutes agreed to provide their feedback. The selected experts were knowledgeable professionals with a substantial working experience in S-OSCM and I4.0, and for uniformity of judgment, identical weights were considered for them (LUTHRA et al., 2020).

Table 21. Interrelation between key enablers (one expert's ratings is given as an example).

	E1	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**	**E9**	**E10**
E1	No	VH	VL	L	L	L	H	H	VL	H
E2	VH	No	VL	L	L	L	L	H	VL	H
E3	L	VL	No	VH	L	VL	H	L	H	L
E4	H	L	VH	No	H	H	H	H	L	VH
E5	H	H	H	H	No	H	L	VH	L	VH
E6	L	L	H	H	VH	No	L	VH	L	VH
E7	L	No	H	L	L	L	No	L	H	L
E8	H	H	L	H	H	H	VL	No	VL	H
E9	VL	No	H	L	L	L	H	L	No	L
E10	H	H	H	H	H	H	L	VH	VL	No

Experts were requested to evaluate the key enablers; thus Table 21 shows an example of an interrelation matrix using the linguistic terms (scale) presented in Table 7. In sequence, Table 22 shows the calculated values of R and D.

Table 22. Cause and effect result for key enablers

Key enabler		Di+Ri	Rank	Di-Ri	Group
Sustainable philosophy	**E1**	7.54	7	-0.14	Effect
Focus on renewable natural resources	**E2**	7.33	10	-0.13	Effect
Consistent data flow	**E3**	7.75	6	0.08	Cause
Data security	**E4**	7.43	8	0.02	Cause
Internal innovation process	**E5**	8.09	4	-0.10	Effect
Innovative business models	**E6**	8.21	2	-0.18	Effect
Effective communication	**E7**	7.87	5	0.11	Cause
Top management commitment	**E8**	8.11	3	0.25	Cause
Collaborative networks	**E9**	7.39	9	0.01	Cause
Strategic alignment	**E10**	8.47	1	0.06	Cause

A preference rating of drivers was also drawn, as shown in Figure 14. This can help managers in making a comparative assessment of the preference of considered enablers for S-OSCM4.0. The interrelationship diagram for key enablers is presented in Figure 15. From Figure 15, it can be deduced that six enablers were in the cause group, and four enablers were categorised in the effect group. Furthermore, the threshold value was calculated, which resulted in being 0.3919. The threshold value revealed the snapshot of mutual interactions among the considered key enablers. Based on this, an interaction matrix of enablers was also developed (see **Table 23**). From Table 22, an impact interrelationship (network) diagram for the enablers was also constructed, as shown in Figure 16.

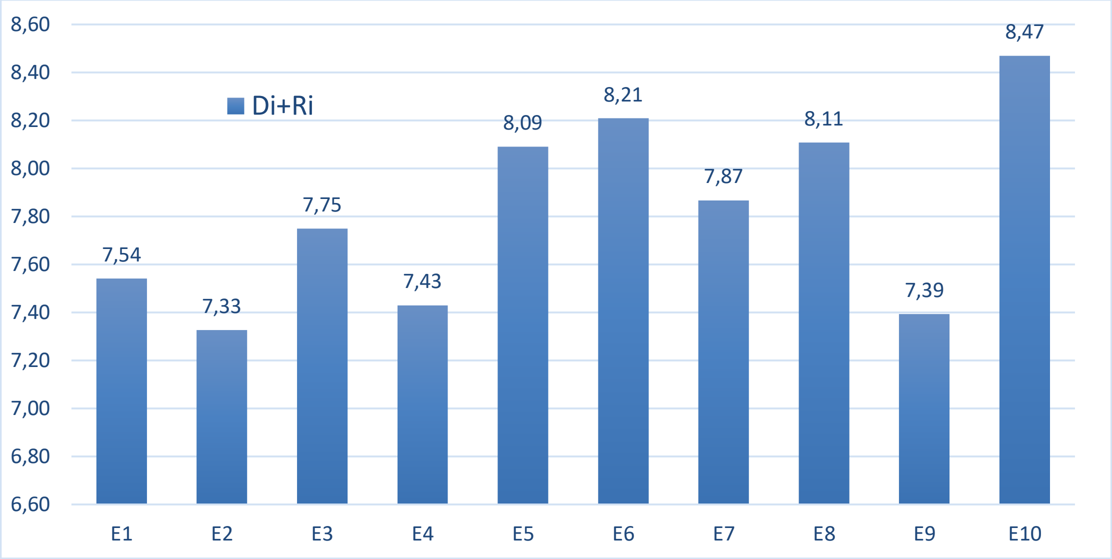

Figure 14. Preference ratings of key enablers

Table 23. Interaction matrix of key enablers

	E1	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**	**E9**	**E10**
E1					●	●				●
E2						●				●
E3				●	●	●	●	●		●
E4			●		●	●				●
E5	●	●	●			●	●	●		●
E6	●	●	●		●		●	●		●
E7	●		●		●	●		●	●	●
E8	●	●	●	●	●	●	●		●	●
E9					●	●				●
E10	●	●	●	●	●	●	●	●	●	

