Sustainable Production and Consumption

Theorizing the Principles of Sustainable Production in the context of Circular Economy and Industry 4.0.

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Theorizing the Principles of Sustainable Production in the context of Circular Economy and Industry 4.0.

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Abstract:

The concept of Sustainable Production is evolving with changes triggered by the emergence of new economic and industrial models such as Circular Economy and Industry 4.0. However, most studies that currently link these concepts are based on the principles of Sustainable Production defined 20 years ago. Therefore, the primary aim of this study is to redefine the principles that should govern Sustainable Production operations in the transition towards a Circular Economy and smart industry models. To this end, an initial proposal of 11 principles was shared with 11 world-class experts (academics and practitioners) and a consensus proposal was sought through a Delphi Panel. Ten principles emerged from this study, which were evaluated by experts according to criteria of significance, parsimony, semantic consistency and empirical adequacy. Additionally, to study the relationships between the ten principles, the Interpretative Structural Model (ISM) technique was applied. The ISM technique identified which principles are independent of or dependent on each other and established relationships between the principles. The findings suggest that Principle 5 ("*Prioritize employees' well-being*"), Principle 6 ("*Enhance management commitment to sustainability*"), Principle 9 ("*Measure and optimize sustainable processes*") and Principle 10 ("*Boost the use of sustainable technologies*") help to establish an ideal context to enhance the development of the rest of the principles that characterize Sustainable Production. The presentation of the ten principles opens new possibilities for researchers while helping managers to better understand sustainability in terms of production and, therefore contribute to achieving SDG 12.

Keywords: Sustainable Production; Principles; Circular Economy; Industry 4.0; Interpretive Structural Modeling; Delphi Panel.

1. Introduction

Although the environmental performance of industries has improved in recent years, industrial activities continue to generate large amounts of waste and pollution, damaging the environment (European Environmental Agenda, 2019; Tanco et al., 2021). However, most companies have not yet made the transformational changes needed to truly integrate environmental and social sustainability into the way they do business (Bocken and Short, 2021). Therefore, ensuring patterns of sustainable consumption and production is one of the 17 Sustainable Development Goals (SDG) adopted by the United Nations as part of the 2030 Agenda for Sustainable Development (United Nations. General Assembly, 2015). The concept of Sustainable Development (SD) was defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987).

Industrial Ecology (IE) emerged in the late 1980s as one approach to the green economy to serve as a guide for the transformation of industrial systems towards SD (Gunasekaran and Spalanzani, 2012; Saavedra et al., 2018); i.e., to guide production strategies towards Sustainable Production (SP). Nowadays, the concept of Circular Economy (CE) is understood as a continuity and extension of the IE concept (Saavedra et al., 2018; Suárez-Eiroa et al., 2019). "The objective of the Circular Economy is to maintain the values and manage stocks of assets from natural, cultural, human, manufactured to financial stocks” (Walter R. Stahel and MacArthur, 2019). CE has been proposed as a very promising concept to guide the achievement of sustainability (Betancourt Morales and Zartha Sossa, 2020), especially for manufacturers (Acerbi and Taisch, 2020).

Furthermore, the implementation of sustainable practices could be enhanced by the implementation of Industry 4.0 technologies, also called "the fourth industrial revolution" (Kagermann and Wahlster, 2013). This concept proposes a new scenario for production that combines information and communication technologies with digital manufacturing technologies (Kang et al., 2016).

Both Industry 4.0 and CE have grown significantly in the last decade, with many studies analyzing their relationship (Laskurain-Iturbe et al., 2021; Nascimento et al., 2019). In general, these studies discuss how the different technologies help to implement different CE strategies; i.e., reducing material, energy, and waste flows. In particular, technologies are investigated to support either the physical implementation of circular strategies in manufacturing or the decision-making process to determine the most appropriate strategy (Acerbi and Taisch, 2020). Many studies have concluded that the implementation of CE strategies in production, i.e., remanufacturing and recycling, can be enhanced by adopting I4.0 technologies (Acerbi and Taisch, 2020).

Additionally, there are numerous examples in the literature that study the link between CE and sustainability concepts (Bertassini et al., 2021; Schöggl et al., 2020) and the relationship between Industry 4.0 and sustainability (Gollavilli et al., 2020; Yadav et al., 2020). A survey carried out in Brazilian companies (Satyro et al., 2022) concluded that, in general, the first motivation for the implementation of Industry 4.0 is linked more closely to productivity and competitive improvements than to improvements related to sustainability (more specifically concerning its social dimension). These same authors warn of the need to better understand the role of promoting and incorporating new technologies in the context of Sustainable Production.