Note: ● represents the presence of inter-relationship between the enablers

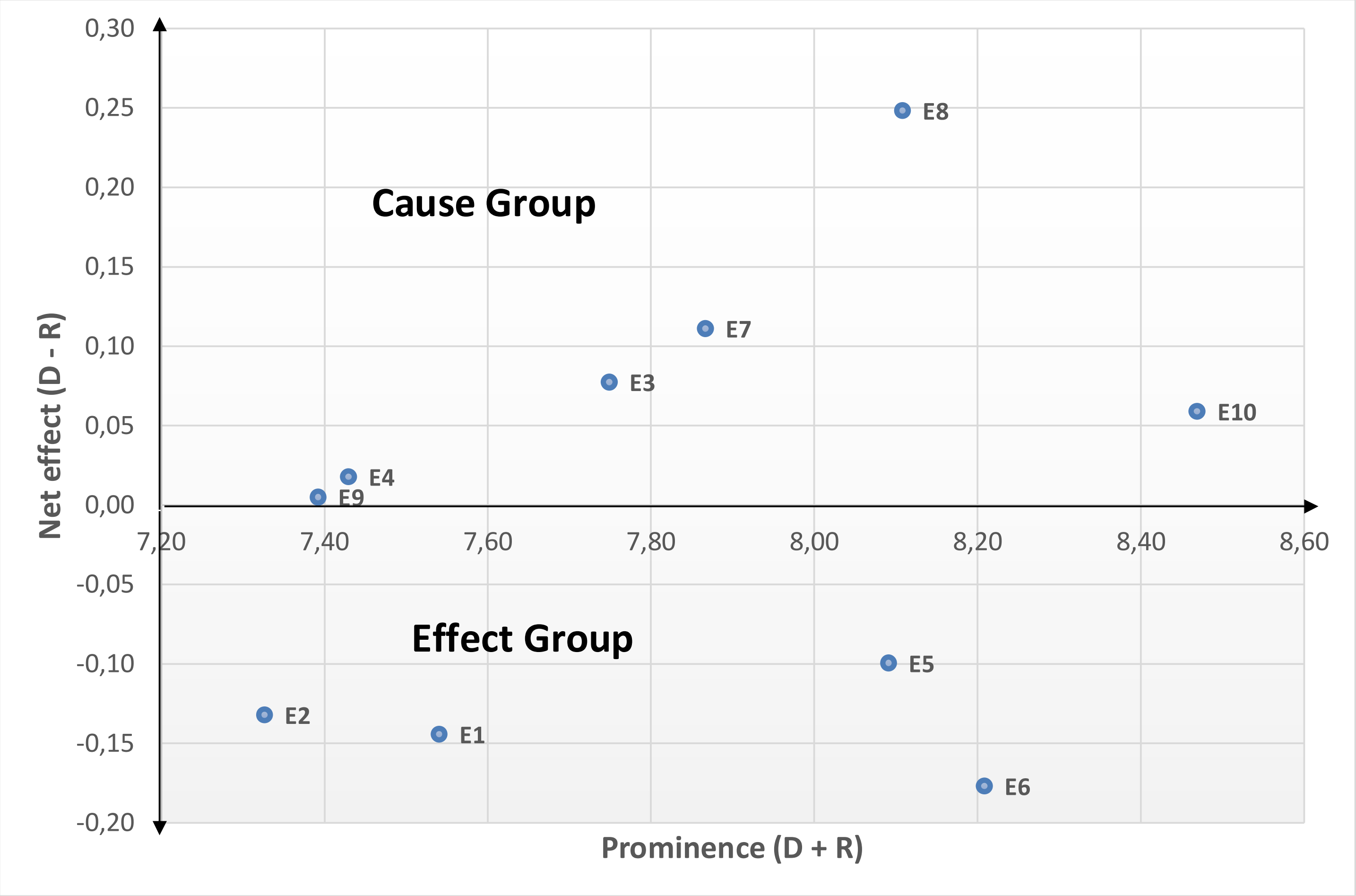

Figure 15. Cause and effect diagram for key enablers

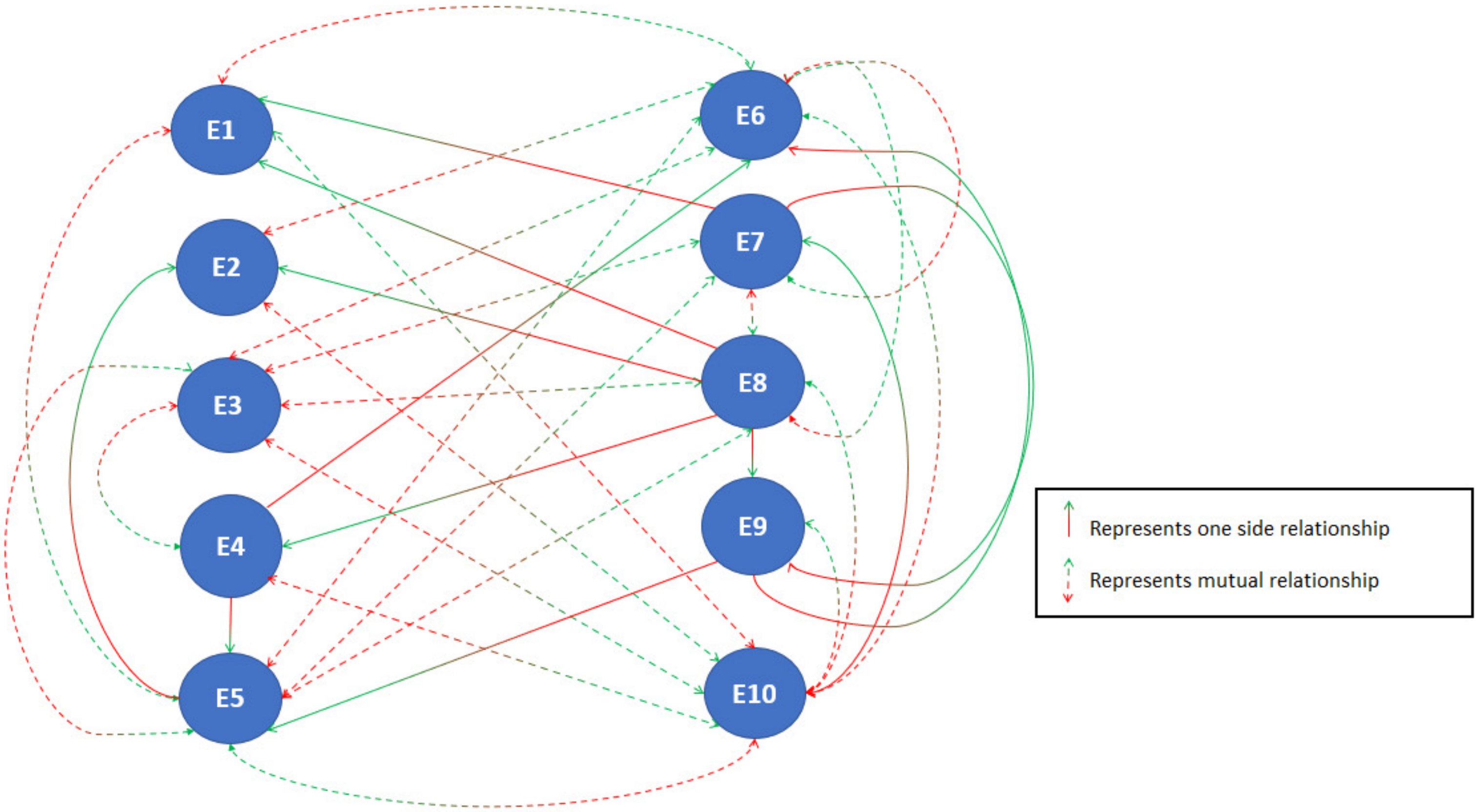

Figure 16. Interrelationships (network) diagram of the key enablers

Figure 16 illustrates the interaction of key enablers with each other. There were two types of interactions among enablers, which included mutual relationships and one-side relationships. In mutual relationships, both enablers influence each other, whereas, in one-side relationships, particular enablers influence other enablers. For instance, ‘Sustainable philosophy (E1)’ and ‘Strategic alignment (E10)’ had mutual interactions. On the other hand, ‘Collaborative networks (E9)’ influenced ‘Internal innovation process (E5)’ to successfully implement sustainable I4.0 within an OSCM context. A proper understanding of mutual and one-side relationships helps managers in effectively managing the adoption of I4.0 to diffuse sustainability in OSCM (LUTHRA et al., 2020). Based upon Di-Ri dataset values, six enablers, namely ‘Consistent data flow (E3)’, ‘Data security (E4)’, ‘Effective communication (E7)’, ‘Top management commitment (E8)’, ‘Collaborative networks (E9)’ and ‘Strategic alignment (E10)’ were categorised as cause group drivers. Therefore, a highly focused approach is required for these cause group key enablers (LUTHRA et al., 2020). The cause and effect diagram for the enablers is presented in Figure 16, which suggests that ‘Top management commitment (E8)’ has the maximum influence on the other enablers. From Figure 16, this enabler has a mutual relationship with several other enablers, except with the enablers ‘Sustainable philosophy (E1)’, ‘Focus on renewable natural resources (E2)’, ‘Data security (E4)’, and ‘Collaborative networks (E9)’ that has a one-side relationship. It means that Top management commitment will play a significant and important role in adopting I4.0 to achieve TBL sustainability in OSCM. The enabler ‘Effective communication (E7)’ resulted in second position in the cause group. After observing Figure 15 and Figure 16, this enabler has a mutual relationship with other enablers, for example Consistent data flow, Internal innovation process, Innovative business models, and Strategic alignment. ‘Consistent data flow (E3)’ is in third position in the cause group, and has mutual relationship with Data security, Internal innovation process, Innovative business models, Effective communication, Top management commitment, and Strategic alignment. Moreover, four enablers namely ‘Sustainable philosophy (E1)’, ‘Focus on renewable natural resources (E2)’,’ Internal innovation process (E5)’ and ‘Innovative business models (E6)’ were categorised into the effect group enablers. This group of enablers was influenced by other enablers and played the important role for the industrial managers and practitioners in understanding which enabler is influenced by other enablers. This will further help managers in framing their business strategy. The effect group enablers can be seen as desired objectives of sustainable I4.0 in OSCM. It is necessary to control cause group enablers to reach a high level of performances with effect group enablers.

4.2.5 Selection of solutions to tackle sets of challenges to implement S-OSCM4.0 in Brazilian organizations

In this section, there was the last stage of the decision support framework through the application of this framework with eight manufacturing companies, in order to assess the adequate sustainable technological solution according to each company's strategic interests to address their most important challenges to S-OSCM4.0. Figure 17 illustrates the criteria and subcriteria (challenges) and the alternatives (solutions) of this MCDM problem, which represents a choice problem (α) to be solved without considering trade-offs between the criteria. The application stage comprises using FAHP to identify individual weights and ELECTRE-I to select a subset of dominant solutions through the graph and the kernel (pointing out the best alternatives).

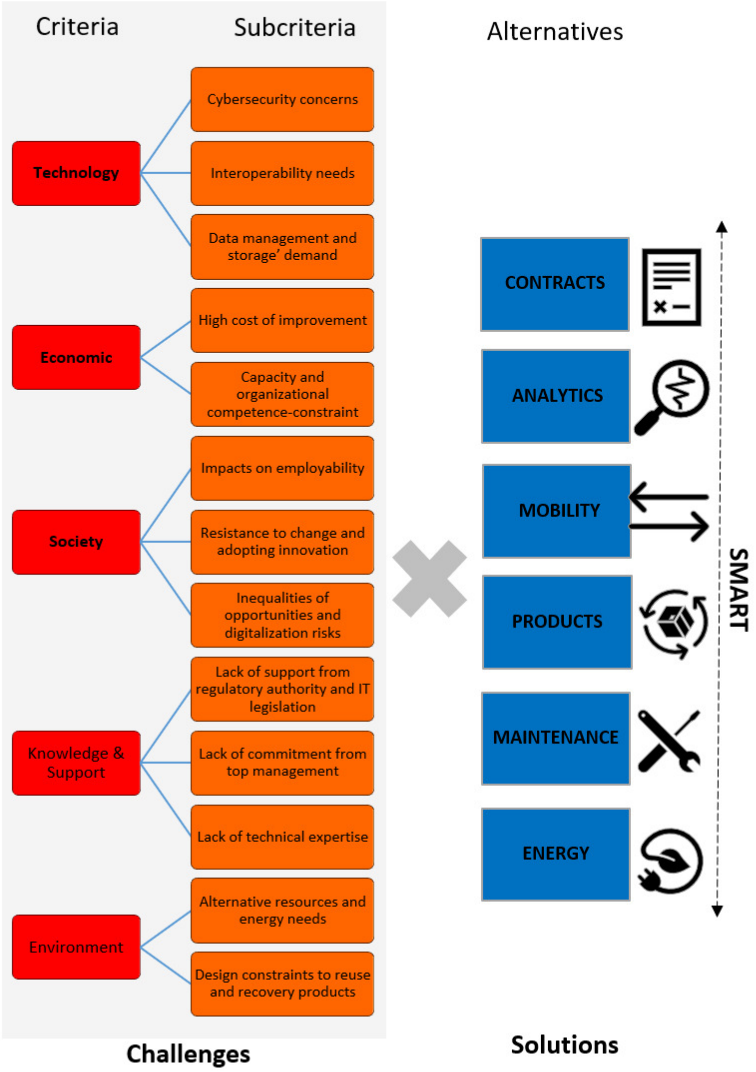

Figure 17. Hierarchy of the problem

First FAHP, adopting Buckley's method, applies triangular fuzzy numbers for calculating the respective weights for the criteria and subcriteria. Table 24 summarizes the size of the eight organizations evaluated. In the sample there were two large, three medium and three micro and small.

Table 24. Organizations size

Size	Organizations
Micro and small	Organization#3, Organization#4, Organization#8
Medium	Organization#1, Organization#2, Organization#7
Large	Organization#5, and Organization#6

One employee of each organization was asked to compare the challenges using AHP with fuzzy set theory in order to reflect human thinking appropriately. Table 25, Table 26, Table 27, Table 28, Table 29, Table 30, Table 31 and Table 32 present the priority weights after defuzzification using the COA method. All consistency ratios (CRm and CRg) were less than 0.1.

Table 25. Weights for Organization #1

Fuzzy AHP (O1)

Dimensions	Weight	Challenges	Local weight	Global weight
TEC	0.115	Cybersecurity concerns	0.713	0.082
		Interoperability needs	0.143	0.016
		Data management and storage' demand	0.143	0.016
ECO	0.044	High cost of improvement	0.5	0.022
		Capacity and organizational competence-constraints	0.5	0.022
SOC	0.665	Impacts on employability	0.425	0.283
		Resistance to change and adopting innovation	0.151	0.100
		Inequalities of opportunities and digitalization risks	0.425	0.283
KNOW&SUP	0.049	Lack of support from regulatory authority and IT legislation	0.156	0.008
		Lack of commitment from top management	0.188	0.009
		Lack of technical expertise	0.656	0.032
ENV	0.127	Alternative resources and energy needs	0.5	0.064
		Design constraints to reuse and recovery products	0.5	0.064

Table 26. Weights for Organization #2

Fuzzy AHP (O2)

Dimensions	Weight	Challenges	Local weight	Global weight
TEC	0.375	Cybersecurity concerns	0.356	0.133
		Interoperability needs	0.098	0.037
		Data management and storage' demand	0.547	0.205
ECO	0.351	High cost of improvement	0.5	0.175
		Capacity and organizational competence-constraints	0.5	0.175
SOC	0.108	Impacts on employability	0.746	0.081
		Resistance to change and adopting innovation	0.119	0.013
		Inequalities of opportunities and digitalization risks	0.134	0.015
KNOW&SUP	0.123	Lack of support from regulatory authority and IT legislation	0.255	0.031
		Lack of commitment from top management	0.491	0.060
		Lack of technical expertise	0.255	0.031
ENV	0.044	Alternative resources and energy needs	0.5	0.022
		Design constraints to reuse and recovery products	0.5	0.022

Table 27. Weights for Organization #3

Fuzzy AHP (O3)

Dimensions	Weight	Challenges	Local weight	Global weight
TEC	0.127	Cybersecurity concerns	0.425	0.054
		Interoperability needs	0.151	0.019
		Data management and storage' demand	0.425	0.054
ECO	0.172	High cost of improvement	0.5	0.086
		Capacity and organizational competence-constraints	0.5	0.086
SOC	0.295	Impacts on employability	0.151	0.044
		Resistance to change and adopting innovation	0.425	0.125
		Inequalities of opportunities and digitalization risks	0.425	0.125
KNOW&SUP	0.038	Lack of support from regulatory authority and IT legislation	0.081	0.003
		Lack of commitment from top management	0.683	0.026
		Lack of technical expertise	0.236	0.009
ENV	0.369	Alternative resources and energy needs	0.1666667	0.061
		Design constraints to reuse and recovery products	0.8333333	0.307

Table 28. Weights for Organization #4

Fuzzy AHP (O4)

Dimensions	Weight	Challenges	Local weight	Global weight
TEC	0.066	Cybersecurity concerns	0.333	0.022
		Interoperability needs	0.333	0.022
		Data management and storage' demand	0.333	0.022
ECO	0.277	High cost of improvement	0.5	0.138
		Capacity and organizational competence-constraints	0.5	0.138
SOC	0.395	Impacts on employability	0.387	0.153
		Resistance to change and adopting innovation	0.227	0.090
		Inequalities of opportunities and digitalization risks	0.387	0.153
KNOW&SUP	0.146	Lack of support from regulatory authority and IT legislation	0.255	0.037
		Lack of commitment from top management	0.491	0.072
		Lack of technical expertise	0.255	0.037
ENV	0.116	Alternative resources and energy needs	0.5	0.058
		Design constraints to reuse and recovery products	0.5	0.058

Table 29. Weights for Organization #5

Fuzzy AHP (O5)

Dimensions	Weight	Challenges	Local weight	Global weight
TEC	0.100	Cybersecurity concerns	0.333	0.033
		Interoperability needs	0.333	0.033
		Data management and storage' demand	0.333	0.033
ECO	0.097	High cost of improvement	0.5	0.049
		Capacity and organizational competence-constraints	0.5	0.049
SOC	0.300	Impacts on employability	0.227	0.068
		Resistance to change and adopting innovation	0.387	0.116
		Inequalities of opportunities and digitalization risks	0.387	0.116
KNOW&SUP	0.389	Lack of support from regulatory authority and IT legislation	0.575	0.224
		Lack of commitment from top management	0.284	0.111
		Lack of technical expertise	0.14	0.055
ENV	0.113	Alternative resources and energy needs	0.75	0.085
		Design constraints to reuse and recovery products	0.25	0.028

Table 30. Weights for Organization #6

Fuzzy AHP (O6)

Dimensions	Weight	Challenges	Local weight	Global weight
TEC	0.075	Cybersecurity concerns	0.098	0.007
		Interoperability needs	0.211	0.016
		Data management and storage' demand	0.691	0.052
ECO	0.122	High cost of improvement	0.6666667	0.081
		Capacity and organizational competence-constraints	0.3333333	0.041
SOC	0.115	Impacts on employability	0.155	0.018
		Resistance to change and adopting innovation	0.177	0.020
		Inequalities of opportunities and digitalization risks	0.668	0.077
KNOW&SUP	0.266	Lack of support from the regulatory authority and IT legislation	0.15	0.040
		Lack of commitment from top management	0.299	0.080
		Lack of technical expertise	0.552	0.147
ENV	0.421	Alternative resources and energy needs	0.8333333	0.351
		Design constraints to reuse and recovery products	0.1666667	0.070

Table 31. Weights for Organization #7

Fuzzy AHP (O7)

Dimensions	Weight	Challenges	Local weight	Global weight
TEC	0.563	Cybersecurity concerns	0.683	0.385
		Interoperability needs	0.236	0.133
		Data management and storage' demand	0.081	0.046
ECO	0.223	High cost of improvement	0.1	0.022
		Capacity and organizational competence-constraints	0.9	0.201
SOC	0.125	Impacts on employability	0.644	0.080
		Resistance to change and adopting innovation	0.222	0.028
		Inequalities of opportunities and digitalization risks	0.133	0.017
KNOW&SUP	0.054	Lack of support from regulatory authority and IT legislation	0.7	0.038
		Lack of commitment from top management	0.241	0.013
		Lack of technical expertise	0.059	0.003
ENV	0.035	Alternative resources and energy needs	0.125	0.004
		Design constraints to reuse and recovery products	0.875	0.030

Table 32. Weights for Organization #8

Fuzzy AHP (O8)

Dimensions	Weight	Challenges	Local weight	Global weight
TEC	0.635	Cybersecurity concerns	0.76	0.483
		Interoperability needs	0.192	0.122
		Data management and storage' demand	0.048	0.030
ECO	0.119	High cost of improvement	0.1666	0.020
		Capacity and organizational competence-constraints	0.8333	0.099
SOC	0.108	Impacts on employability	0.752	0.081
		Resistance to change and adopting innovation	0.185	0.020
		Inequalities of opportunities and digitalization risks	0.064	0.007
KNOW&SUP	0.073	Lack of support from regulatory authority and IT legislation	0.121	0.009
		Lack of commitment from top management	0.234	0.017
		Lack of technical expertise	0.646	0.047
ENV	0.065	Alternative resources and energy needs	0.3333	0.022
		Design constraints to reuse and recovery products	0.6666	0.043

Figure 18 also presents a graph with the variation of the global weights of the eight organizations and the group in order to represent, in an illustrative way, the sensitivity of the priority vector in relation to the criteria and sub-criteria. Table 33 illustrates the aggregated weights.

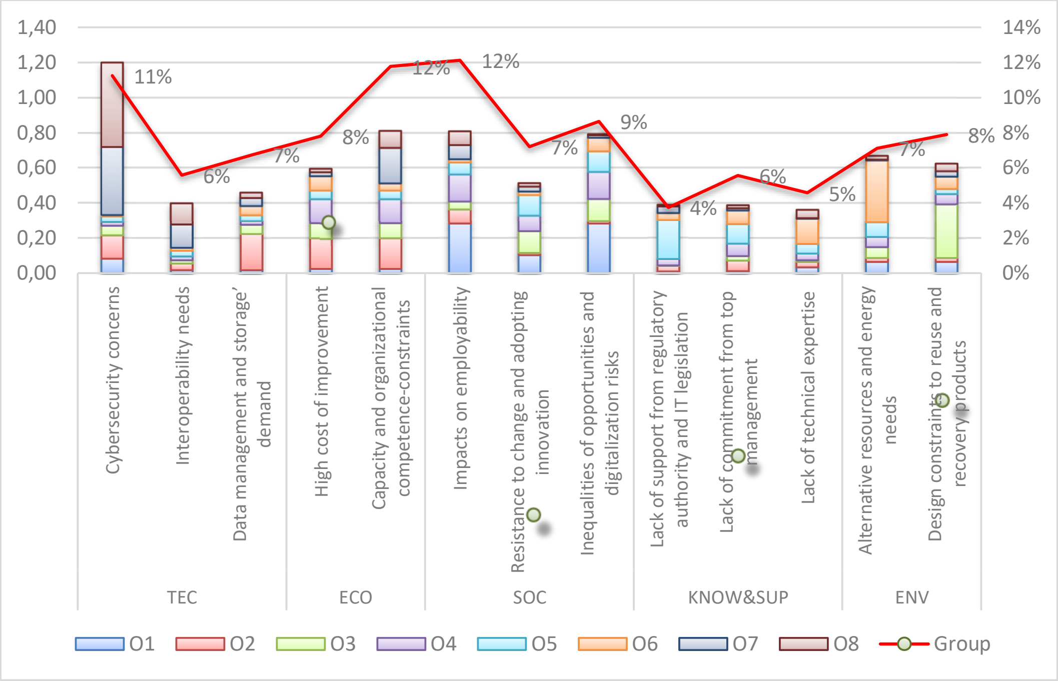

Figure 18. Weights sensitivity

Table 33. Aggregated weights for the group of organizations

Dimensions	Weight	Fuzzy Weights			Challenges	Fuzzy Weights (local)			Local weight	Fuzzy Weights (global)			Global weight
TEC	0.236	0.1646	0.2341	0.3386	Cybersecurity concerns	0.3563	0.4779	0.6396	0.4776	0.0587	0.1119	0.2166	0.113
					Interoperability needs	0.1764	0.2352	0.3191	0.2368	0.0291	0.0551	0.1081	0.056
					Data management and storage' demand	0.2137	0.2868	0.3809	0.2856	0.0352	0.0671	0.1290	0.067
ECO	0.196	0.1367	0.1951	0.2806	High cost of improvement	0.1000	0.4292	0.6667	0.3986	0.0137	0.0837	0.1871	0.078
					Capacity and organizational competence-constraints	0.3333	0.5708	0.9000	0.6014	0.0456	0.1114	0.2526	0.118
SOC	0.280	0.1980	0.2837	0.3938	Impacts on employability	0.2966	0.4286	0.6318	0.4336	0.0587	0.1216	0.2488	0.121
					Resistance to change and adopting innovation	0.1786	0.2572	0.3704	0.2576	0.0354	0.0730	0.1459	0.072
					Inequalities of opportunities and digitalization risks	0.2232	0.3141	0.4295	0.3089	0.0442	0.0891	0.1692	0.086
KNOW&SUP	0.139	0.0960	0.1379	0.1997	Lack of support from regulatory authority and IT legislation	0.1873	0.2665	0.3986	0.2696	0.0180	0.0367	0.0796	0.037
					Lack of commitment from top management	0.2589	0.4037	0.6044	0.4008	0.0248	0.0557	0.1207	0.056
					Lack of technical expertise	0.2246	0.3298	0.4876	0.3296	0.0215	0.0455	0.0974	0.046
ENV	0.150	0.1053	0.1492	0.2145	Alternative resources and energy needs	0.1250	0.4635	0.8333	0.4740	0.0132	0.0692	0.1788	0.071
					Design constraints to reuse and recovery products	0.1667	0.5365	0.8750	0.5260	0.0175	0.0801	0.1877	0.079

It is observed by Figure 18 and Table 33 that the most important challenges to the group of organizations are Cybersecurity concerns (technological dimension), Capacity and organizational competence-constraints (economic dimension) and Impacts on employability (social dimension). From the perception of organizations #1 and #4, social challenges should be prioritized, especially Impacts on employability and Inequalities of opportunities and digitalization risks. According to the perception of organizations #7 and #8, technological challenges should be highlighted, such as "Cybersecurity concerns" and "Interoperability needs". From the perception of organizations #3 and #6, environmental challenges are more important, such as Alternative resources and energy needs and Design constraints to reuse and recovery products.

In the second part of the application ELECTRE I method was used as the assessment tool to assist in the definition of the most adequate (preferred) set of solutions to each organization. As an outranking method, ELECTRE I focus on pairwise comparisons of alternatives, and the starting point was the decision matrix describing the performance of the solutions to be evaluated with respect to the challenges to S-OSCM4.0. Therefore, it seeks to obtain a subset of alternatives, in which the alternatives that are part of this subset outrank those that are not. Thus, the size of the set of alternatives is reduced by exploring the concept of dominance. Based on the evaluation of the concordance and discordance indices is buided an outranking relation that can be presented visually by an outranking graph. Figure 19 shows eight outranking graphs according to each organization's assessment. Then the preferred set of solutions are segregated into the Kernel, a non-dominated set of alternatives between which there is no outranking relationship or all alternatives in the set are incomparable.