Despite recent exponential growth in the literature on sustainability in production, the concept of Sustainable Production is more than 20 years old (Lowell Center for Sustainable Production, 1998; O’Brien, 1999; Veleva and Ellenbecker, 2001). More definitions of this same concept have recently been proposed (EPA, 2018; Moldavska and Welo, 2017). Moldavska and Welo (2017) concluded that a unified understanding of the concept of sustainable manufacturing had not yet been reached, which demonstrates the intrinsic complexity of this concept (Ciliberto et al. 2021). It also helps us to understand why it is difficult for organizations to make progress in terms of sustainability (Alayón et al., 2017).

Recent studies consider Green-circular premium and Sustainability certifications as effective organizational approaches to leverage sustainability as a competitive advantage factor (Appolloni et al., 2022). Currently, environmental management systems (EMSs) are used by most organizations to fulfill national and/or international environmental standards and ensure a comprehensive assessment of their processes and their impact on the environment. While the latest revision of ISO 14001 (2015) offers opportunities to align and manage initiatives such as the use of a life cycle perspective, circular economy strategies or stakeholder interactions that go beyond operational optimizations, it is still unclear how companies can integrate circular and sustainability principles into EMSs (Kristensen et al., 2021).

The concept of SP goes beyond setting and assessing environmental, economic, and social objectives for processes and products (Bonvoisin et al. 2017); it also involves the interaction between production systems. From this perspective, it is easy to understand that summarizing the meaning of Sustainable Production in a few sentences is complicated. This can give rise to multiple interpretations with academic and practical consequences (difficulty in understanding and applying the concept, difficulty in carrying out comparative case studies related to SP, and lack of alignment and focus in the way of evaluating SP, among others). For manufacturing firms, it is not clear how companies can adequately adapt their production systems to sustainability requirements (Waltersmann et al., 2019), constituting a gap that needs to be addressed.

Veleva and Ellenbecker (2001) wrote nine principles of Sustainable Production, describing the characteristics of SP in detail. These principles included sustainable attributes for product, materials, work tasks, management style and people management. However, they are based on a definition of SP that was built under a linear mode of production. More recently, Suárez-Eiroa et al. (2019) proposed a set of seven principles of circular economy for sustainable development. The core principles presented by the authors are closing the system, maintaining resource value within the system and reducing the system size. However, the role of social goals for CE was not considered while defining the principles. In the same context, Velenturf and Purnell (2021) defined principles for a sustainable circular economy. The list consists of ten principles, but only two are mentioned regarding production, i.e. design for circularity and circular business models. Additionally, these studies are focused on CE, with no reference to the new technologies proposed in Industry 4.0.

Consequently, the concept of Sustainable Production is evolving, immersed in a changing context and with the emergence of new paradigms (Hussain and Jahanzaib, 2018). However, to the best of our knowledge, most studies linking the concepts of Circular Economy, Industry 4.0 and Sustainability are based on the definitions of Sustainable Production principles identified 20 years ago. While these definitions are quite conceptual, they constitute an important guide to help companies move steadily towards more Sustainable Production (Alayón et al., 2017). In this new context of CE and Industry 4.0, a common understanding of Sustainable Production principles is essential as a point of departure for studying how manufacturers can make their operations more sustainable (Alayón et al. 2017). Additionally, the potential relationships between the principles of SP are under-represented in literature.

In order to address the above-mentioned gaps in the academic literature, this study contributes to the field of production by addressing the following research questions:

RQ1. *What are the principles of Sustainable Production in the context of Circular Economy and Industry 4.0?*

RQ2. *How are these principles interrelated?*

Therefore, this study analyzes the information available in the literature on Sustainable Production and proposes ten principles for SP in the context of Circular Economy and Industry 4.0 derived from an update of the nine principles of SP presented by Veleva and Ellenbecker (2001). Eleven principles were initially proposed and subsequently validated by 11 experts (academics and practitioners) from around the world following the Delphi Panel method (Okoli and Pawlowski, 2004). Moreover, an Interpretative Structural Model (ISM) was used to study the possible relationships between the principles. This work has allowed us to review the existing principles and reach a consensus on principles for Sustainable Production operations in the current economic and industrial context as well as understand the interrelations among them.

One of the limitations of this study is that while defining these principles, we realized that the sustainable management of production operations should not be treated independently from the rest of the value chain. However, consumer and end-of-life issues have not been addressed because currently, they have less influence on the internal manufacturing activities and procedures used by companies (Acerbi and Taisch, 2020).

From both theoretical and managerial perspectives, this research provides three major contributions.

i. From a conceptual point of view, the definition of SP principles and the analysis of the relationships among them aim to clarify the organizational, human, and technological implications associated with Sustainable Production in the context of Circular Economy and Industry 4.0. A clear understanding of the key aspects that define SP will help researchers delve deeper into the study of how organizations can adequately adapt their production systems to sustainability requirements and even how to measure whether they are meeting those requirements.
ii. From a regulatory perspective, defining the principles of SP within the framework of a circular economy can help integrate circular and sustainability principles into EMSs. By doing so, Sustainable Production is expressed in a more visionary manner and makes it possible to identify which operational and production processes sustainability and circularity objectives should be applied.
iii. From a practical viewpoint, having clearly defined principles governing SP operations will contribute to achieving the SDG 12 target 12.8: "By 2030 ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature." In addition, knowing how these principles interact could contribute to the orderly transition of a company’s production processes to Sustainable Production.

The layout of this article is as follows. Section 2 takes a deeper look at the concept of Sustainable Production, Circular Economy, and Industry 4.0. Section 3 presents the three-step methodology used in the present study: the initial proposal of principles, the Delphi Panel process carried out, and the ISM technique. Section 4 presents an initial proposal of the principles adapted from Veleva and Ellenbecker (2001). The main results from the Delphi Panel and the ISM model are also presented in Section 4. Section 5 discusses the results, the contribution of the study to SDG 12, and the limitations of the study. Finally, Section 6 presents the conclusions and suggestions for future work.

2. Theoretical background

The literature review consists of three subsections. The first two provide the context in which the principles of Sustainable Production are defined in the present study. The third subsection reviews and discusses the prior knowledge of Sustainable Production and its principles.

2.1 Sustainable Circular Economy

Production, together with distribution and consumption, is one of the main activities of an economic system. The economic system of 20 years ago was based on a linear model, which means creating, using, and discarding everything that has been produced when no longer useful. Since the earliest definition of the concept of SP, the search for more sustainable products and processes has promoted innovations aimed at reducing the use of natural resources and reusing or recycling used materials or resources (3Rs Sustainable Production strategies). Subsequently, another three Rs were added (Recover, Redesign, Remanufacture), extending the scope of action from 3Rs to 6Rs to achieve more Sustainable Production (Joshi, K., Venkatachalam, A., Jawahir, 2006). Currently, the scientific community refers to the 9Rs strategies (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover) as the way to produce in the context of Circular Economy (Potting et al., 2017).

The term 'Circular Economy' was first coined by Pearce and Turner in 1990 (Prieto-Sandoval et al., 2018), but since 2012 has gained popularity in civil society through the work carried out by Ellen MacArthur Foundation (Loiseau et al., 2016). Today, CE is presented as an alternative to the traditional linear economic model to help society become more sustainable (Velenturf and Purnell, 2021). Korhonen et al. (2018a) are among the authors who most clearly define the Circular Economy from the perspective of sustainability. From the perspective of SD, they defined the concept of CE scientifically as follows: *"Circular Economy is an economy constructed from societal production-consumption systems that maximizes the service produced from the linear nature-society-nature material and energy throughput flow. This is achieved by using cyclical materials flows, renewable energy sources and cascading-type energy flows."*

Some recent studies have defined CE principles for sustainable development (Suárez-Eiroa et al., 2019; Velenturf and Purnell, 2021). In these articles, the principles are defined for the three main economic activities: production, distribution and consumption. Overall, the principles defined by these authors are based on the three main principles defined by the Ellen MacArthur Foundation (2021), namely: eliminate waste and pollution, circulate products and materials by closing production cycles, and regenerate nature. These principles are all driven by design (EMF, 2021a) since the design for circularity constitutes one of the main principles for transforming production (Velenturf and Purnell, 2021; Suárez-Eiroa et al., 2019).