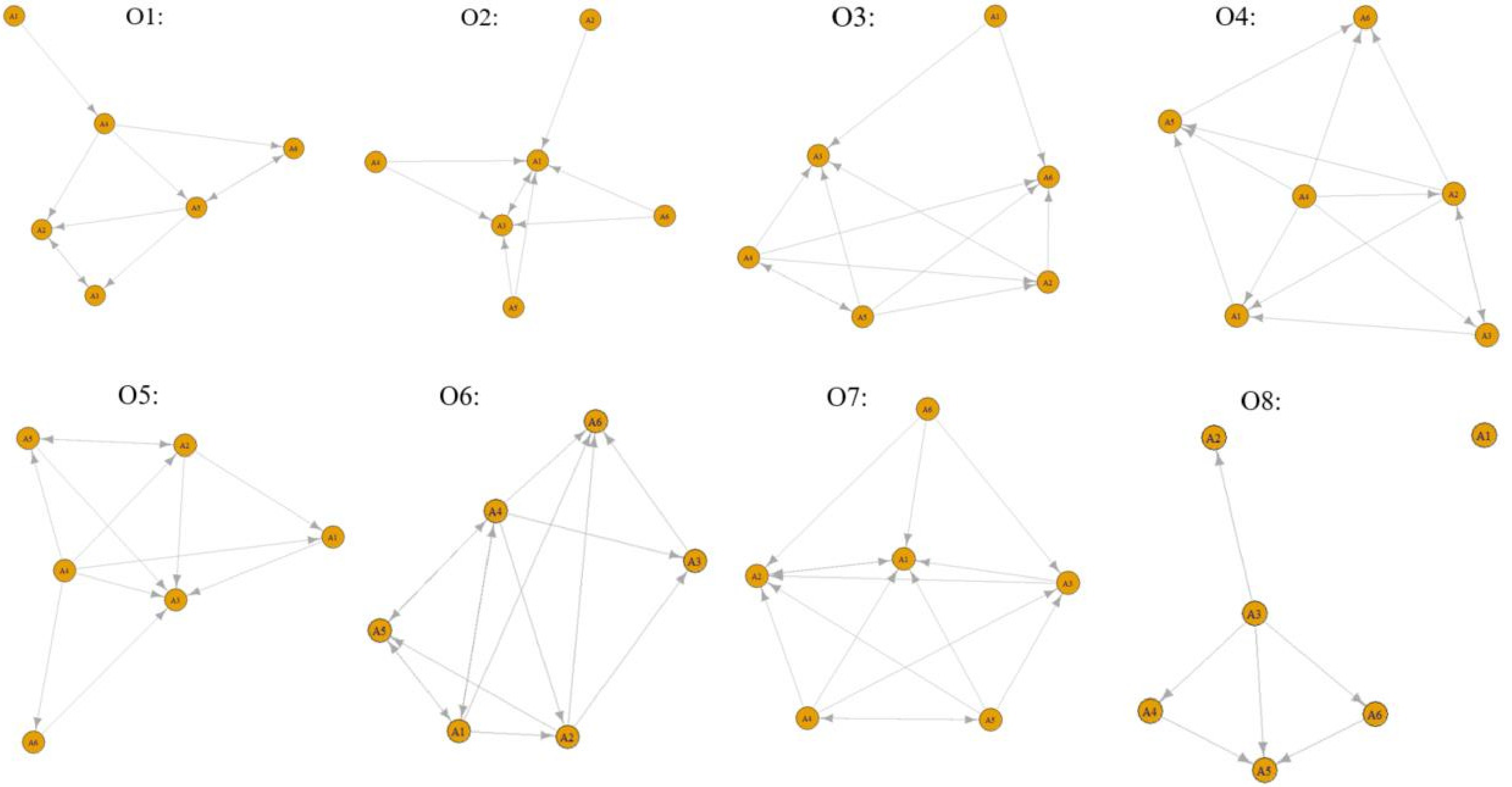

Figure 19. Outranking graphs of solutions according to each organization's perspective

Based on the results, it is observed that the solution of the fourth alternative (A4), which is Smart Products, was the most repeated in the Kernel of the eight companies (see Table 34), which is also true when analysing the companies in an aggregated way as a group. It was not possible to identify a consensus regarding the best solution based on the size of the companies. There have been cases where there is more than one Kernel subset, as in the case of organizations #3 and #7, or cases where a Kernel was not found, as in the case of organization #6. In these cases, it is recommended that a Sensitivity and Robustness Analysis be carried out in order to examine the impact of changes in the values of the thresholds (c and d) to define the outranking relation.

Table 34. Kernel sets

Company size	Cases	Weights	Concordance threshold	Discordance threshold	Kernel
Medium	O1	w = {0.0817, 0.0163, 0.0163, 0.0219, 0.0219, 0.2827, 0.1004, 0.2827, 0.0076, 0.0092, 0.0322, 0.0635, 0.0635}	c = 0.7294	d = 0.6611	{A1}
Medium	O2	w = {0.0817, 0.0163, 0.0163, 0.0219,0.0219, 0.2827, 0.1004, 0.2827, 0.0076, 0.0092, 0.0322, 0.0635 0.0635}	c = 0.7743	d = 0.6612	{A2, A4, A5, A6}
Micro and small	O3	w = {0.0540, 0.0192, 0.0540, 0.0858, 0.0858, 0.0444, 0.1252, 0.1252, 0.0030, 0.0259, 0.0089, 0.06141 0.3070}	c = 0.6742	d = 0.6931	{A1, A4} or {A1,A5}
Micro and small	O4	w = {0.02187, 0.02187, 0.02187, 0.1382, 0.1382, 0.1530, 0.0897, 0.1530, 0.0373, 0.0718, 0.0373, 0.0579, 0.0579}	c = 0.6470	d = 0.7535	{A4}
Large	O5	w = {0.0333, 0.0333, 0.0333, 0.0485, 0.0485, 0.0681, 0.1162, 0.1162, 0.2238, 0.1105, 0.0545, 0.0849, 0.0283}	c = 0.7470	d = 0.6145	{A4}
Large	O6	w = {0.0073, 0.0159, 0.0521, 0.0814, 0.0407, 0.0178, 0.0203, 0.0768, 0.0399, 0.0795, 0.1468, 0.3510, 0.0702}	c = 0.6466	d = 0.7236	-
Medium	O7	w = {0.3848, 0.1329, 0.0456, 0.0223, 0.2007, 0.0802, 0.0276, 0.0165, 0.0379, 0.0130, 0.0031, 0.0043, 0.0304}	c = 0.6326	d = 0.5399	{A4, A6} or {A5,A6}
Micro and small	O8	w = {0.4827, 0.1219, 0.0304, 0.0198, 0.0992, 0.0810, 0.0199, 0.0068, 0.0088, 0.0170, 0.0471, 0.0216, 0.0433}	c = 0.7025	d = 0.6822	{A1, A3}
-	Group	w = {0.1125, 0.0558, 0.0673, 0.0780, 0.1177, 0.1213, 0.0720, 0.0864, 0.0373, 0.0555, 0.0456, 0.0710, 0.0788}	c = 0.5054	d = 0.7247	A4

Finally, although the organizations do not have common goals, as seen in the separate analysis, an analysis of the group as a single decision unit was also carried out. To obtain a group MCDM, with the consensus of the perception of the eight organizations in a single decision matrix, aggregation by geometric mean was used. Figure 20 illustrates the summary of the group decision.

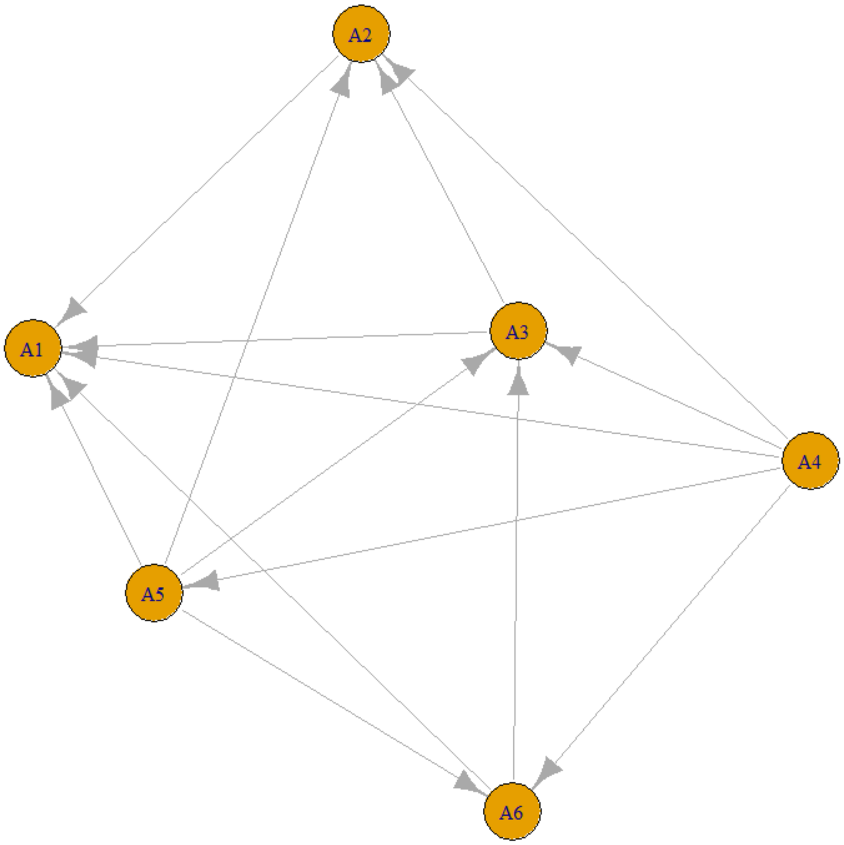

Figure 20. Outranking graphs of solutions according to group perspective

4.3 Decision support framework for S-OSCM4.0 and discussion

The decision support framework in this study, shown in Figure 21, focuses on the linkage between 10 benefits, ten key enablers, six solutions and 13 challenges. The framework may be generalised; in other words, it may be used for different applications because it was formed (constructed) based on the triangulation of past studies and the perspective of multiple experts. However, the application is specific to the company, which make the results unique to the organisation. As Hervani et al. (2005) states: *"there is no perfect tool for performance measurement systems, and their usage is greatly dependent on acceptance by organisations".* The solutions selected to face S-OSCM4.0 challenges are specific to the organisations; therefore, there is no generally applicable tool or approach for generalising the results (KAZANCOGLU et al., 2021)

The first ranked key enabler was Strategic alignment and the second was Top management commitment, which means that before integrating I4.0 technologies and sustainable practices into OSCM, it is necessary that the strategic level realizes this sustainable digital transformation process must be aligned with the organizational strategy and that management supports and prioritizes these new practices. The most selected solution was "Smart Products", which indicates that there is a greater concern with "what" will be delivered to stakeholders who are increasingly socio-environmentally aware, for example the influence of digital technologies is now being considered in the life cycle of the product and its residues. In the same way, there is also a change in the "how" this product is delivered and used, which, due to new business models, can also be a service. For Fahimnia et al. (2017), truly sustainable organizations attach strategic importance to the way their operations and supply chains are designed and managed. The leading role of the focal company in this context is a crucial factor in the development of the supply chain. Innovative organizations will be leaders in sustainability (CHRISTMANN, 2000), and senior management needs to be proactive or committed (KLASSEN; WHYBARK, 1999).