The studies mentioned before offer some practical strategies related to circular design, such as designing new business models, designing transparent, reproducible, scalable products to build the same products in other places from local resources, designing new methodologies to ensure continuous improvement, and thinking about practical utilities and consumer preferences. In this study, the definition of CE proposed by Korhonen et al. (2018b) and the principles of CE from the articles by Velenturf and Purnell (2021) and Suárez-Eiroa et al. (2019) serve to contextualize the economy in which the updated principles of SP should be deployed.

2.2 Contribution of Industry 4.0 to Sustainable Circular Economy

Since 2011, the so-called "Fourth Industrial Revolution," or Industry 4.0 (Kagermann and Wahlster, 2013), has been proposing a new scenario for manufacturing that combines information and communication technologies with digital manufacturing technologies (Kang et al., 2016). In recent years, authors have identified this new manufacturing approach as an enabling scenario for a more sustainable industry (Machado et al., 2020; Gupta et al., 2021).

The central idea of Industry 4.0 is to use emerging technologies so that all industrial processes are integrated, thus making production work flexible, efficient and intelligent with high quality and low cost (Machado et al., 2020). The major Industry 4.0 technologies include Additive Manufacturing (AM), Cyber-Physical Systems (CPS), Blockchain, Artificial Intelligence, Artificial Vision, Big Data & Advanced Analytics, Cybersecurity, Internet of Things, Robotics, and Virtual and Augmented Reality (Laskurain-Iturbe et al., 2021). These technologies help companies to improve circularity since they contribute to reducing material and energy consumption and the generation of waste and emissions (Laskurain-Iturbe et al., 2021). In this vein, a literature review conducted by Acerbi and Taisch (2020) concluded that Additive Manufacturing constitutes one of the most diffused I4.0 technologies. AM has been studied by recycling materials such as plastic, metal and organic waste. Additionally, it has been implemented to design circular products to facilitate resource circularity at products end-of-life. Comparing AM to conventional production, it has been shown to be more energy and cost-efficient (Acerbi and Taisch, 2020). Other CE strategies in production such as resource recovery, recycling and waste minimization (Fisher et al., 2018) have been also supported by the implementation of digital technologies.

Regarding the link between Industry 4.0 and sustainability, Lopes de Sousa Jabbour et al. (2018) suggested that Industry 4.0 technologies contribute to the decision-making process regarding sustainable operations management and the development of new business models by integrating value chains through data collection and sharing. Machado et al. (2020) presented evidence that corroborates that reinforcing the integration of horizontal and vertical systems and real-time data management favors the closing of circles in productive processes and product life-cycle management. The same authors also highlighted that modelling and simulating the activities that occur throughout the product value chain are methods that can help decision-making for sustainable process improvements.

However, not everything related to Industry 4.0 technologies seems to favor sustainability. For example, Rejeski et al. (2018) argued that Additive Manufacturing had the potential to contribute to sustainability through its combination with IoT technology, but the full implications of its realization were still difficult to assess. More recently, some authors identified gaps in the contribution of these technologies to the social dimension of sustainability (Machado et al., 2020). There is still a lack of knowledge and uncertainty in the relationship between Industry 4.0 technologies and sustainability (Bai et al., 2020; Satyro et al., 2022).

2.3 Sustainable Production

Already in 1999, O'Brien recognized the need to develop SP systems that minimized the pressing environmental issues at the time. O'Brien (1999) described generic characteristics that he considered SP should meet. "*Environmental consciousness throughout the culture of the whole organization, both product and process design addressing sustainable issues, maximum use and reuse of recycled components and materials, product life-cycle concepts applied to the whole manufacturing system, factories reconfigurable to respond flexibly to changes in products, volumes, process technologies etc., organization lean as well as clean, re-engineering addressing environmental and sustainable issues, Kaizen activities addressing environmental issues, metrics according sustainability issues and use of clean technologies* (O'Brien 1999)."

Veleva and Ellenbecker (2001) presented a framework and a methodology for measuring SP by introducing the principles that would govern the concept of SP. They based their SP definition on an earlier definition by the Lowell Center for Sustainable Production (LCSP), University of Massachusetts Lowell (Lowell Center for Sustainable Production, 1998). LCSP defines Sustainable Production as *"the creation of goods and services using processes and systems that are non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for employees, communities and consumers; and socially and creatively rewarding for all working people".* They also presented nine principles that would determine the basis for the development of SP (Veleva and Ellenbecker, 2001). These principles are shown in Table 1.

Table 1. Principles of Sustainable Production (Extracted from Veleva and Ellenbecker (2001))

	Principles of Sustainable Production
1	Products and packaging are designed to be safe and ecologically sound throughout their life cycles; services are designed to be safe and ecologically sound.
2	Wastes and ecologically incompatible byproducts are continuously reduced, eliminated, or recycled.
3	Energy and materials are conserved, and the forms of energy and materials used are most appropriate for the desired ends.
4	Chemical substances, physical agents, technologies, and work practices that present hazards to human health or the environment are continuously reduced or eliminated.
5	Workplaces are designed to minimize or eliminate physical, chemical, biological, and ergonomic hazards.
6	Management is committed to an open, participatory process of continuous evaluation and improvement, focused on the long-term economic performance of the firm.
7	Work is organized to conserve and enhance the efficiency and creativity of employees.
8	The security and well-being of all employees are a priority, as is the continuous development of their talents and capacities.
9	The communities around workplaces are respected and enhanced economically, socially, culturally and physically; equity and fairness are promoted.

Recently, more definitions of this same concept of SP have been proposed (EPA, 2018; Bonvoisin et al., 2017). Specifically, in 2017, Moldavska and Welo (2017) analyzed different definitions of "sustainable manufacturing," as a concept similar to SP. In their article, Moldavska and Welo (2017) concluded that a unified understanding of the concept of sustainable manufacturing had not yet been reached and that there was a lack of unity in the terminology and vocabulary used to define this concept. They further argued that it is important to differentiate between an organization's actual contribution to sustainability and the existence of sustainability-oriented organizational structures and management instruments, which in itself is no guarantee of sustainability (Moldavska and Welo, 2017).

As observed in the present literature review, the movement of industry towards sustainability requires important changes that range from behavior to technology. These changes must be considered from a holistic perspective, even if acting locally (Despeisse et al., 2013). The evolution of the concept and operationalization of green economy and green production over the last 20 years, together with a manufacturing scenario that has been moving towards greater factory digitalization and more efficient and intelligent manufacturing in the last ten years, suggests the need to adapt the principles governing Sustainable Production to the new economic and industrial context.

Consequently, we consider it pertinent to analyze, adapt and update the principles of SP identified by Veleva and Ellenbecker in 2001 to fit the current economic and industrial context and to study the potential relationships between the new defined principles of Sustainable Production.

Figure 1 represents the relationship between the three pillars of sustainability. It suggests that the economy and society are embedded into the environment, which means that any decision towards sustainability should be considered holistically. In this scenario, companies are part of this embedded system and therefore should adapt their production processes to fit the principles of a sustainable and circular economy. To achieve this, today's organisations are increasingly using smart technologies.