As seen, Smart product solutions may involve the use of multiple I4.0 technologies such as IoT, BDA, cloud and AM, and needs the following key enablers: Sustainable philosophy, Focus on renewable natural resources, Data security, Internal innovation process, Top management commitment, and Strategic alignment. This result signals the need for a DCV theory, highlighting the need to dynamic capabilities that facilitate these constant changes (AMBROSINI; BOWMAN, 2009), being the company's ability to integrate, build and reconfigure internal and external competencies to deal with rapidly changing environments. Unlike the resource-based view (RBV) (BARNEY, 1991), which is a static theory, DCV states that organizations should be able to prepare to develop innovative solutions to address customer requirements in dynamic environments, for example, by combining these key enablers and I4.0 technologies in OSCM, to build smart products to address customer needs in I4.0 environment.

Developing responsible conditions for production and consumption is not just another trend; it is a necessary reality for the survival of companies. In this aspect, the new business models of the digital era start to consider social and environmental issues no longer as peripheral issues but relevant to the development of corporate strategies aimed at the digital transformation of processes and operations. The need to create competitive production conditions involves access to information about the production stages prior to the company's operations, essentially involving the sustainable management of the supply chain, in order to answer questions such as: *What safer, smarter and greener practices are applied throughout sustainable suppliers processes and operations? How to integrate these actors to innovative business models?* The need for new perspectives on OSCM, in order to internalize sustainability precepts to digitalization, makes the strategy a key factor for its success.

Therefore, based on the decision support framework presented, this study also proposes three guidelines that can be adjusted to the objectives and strategies of the organizations in favour of achieving the S-OSCM4.0 in line with the precepts of the 2030 Agenda:

- *Guideline 1: Manage and integrate the key enablers into OSCM to achieve Agenda 2030 benefits;*
- *Guideline 2: Build sustainable technological solutions combining I4.0 technologies and key enablers;*
- *Guideline 3: Overcome the challenges of the sustainability-I4.0 integration in OSCM.*

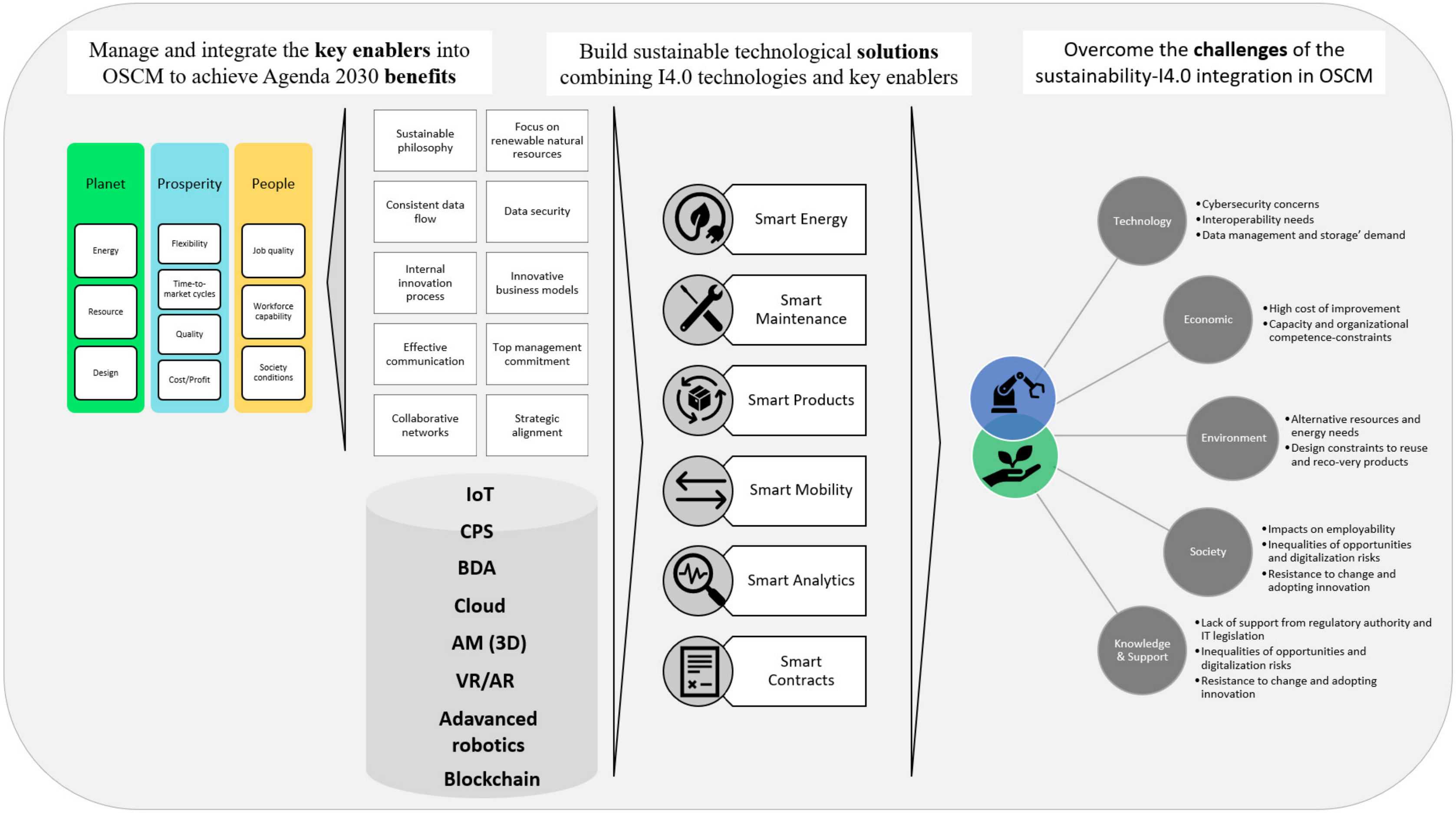

Figure 21. Decision support framework for S-OSCM4.0

Based on the SLR, it can be noticed that no previous studies discuss the concepts of S-OSCM 4.0 using MCDM methods. Since some studies deal with sustainable I4.0 in general, they are usually limited and do not allow the best solution to be selected from the available alternatives. By taking into account the gaps in knowledge in the previous articles, this paper proposes a hybrid method of decision-making. The thesis proposes a two-stage decision-making framework. With the combination of FDM, FAHP, FVIKOR, FDEMATEL and ELECTRE I. It allows the assessment of interdependencies and the importance of key enablers and their prioritization.

This thesis has its relevance attested by its contribution to the current debate about state of the art on digitally activated sustainable operations and supply chains and, in particular, it presents a S-OSCM4.0 framework that indicates how the technologies of the fourth industrial revolution have the potential to reshape OSCM sustainability (GOVINDAN et al., 2018). From there, it establishes a scientific link between I4.0 and sustainability aspects and provides a global vision that focuses on what the sustainable digitalization of the industry should be – through an inclusive and sustainable digital transformation – and not just on how much positive influence I4.0 will have on sustainable development. In this framework, the concrete implementation (of technologies and critical factors) of I4.0 is seen as a platform for the realization of the SDGs (BEIER et al., 2020), shaping operations and sustainable supply chains. This will help organizations balance the need for operational excellence in their production and service systems while remaining committed to environmental concerns and social justice.

The main contribution of this research is the development and application of a decision support model composed of multi-method with hybrid multi-criteria decision support tools to assess solutions, composed by enablers, to improve the sustainable digitalization in OSCM. This model shows which enablers should be prioritized to achieve the SD benefits aligned with the Agenda 2030 and indicates which enablers and I4.0 technologies could be focused on to build adequate solutions according to the organization's priorities. Thus, this study shows how I4.0 and its technologies can benefit the other dimensions (and aspects) of sustainability, and the decision support framework can contribute to continuous improvement - defining the priority of improvement actions for incremental advancement in the implementation of S-OSCM4.0. It also contributes with an empirical study through real case studies in eight companies to assess the most appropriate solution to face the challenges of sustainable digitalization in OSCM, and the results can serve as a benchmark for future operations and strategies in OSCM.

Furthermore, this thesis can provide academics and professionals with a better overview to understand the alignment between the main specific challenges for achieving a sustainable/digital OSCM, as well as for integrating I4.0 and sustainability into OSCM, and potential solutions involving digital technologies and key enablers to overcome these challenges and reap benefits associated with the 17 SDGs. Thus, the results of this thesis can offer managerial implications for professionals who wish to integrate sustainable challenges with I4.0 solutions to achieve sustainable development, contributing to the sustainability of the value chain and, at a global level, to Agenda 2030.

This research also seeks to respond to the growing need for sustainable performance measures that are aligned with the three dimensions of sustainability, economic, environmental, social, also called Triple bottom line (TBL), as well as the principles of I4.0, to ensure comprehensive and robust support for the decision-making process. And, it also aims to fill the knowledge gap when it comes to sustainable performance measures by comparing state of the art with the results of an applied study.

Finally, governments and public organizations may find the proposed decision support framework interesting, as they have the main role in terms of investment, training, legislation and management, planning, operation and control of sustainable performance. Thus, government initiatives could facilitate the implementation of the S-OSCM4.0 framework and encourage the adoption of these sustainable strategies in the public and private sectors.

5 CONCLUSIONS, IMPLICATIONS AND FUTURE PERSPECTIVES

5.1 Concluding remarks

This work is aimed at developing a pioneering framework for the implementation of S-OSCM4.0 by aligning taxonomies of enablers, challenges, and sustainable technological solutions and benefits, headed to Agenda 2030. The proposed framework and taxonomies were built by investigating the current state of research on the topic of S-OSCM4.0 by performing an SLR on selected publications through an appropriate review methodology. Forty-eight (48) articles were thoroughly analyzed for this purpose. The result of this SLR indicates that S-OSCM4.0 is an emerging area with an increase in the number of publications over the past few years.

In the quest for clarity and consensus on the content of S-OSCM 4.0 we hope that the proposed taxonomies not only clarify the proliferation of area nomenclature, but also, more importantly, provide in the form of a framework a useful guide for research and formulation of good management practices, public policies and new research. Like other taxonomies, the proposals in this research are not intended to be a finished product and instead can offer subject matter experts in various aspects for their evaluation, testing, review and verification (BASHSHUR et al., 2011).

The proposed framework is the first to combine novel concepts from the I4.0 and S-OSCM with the Sustainable Development Goals, thus providing new directions for future research. It represents a thorough and important advance in this emerging field (S-OSCM4.0). Additionally, this article is innovative in addressing a technological theme— sustainable technological solutions —from multiple OSCM perspectives.