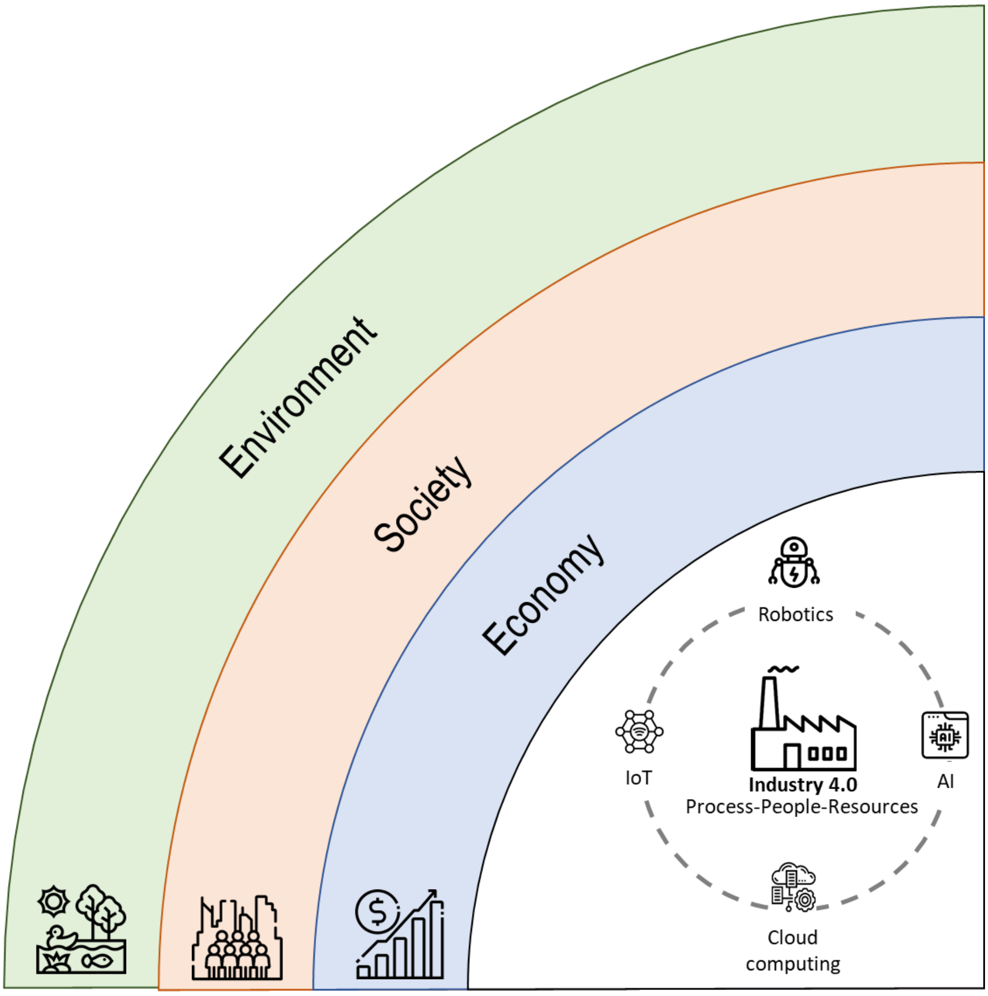

Figure 1. Sustainability-related concepts in a CE and Industry 4.0 context (icons extracted from www.flaticon.com)

3. Methodology

The main objective of this study is to identify the principles of Sustainable Production in the context of Circular Economy and Industry 4.0. It also proposes a theoretical model that establishes the relationships between these principles. To address these two objectives, we followed a three-phase research methodology which included an extensive review of the extant literature on Sustainable Production, a Delphi study, and an ISM and MICMAC analysis. The methodology used to present an updated version of the SP principles is presented in Figure 2.