This study provides significant implications towards the adoption and implementation of S-OSCM4.0, because unlike the majority of previous studies in extant literature that provided sustainability or I4.0 frameworks validated using case study approach (GUPTA; KUMAR; WASAN, 2021), the present research combines multiple case approach with hybrid fuzzy group MCDM tools to validate a decision support framework to leverage sustainable I4.0 implementation in OSCM. This framework unites precepts of I4.0 and sustainability applied to SCM and POM, and provides a hybrid self-assessment framework, which is relatively easy to apply in practice, with three general guidelines to develop action plans to implement sustainable I4.0. The proposed solutions and key enablers can also be translated into a set of measures or recommended actions to support the decision in OSCM domain. This could also pave the way for future work to do research involving the use of other hybrid fuzzy methods to support the decision-making process regarding the choice of sustainable technological solutions.

5.2 Theoretical and managerial implications

The present study possesses strong theoretical and practical contributions towards the domain of OSCM, particularly the sustainable operations and supply chains and Industry 4.0 streams of research (KOVÁCS et al., 2020). The findings of the SLR in the form of a proposed taxonomies-based framework is one of the initial efforts to contribute to the theory of S-OSCM4.0 and the relationships between enablers, challenges, solutions, and benefits. It proposes that the implementation of S-OSCM4.0 leads to unlocking the SD benefits in line with SDGs. Hence this study makes a significant theoretical contribution to the literature in the form of a detailed SLR on S-OSCM4.0 that generated two products: taxonomy and framework (TORRACO, 2005). This taxonomy can be used to improve the specification of interventions in the S-OSCM4.0 field, thus improving replication, implementation, and evidence syntheses. We propose a S-OSCM4.0 framework based on the findings of the literature with enablers, challenges, solutions, and benefits as the critical components of this framework.

The framework will act as a ready reckoner for the practitioners (and policymakers) in the field of OSCM while developing the guidelines for the implementation of sustainable digitalization. Thus, the framework will guide the practitioners towards the implementation of S-OSCM4.0, and they will acknowledge the critical role of enablers to integrate I4.0 and sustainability, the role of I4.0 technologies to pursue sustainable technological solutions, and the importance to combine enablers and solutions to obtain SD benefits in OSCM. Moreover, it could be argued that testing the proposed framework may be a starting point for implementing S-OSCM4.0. The proposed framework sheds light on the potential of sustainable I4.0 in terms of maximizing company contributions to the SDGs, aligning their course to ensure that sustainability is an outcome of core business strategy.

The novelty of this doctoral thesis will be verified through an SLR to identify whether there are researches that describe the object of this study by the paradigm of sustainable development and, mainly, if there is a proposal to develop a decision support framework, considering the alignment of I4 .0 and sustainability, and contributions to the achievement of UN sustainable development goals and to aspects of sustainability beyond efficiency and productivity (BEIER et al., 2020). As an exploratory study, the originality is sought through the intersection of the themes Industry 4.0, OSCM, Sustainability, ODS and fuzzy MCDM. From that, this thesis brings multiple new contributions, providing academics and professionals with a better panorama to achieve SD through the alignment of I4.0 with sustainability in OSCM to achieve the SDGs.

The research intends to contribute to the scientific community on the studied topic, as it will present a representative selection of international research in an interdisciplinary area. Thus, in summary, the following can be highlighted as the main distinguishing features of this doctoral thesis: 1) expand the literature review of sustainable I4.0; 2) highlight challenges, potential solutions and enablers involving the integration between I4.0 and sustainability in OSCM; 3) Identify social and environmental benefits, shaped in Agenda 2030, of the integration of I4.0 and sustainability for OSCM, 4) propose an S-OSCM4.0 framework with an empirical study approach and treatment of decision support method to increase the applicability of the developed framework (YADAV et al., 2020a), and 5) to propose and apply a hybrid multicriteria decision support framework to drive the implementation of S-OSCM4.0. Therefore, it is expected that this study will inspire further investigation and exploration in the areas of sustainable I4.0 and fuzzy group decision making in OSCM.

Finally, this research is one of the few embryonic studies that explore how the UN SDGs can be integrated into OSCM sustainability. Therefore, this Thesis fills the research gap in the OSCM domain related to a holistic and integrated vision of sustainability, using the SDG Compass, which counts on the collaboration between the GRI (Global Reporting Initiatives), the UN Global Compact and the Council World Business for Sustainable Development (WBCSD) (SUDUSINGHE; JAYARATNE; KUMARAGE, 2018), to align OSCM digitalization solutions for manufacturing organizations with the scope of the 2030 Agenda.

5.3 Limitations and suggestions for further work

As with most studies, this research has some limitations that should be acknowledged. First, selecting the Scopus and WoS databases may be one of the limitations of this paper, as there might be articles outside of these databases that might be relevant to the scope of the study that has not been considered. There was a temporal limitation because the data are collected on a date, and if there are new authors or new articles, these will not be part of the selected portfolio of articles. The perception of the author who developed this research is limited, from the decision on alignment with the topic or even observations. Furthermore, as the focus was on articles from academic journals in English, articles from other languages were excluded, as well as other types of publications. Finally, due to the identification of publications based on keywords, it is possible that publications that match the focus of the research were not found because they do not contain the necessary keywords in their titles or abstracts.

Second, this study has as its purpose the "development and application of a two-stages decision support framework for the implementation of S-OSCM4.0, aligned with the 2030 Agenda (#17 ODS)", being delimited by its objective to propose and validate a framework to guide the implementation of S-OSCM4.0 in organizations OSCM. There were panels and interviews with experts for the construction and application of the proposed framework, the selection of the most relevant criteria for the framework and the determination of the weight of its dimensions, specialists in the managerial position, with experience in OSCM, sustainability and I4.0, were chosen; because, according to Nonaka e Takeuchi, (2007), they are knowledge engineers, as they are at the middle level of the organization, being responsible for transferring strategy to practice. Thus, they are able to pinpoint the exact knowledge assets critical for integration. Therefore, the study was limited to Brazilian organizations, being limited to the context of a developing country. In this sense, in further research the S-OSCM 4.0 framework should be presented to other stakeholders (e.g. Government) for refinement (CUNHA et al., 2021). The application of the framework to different cultures, nations, and continents should further highlight cultural aspects and implementation challenges that should be considered when adopting the ideas of this work. We also suggest conducting in-depth case studies to understand the 'soft side' of integrating I4.0 and sustainability in OSCM, by qualitatively exploring enablers and challenges to S-OSCM4.0, which This understanding should prove in valuable to better promote and encourage adoption of the various results from quantitative studies (DE SOUSA JABBOUR et al., 2018) resulting from the step-by-step framework.

Third, the proposed framework may be used in further studies to conduct explanatory studies for developing the measurement constructs for S-OSCM4.0, considering enablers, challenges, sustainable technological solutions, and benefits. Empirical studies may be conducted for analysing the proposed relationships using structural equation modelling (BAG et al., 2020). We also strongly recommend that the RPs be developed further, by conducting qualitative research or by converting the propositions into hypotheses that will be tested through quantitative methods. We also encourage further researchers to investigate other relations of the S-OSCM4.0 framework, such as: the relation between enablers and challenges to S-OSCM4.0; and the trade-off between challenges and benefits to achieve S-OSCM4.0.

Fourth, these MCDM methods cannot always be considered a complete panacea, as these methods may point to some of the decision maker's inconsistencies or contradictions, which means re-evaluating the judgements. For example, concerning the ELECTRE-I method, clearly, sensitivity and robustness analysis is an important part of the decision process. Unfortunately, it is not possible to do this in any automated or interactive way, so that the analysis becomes an *ad hoc* investigation into the effect of changing values. Thus, it is suggested that further practical research use sensitivity analysis as a learning tool to understand decision-maker values and preferences and achieve a rich set of outranking relations.

Fifth, future research studies may also investigate the maturity of S-OSCM4.0 in the different industrial setups. It is expected that the proposed framework be adapted based on the OSCM4.0 model by Caiado et al. (2021)to have as a differential the possibility of comparing the OSCM sustainability of organizations from different industries.

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APPENDIX A - Summary of the articles reviewed

Source	Title
Prause (2015)	Sustainable business models and structures for industry 4.0
Hazen et al. (2016)	Big data and predictive analytics for supply chain sustainability: A theory-driven research agenda
May, Stahl and Taisch, (2016)	Energy management in manufacturing: Toward eco-factories of the future - A focus group study
Strandhagen et al. (2017)	Logistics 4.0 and emerging sustainable business models
Murmura and Bravi, (2017)	Additive manufacturing in the wood-furniture sector: Sustainability of the technology, benefits and limitations of adoption
Bag et al. (2018)	Industry 4.0 and supply chain sustainability: framework and future research directions
Bonilla et al. (2018)	Industry 4.0 and Sustainability Implications: A Scenario-Based Analysis of the Impacts and Challenges
Kamble et al. (2018)	Sustainable Industry 4.0 framework: A systematic literature review identifying the current trends and future perspectives
Luthra and Mangla (2018)	Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies
Müller at al. (2018)	What Drives the Implementation of Industry 4.0? The Role of Opportunities and Challenges in the Context of Sustainability
Stock et al. (2018)	Industry 4.0 as enabler for a sustainable development: A qualitative assessment of its ecological and social potential
Jabbour et al. (2018)	Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations
Ding (2018)	Pharma Industry 4.0: Literature review and research opportunities in sustainable pharmaceutical supply chains
Jabbour et al. (2018)	When titans meet – Can industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors
Braccini and Margherita, (2018)	Exploring organizational sustainability of Industry 4.0 under the triple bottom line: The case of a manufacturing company
Brenner (2018)	Transformative sustainable business models in the light of the digital imperative-a global business economics perspective
Kusiak (2018)	Smart manufacturing
Dubey et al. (2019)	Can big data and predictive analytics improve social and environmental sustainability?
Manavalan and Jayakrishna (2019)	A review of Internet of Things (IoT) embedded sustainable supply chain for industry 4.0 requirements
Ren et al. (2019)	A comprehensive review of big data analytics throughout product lifecycle to support sustainable smart manufacturing: A framework, challenges and future research directions
Raut et al. (2019)	Linking big data analytics and operational sustainability practices for sustainable business management
Belaud et al. (2019)	Big data for agri-food 4.0: Application to sustainability management for by-products supply chain
Nascimento et al. (2019)	Exploring Industry 4.0 technologies to enable circular economy practices in a manufacturing context: A business model proposal
Varela et al. (2019)	Evaluation of the Relation between Lean Manufacturing, Industry 4.0, and Sustainability
Birkel et al. (2019)	Development of a Risk Framework for Industry 4.0 in the Context of Sustainability for Established Manufacturers
Bag et al. (2020)	Big data analytics as an operational excellence approach to enhance sustainable supply chain performance
Esmaeilian et al. (2020)	Blockchain for the future of sustainable supply chain management in Industry 4.0
Jabbour et al. (2020)	Digitally-enabled sustainable supply chains in the 21st century: A review and a research agenda
Machado et al. (2020)	Sustainable manufacturing in Industry 4.0: an emerging research agenda
Oláh et al. (2020)	Impact of Industry 4.0 on Environmental Sustainability
Bai et al. (2020)	Industry 4.0 technologies assessment: A sustainability perspective
Li, Dai and Cui (2020)	The impact of digital technologies on economic and environmental performance in the context of industry 4.0: A moderated mediation model
Ozkan-Ozen, Kazancoglu and Kumar Mangla (2020)	Synchronized Barriers for Circular Supply Chains In Industry 3.5/Industry 4.0 Transition for Sustainable Resource Management
Yadav et al. (2020b)	A framework to overcome sustainable supply chain challenges through solution measures of industry 4.0 and circular economy: An automotive case

Ivascu (2020)	Measuring the implications of sustainable manufacturing in the context of industry 4.0
Luthra et al. (2020)	Industry 4.0 as an enabler of sustainability diffusion in supply chain: an analysis of influential strength of drivers in an emerging economy
Dev, Shankar and Qaiser (2020)	Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance
Mastos et al. (2020)	Industry 4.0 sustainable supply chains: An application of an IoT enabled scrap metal management solution
Yadav et al., (2020a)	A framework to achieve sustainability in manufacturing organisations of developing economies using industry 4.0 technologies' enablers
Muñoz-La Rivera et al. (2020)	The sustainable development goals (SDGs) as a basis for innovation skills for engineers in the industry 4.0 context
Leng et al. (2020)	Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey
Khanzode et al. (2020)	Modeling the Industry 4.0 Adoption for Sustainable Production in Micro, Small & Medium Enterprises
Bag, Harm and Pretorius (2020)	Relationships between industry 4.0, sustainable manufacturing and circular economy: proposal of a research framework
Ghobakhloo (2020)	Industry 4.0, digitization, and opportunities for sustainability
Pinzone et al. (2020)	A framework for operative and social sustainability functionalities in Human-Centric Cyber-Physical Production Systems
Hahn (2020)	Opportunities for Socially Responsible Industry 4.s
Kouhizadeh, Saberi and Sarkis (2021)	Blockchain technology and the sustainable supply chain: Theoretically exploring adoption barriers
Bag, Gupta and Kumar (2021)	Industry 4.0 adoption and 10R advance manufacturing capabilities for sustainable development

APPENDIX B - Taxonomy of enablers to S-OSCM4.0

Taxonomy	ID	Critical success factor	Source
Circular & Sustainability	1	Sustainable philosophy	May et al., (2016); Yadav et al., (2020a); Yadav et al., (2020b)
	2	Focus on renewable natural resources	Oláh et al., (2020); Bonilla et al., (2018)
	3	Interdisciplinary and holistic integration	May et al., (2016); Bag et al., (2018); Nascimento et al., (2019); Yadav et al., (2020a); Yadav et al., (2020b)
	4	Sharing economy	Brenner (2018)
	5	Life cycle thinking	Nascimento et al., (2019); Oláh et al., (2020); Yadav et al., (2020a); Yadav et al., (2020b)
	6	Circular processes	Brenner (2018); Raut et al., (2019); Ozkan-Ozen et al., (2020); Yadav et al., (2020a); Yadav et al., (2020b); Bag et al., (2021)
Information & Technology	7	I4.0 readiness	Prause et al., (2015); Hazen et al., (2016) ; Bonilla et al., (2018); Yadav et al., (2020a) ; Mastos et al., (2020); Yadav et al., (2020b) ; Bag et al., (2021)
	8	Adoption of smart factory components	Yadav et al., (2020a); Mastos et al., (2020); Yadav et al., (2020b)
	9	Data-centered solutions	Müller et al., (2018); Kusiak (2018); Oláh et al., (2020); Ozkan-Ozen et al., (2020) ; Bag et al., (2020); Yadav et al., (2020a); Yadav et al., (2020b); Bag and Pretorius (2020)
	10	Consistent data flow	Pinzone et al., (2020); Ozkan-Ozen et al., (2020); Leng et al., (2020); Ghobakhloo (2020)
	11	Modular design	Stock et al., (2018); Mastos et al., (2020) ; Yadav et al., (2020b) ; Ghobakhloo (2020)
	12	Information transparency	May et al., (2016) ; Bag et al., (2018) ; Ozkan-Ozen et al., (2020) ; Luthra et al., (2020) ; Yadav et al., (2020b) ; Esmaeilian et al., (2020)
	13	Data security	Bag et al., (2018); Yadav et al., (2020a); Esmaeilian et al., (2020); Leng et al., (2020); Bag and Pretorius (2020)
Innovation	14	Internal innovation process	Braccini and Margherita (2018); Raut et al., (2019); Bag et al., (2020); Machado et al., (2020); Yadav et al., (2020b)
	15	Open innovation	Prause et al., (2015); Kusiak (2018)
	16	Change management	Bag et al., (2018) ; de Sousa Jabbour et al., (2018) ;
	17	Dynamic capabilities	Bag et al., (2018); Prause et al., (2015); Brenner (2018); Manavalan and Jayakrishna (2019); Li et al., (2020); Ivascu (2020); Muñoz-La Rivera et al., (2020); Bag and Pretorius (2020); Ghobakhloo (2020); Bag et al., (2021)
	18	Innovative business models	Ghobakhloo (2020); Prause et al., (2015) ; Strandhagen et al., (2017) ; Brenner (2018); Luthra et al., (2020)
	19	Service design solutions	Prause et al., (2015); Brenner (2018)
People & Culture	20	Knowledge sharing	Brenner (2018); Pinzone et al., (2020); Braccini and Margherita (2018); Dubey et al., (2019); Luthra et al., (2020); Yadav et al., (2020b); Bag and Pretorius (2020); Ghobakhloo (2020)
	21	Effective communication	de Sousa Jabbour et al., (2018); Ren et al., (2019); Yadav et al., (2020b)
	22	Individual incentive schemes	Stock and Seliger (2016); Yadav et al., (2020a); Yadav et al., (2020b)
	23	Employee’s empowerment	de Sousa Jabbour et al., (2018); Ozkan-Ozen et al., (2020); Khanzode et al., (2020)
	24	Experimentation	Hahn (2020)
	25	Education and training focused on soft and technical skills	Stock and Seliger (2016); Bag et al., (2018); de Sousa Jabbour et al., (2018) Müller et al., (2018); Murmura and Bravi (2017); Ozkan-Ozen et al., (2020); Bag et al., (2020); Mastos et al., (2020); Yadav et al., (2020b); Muñoz-La Rivera et al., (2020); Bag and Pretorius (2020); Bag et al., (2021)
	26	Transformational leadership	de Sousa Jabbour et al., (2018); Braccini and Margherita (2018); Raut et al., (2019); Bag et al., (2020); Bag and Pretorius (2020)
	27	Top management commitment	Luthra and Mangla (2018); Bag et al., (2018); de Sousa Jabbour et al., (2018); Ivascu (2020); Luthra et al., (2020); Yadav et al., (2020b); Leng et al., (2020); Bag and Pretorius (2020); Bag et al., (2021)
Supply Chain Organization & Processes	28	Customer and supplier integration	Ivascu (2020); Prause et al., (2015); Raut et al., (2019); Yadav et al., (2020a); Yadav et al., (2020b)
	29	Support of unconventional partners	Bag et al., (2018); Ivascu (2020); Hahn (2020)

	30	Governmental and institutional pressures	Bag et al., (2018); Raut et al., (2019); Luthra et al., (2020); Yadav et al., (2020b); Ghobakhloo (2020); Bag and Pretorius (2020)
	31	Collaborative networks	Pinzone et al., (2020); Prause et al., (2015); May et al., (2016); de Sousa Jabbour et al., (2018); Brenner (2018); Kusiak (2018); Raut et al., (2019); Nascimento et al., (2019); Li et al., (2020); Yadav et al., (2020a); Luthra et al., (2020); Machado et al., (2020); Mastos et al., (2020); Bag and Pretorius (2020); Ghobakhloo (2020); Hahn (2020)
	32	Adoption of advanced quality improvement techniques	de Sousa Jabbour et al., (2018); Oláh et al., (2020); Yadav et al., (2020a); Ivascu (2020); Yadav et al., (2020b); Leng et al., (2020); Machado et al., (2020);
	33	Re-designing and decentralized structure	Murmura and Bravi (2017); Machado et al., (2020) ; Yadav et al., (2020b); Esmaeilian et al., (2020); Bag and Pretorius (2020); Stock et al., (2018) ; Ozkan-Ozen et al., (2020)
	34	Strategic alignment	Bag et al., (2018) ; de Sousa Jabbour et al., (2018); Nascimento et al., (2019); Machado et al., (2020); Mastos et al., (2020)

APPENDIX C - Taxonomy of challenges to S-OSCM4.0

Taxonomy	ID	Challenge	Source
Technology	1	Cybersecurity concerns	Bonilla et al. (2018); Kamble et al. (2018); Jabbour A.B. et al. (2018); Ding, B. (2018); Bag et al. (2018); Kusiak, A.(2018); Raut et al. (2019); Birkel (2019); Chiappetta Jabbour et al (2020); Oláh et al (2020); Ozkan-Ozen et al. (2020); Esmaeilian et al (2020); Ghobakhloo (2020); Stock et al. (2018); Luthra and Mangla (2018); Bai et al. (2020); Leng et al. (2020); Kouhizadeh et al. (2021);
	2	Interoperability needs	Jabbour et al. (2018); Ding, (2018); Bag et al. (2018); Kusiak, A.(2018); Raut et al. (2019); Birkel (2019); Ren et al. (2019); Dubey et al. (2019); Chiappetta Jabbour et al (2020); Ozkan-Ozen et al. (2020); Ivascu (2020); Machado et al. (2020); Esmaeilian et al (2020); Bag and Pretorius (2020); Ghobakhloo (2020); May et al. (2016); Strandhagen et al. (2016); Yadav et al (2020); Yadav et al. (2020b); Leng et al. (2020); Bag and Pretorius (2020); Luthra and Mangla (2018); Müller et al. (2018); Kouhizadeh et al. (2021)
	3	Data management and storage’ demand	Dubey et al. (2019); Chiappetta Jabbour et al (2020); Luthra and Mangla (2018); Kusiak (2018); Bai et al. (2020); Ozkan-Ozen et al. (2020); Esmaeilian et al (2020); Leng et al. (2020); Ren et al. (2019)
Economic	4	High cost of improvement	Bonilla et al. (2018); Bag et al. (2018); Braccini and Margherita (2018); Murmura and Bravi (2018); Raut et al. (2019); Nascimento et al. (2019); Manavalan and Jayakrishna (2019); Birkel (2019); Oláh et al (2020); Ozkan-Ozen et al. (2020); Ivascu, L. (2020); Dev et al. (2020); Machado et al. (2020); Yadav et al. (2020); Bag and Pretorius (2020); Ghobakhloo (2020); Ding, B. (2018); Hazen et al. (2016); May et al. (2016); Luthra and Mangla (2018); Müller et al. (2018); Pinzone et al. (2020); Kouhizadeh et al. (2021)
	5	Capacity and organizational competence-constraints	May et al. (2016); Ozkan-Ozen et al. (2020); Yadav et al (2020); Yadav et al. (2020)b; Bag and Pretorius (2020); Luthra and Mangla (2018); Birkel (2019)
Society	6	Impacts on employability	Ding, B. (2018); Luthra and Mangla (2018); Bag et al. (2018); Braccini and Margherita (2018); Kusiak, A.(2018); Stock et al. (2018); Birkel (2019); Bai et al. (2020); Bag and Pretorius (2020); Ghobakhloo (2020); Pinzone et al. (2020); Bag et al. (2021)
	7	Resistance to change and adopting innovation	Ivascu, L. (2020); Bag and Pretorius (2020); May et al. (2016); Ozkan-Ozen et al. (2020); Yadav et al. (2020)b; Bag and Pretorius (2020); Luthra and Mangla (2018); Birkel (2019); Leng et al. (2020); Kouhizadeh et al. (2021)
	8	Inequalities of opportunities and digitalization risks	Ghobakhloo (2020); Hahn (2021); Ozkan-Ozen et al. (2020)
Knowledge & Support	9	Lack of support from regulatory authority and IT legislation	Bonilla et al. (2018); Bag et al. (2018); Manavalan and Jayakrishna (2019); Birkel (2019); Chiappetta Jabbour et al (2020); Ozkan-Ozen et al. (2020); Esmaeilian et al (2020); Leng et al. (2020); Bag and Pretorius (2020); Ding, B. (2018); Nascimento et al. (2019); Luthra and Mangla (2018); Raut et al. (2019); Bai et al. (2020); Kouhizadeh et al. (2021); Hahn (2021)
	10	Lack of commitment from top management	Bag et al. (2018); Kusiak, A.(2018); Oláh et al (2020); Ozkan-Ozen et al. (2020); Yadav et al (2020); Yadav et al. (2020)b; Bag and Pretorius (2020); Luthra and Mangla (2018); Khanzode et al.,2020; Raut et al. (2019); Birkel (2019); Kouhizadeh et al. (2021)
	11	Lack of technical expertise	Bonilla et al. (2018); Jabbour A.B. et al. (2018); Bag et al. (2018); Murmura and Bravi (2018); Nascimento et al. (2019); Oláh et al (2020); Ozkan-Ozen et al. (2020); Ivascu, L. (2020); Machado et al. (2020); Bag and Pretorius (2020); Ding, B. (2018); Stock et al. (2018); Kamble et al. (2018); Yadav et al (2020); Yadav et al. (2020)b; Jabbour et al. (2018); Luthra and Mangla (2018); Müller et al. (2018); Birkel (2019); Rivera et al. (2020); Kouhizadeh et al. (2021)
Environment	12	Alternative resources and energy needs	Esmaeilian et al (2020); Raut et al. (2019); Oláh et al (2020); Bonilla et al (2018); Stock et al. (2018); Birkel (2019); Bai et al. (2020); Ghobakhloo (2020)
	13	Design constraints to reuse and recovery products	Kusiak (2018); Nascimento et al. (2019); Yadav et al (2020); Birkel (2019); Ren et al. (2019); Ozkan-Ozen et al. (2020); Ghobakhloo (2020)

APPENDIX D - I4.0 technologies combined in the taxonomy of Sustainable technological solutions

ID	Taxonomy	IoT	CPS	BDA	Cloud	AM (3D)	VR/AR	Advanced robotics	Blockchain	Sources
1	**Smart ENERGY**	●		●	●		●	●	●	(Bonilla et al., 2018); (Bai et al., 2020a); (Stock et al., 2018); (Ghobakhloo, 2020); (Machado et al., 2020); (Leng et al., 2020)
2	**Smart MAINTENANCE**	●	●				●	●	●	(Bonilla et al., 2018); (Manavalan and Jayakrishna 2019); (Bai et al., 2020a); (Ghobakhloo, 2020); (Kamble et al., 2018); (Ren et al., 2019); (Chiappetta Jabbour et al., 2020); (Esmaeilian et al., 2020); (Leng et al, 2020)
3	**Smart PRODUCTS**	●		●	●	●				(May et al., 2016); (Strandhagen et al., 2017); (Bonilla et al., 2018); (Esmaeilian et al., 2020); (Ghobakhloo, 2020); (Bai et al., 2020a); (Li et al., 2020)
4	**Smart MOBILITY**	●		●				●	●	(Prause, 2015); (May et al., 2016); (Strandhagen et al., 2017); (Kusiak, 2018); (Kamble et al., 2018); (Stock et al., 2018); (Manavalan and Jayakrishna, 2019); (Bai et al., 2020a); (Esmaeilian et al., 2020)
5	**Smart ANALYTICS**	●		●	●				●	(Bonilla et al., 2018); (Stock et al., 2018); (Dubey et al., 2019); (Raut et al., 2019); (Li et al., 2020); (Ghobakhloo 2020); (Bai et al., 2020a); (Ozkan-Ozen et al., 2020); (Leng et al, 2020); (Esmaeilian et al., 2020)
6	**Smart CONTRACTS**			●	●				●	(Stock and Seliger, 2016); (Leng et al, 2020); (Ghosh et al., 2020).

APPENDIX E - Benefits of S-OSCM4.0 and their potential alignment with Agenda 2030

Taxonomy	ID	Benefit	Source	SDG
Planet	1	Energy	Gunnar Prause, (2015); Stock et al. (2018); Kamble et al. (2018); Jabbour et al. (2018); Varela et al. (2020); Birkel (2019); Ren et al. (2019); Bai et al. (2020); Luthra et al. (2020); Machado et al. (2020); Rivera et al. (2020); Leng et al. (2020); Ghobakhloo, M. (2020)	**SDG#7:** ensure universal access to affordable, reliable and modern energy services (7.1); and facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology (7.2).
	2	Resource	Gunnar Prause, (2015); Hazen et al. (2016); Bonilla et al. (2018); Stock et al. (2018); Kamble et al. (2018); Ding, B. (2018); Jabbour et al. (2018); Braccini and Margherita (2018); Müller et al. (2018); Murmura and Bravi (2018); Kusiak, A.(2018); Raut et al. (2019); Nascimento et al. (2019); Manavalan and Jayakrishna (2019); Varela et al. (2020); Birkel (2019); Ren et al. (2019); Chiappetta Jabbour et al (2020); Bai et al. (2020); Oláh et al (2020); Li et al (2020); Ivascu, L. (2020); Luthra et al. (2020); Machado et al. (2020); Mastos et al (2020); Esmaeilian et al (2020); Rivera et al. (2020); Khanzode et al. (2020); Bag and Pretorius (2020); Ghobakhloo, M. (2020)	**SDG#9:** upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes (9.4) **SDG#12:** achieve efficient use of natural resources (12.2);
	3	Design	Luthra and Mangla (2018); Jabbour et al. (2018); Murmura and Bravi (2018); Kusiak, A.(2018); Raut et al. (2019); Ren et al. (2019); Li et al (2020); Ghobakhloo, M. (2020)	**SDG#12:** achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in to minimize their adverse impacts on human health and the environment (12.4); substantially reduce waste generation through prevention, reduction, recycling and reuse (12.5).
Prosperity	4	Flexibility	May et al. (2016); Strandhagen et al. (2016); Bonilla et al. (2018); Ding, B. (2018); Müller et al. (2018); Murmura and Bravi (2018); Birkel (2019); Bai et al. (2020); Li et al (2020); Dev et al. (2020); Machado et al. (2020); Ghobakhloo, M. (2020); Pinzone et al. (2020)	**SDG#8:** achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high value added and labour-intensive sectors (8.2);
	5	Time-to-market cycles	Gunnar Prause, (2015); Müller et al. (2018); Murmura and Bravi (2018); Ren et al. (2019); Chiappetta Jabbour et al (2020); Ivascu, L. (2020); Ghobakhloo, M. (2020); Pinzone et al. (2020)	**SDG#9:** Enhance scientific research, encouraging innovation and substantially increasing the number of research and development workers (9.5);
	6	Quality	Jabbour et al. (2018); Braccini and Margherita (2018); Müller et al. (2018); Murmura and Bravi (2018); Birkel (2019); Ren et al. (2019); Oláh et al (2020); Li et al (2020); Ghobakhloo, M. (2020); Pinzone et al. (2020); Pinzone et al. (2020)	**SDG#8:** support productive activities, creativity and innovation (8.5), **SDG#9: d**evelop quality, reliable, sustainable and resilient infrastructure (9.1)
	7	Costs / Profit	Gunnar Prause, (2015); Hazen et al. (2016); Bonilla et al. (2018); Kamble et al. (2018); Braccini and Margherita (2018); Müller et al. (2018); Murmura and Bravi (2018); Kusiak, A.(2018); Raut et al. (2019); Nascimento et al. (2019); Varela et al. (2020); Birkel (2019); Ren et al. (2019); Chiappetta Jabbour et al (2020); Bai et al. (2020); Oláh et al (2020); Li et al (2020); Bag et al (2020); Ivascu, L. (2020); Luthra et al. (2020); Mastos et al (2020); Khanzode et al. (2020); Bag and Pretorius (2020); Ghobakhloo, M. (2020); Pinzone et al. (2020)	**SDG#8:** improve progressively, resource efficiency in consumption and production (8.4); **SDG#9:** increase the access of small-scale industrial and other enterprises, in particular in developing countries, to financial services, and their integration into value chains and markets (9.3); **SDG#11:** provide access to affordable, accessible and sustainable transport systems for all, improving road safety (11.2); **SDG#12:** achieve the sustainable management and efficient use of natural resources (12.2); **SDG#17:** promote the development, transfer, dissemination and diffusion of environmentally sound technologies to developing countries on favourable terms (17.7);
People	8	Job quality	Stock et al. (2018); Kamble et al. (2018); Müller et al. (2018); Varela et al. (2020); Birkel (2019); Bai et al. (2020); Oláh et al (2020); Bag et al (2020); Machado et al. (2020); Mastos et al (2020); Ghobakhloo, M. (2020); Pinzone et al. (2020)	**SDG#8:** support decent job creation (8.3); achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value (8.5);
	9	Workforce capability	Stock et al. (2018); Raut et al. (2019); Varela et al. (2020); Bai et al. (2020); Bag et al (2020); Luthra et al. (2020); Machado et al. (2020); Mastos et al (2020); Khanzode et al. (2020); Bag and Pretorius (2020); Ghobakhloo, M. (2020); Pinzone et al. (2020)	**SDG#8:** substantially reduce the proportion of youth not in employment, education, or training (8.6); **SDG#9:** Upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries (9.5); **SDG#12:** support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production (12.a);
	10	Society conditions	Stock et al. (2018); Luthra and Mangla (2018); Braccini and Margherita (2018); Murmura and Bravi (2018);Raut et al. (2019); Nascimento et al. (2019); Varela et al. (2020); Chiappetta Jabbour et al (2020); Bai et al. (2020); Machado et al. (2020); Ghobakhloo (2020)	**SDG#10:** empower and promote the social and economic inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion or economic or other status (10.2), ensure equal opportunity and reduce inequalities of outcome, including (10.3).