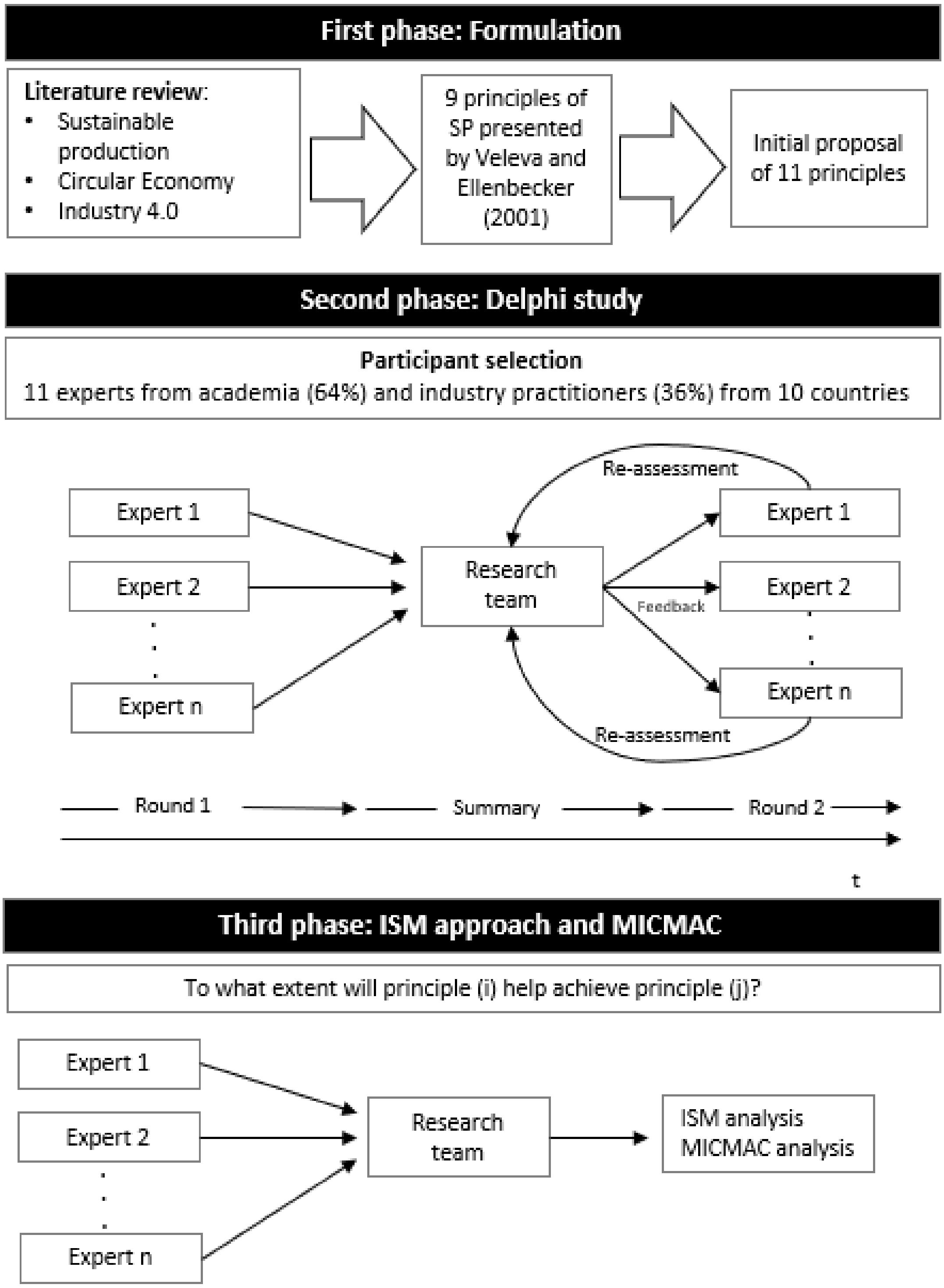

Figure 2. Phases followed by the present study (adapted from Gebhardt et al., 2022).

3.1 Phase 1: Literature review

According to Suárez-Eiroa et al. (2019), the principles of a system are understood as a set of basic characteristics necessary to understand and operate the system. An operational principle could be used to describe theoretical strategies that explain how a system operates. In this article, we consider the definition of principle to encompass both ideas.

To develop the SP principles, we first conducted a literature review based on the snowball strategy focused on the research already carried out on Sustainable Production and the new economic and industrial context related to production.

Firstly, the keywords "Sustainable Production" and "sustainable manufacturing" were used to search for papers in the Web of Science and Scopus database. Subsequently, the 'snowball' technique was applied since it allows citations to be traced backwards and forward to locate leads to other related articles (Lim et al., 2018).

The snowball strategy was selected since it involved reviewing all bibliographical references cited in the literature specific to the research topic being addressed (Wohlin, 2014). This way of conducting the literature review benefited not only from examining the initial list of references but also from complementing it by examining where the documents were cited (Suárez-Eiroa B. et al., 2019). Snowballing constitutes a better method for expanding systematic literature investigations than a database search (Wohlin, 2014).

Initially, a proposal of 11 SP principles was presented based on the nine principles of SP defined by Veleva and Ellenbecker (2001). These principles were defined by applying a critical analysis of the literature and the knowledge and experience of the authors, trying to coherently integrate what was already known with the latest scientific approaches to the subject in question.

3.2 Phase 2: Delphi method

To validate the initial proposal of principles, a Delphi study was conducted. In comparison with other methods that could have been implemented for this research, i.e survey, the Delphi method is a stronger methodology for a rigorous query of experts (Okoli and Pawlowski, 2004).

In the absence of prior knowledge, experts' assessments and opinions can be gathered using the Delphi method to evaluate a phenomenon (Garza-Reyes et al., 2019). Furthermore, in this study, the Delphi method makes it possible to collect richer data, which leads to a deeper understanding of the topics (Okoli and Pawlowski, 2004). It also provides access to the opinion of multiple experts from diverse professional backgrounds with reasonable effort (Prieto-Sandoval et al., 2018b). It is characterized by iteration, statistical group response, controlled feedback, and anonymity (Habibi et al., 2015). This anonymous participation avoids group thinking; therefore, it gives experts the freedom to express their views. Another advantage is that the iterations allow specialists to reassess their initial opinions on the proposed topic. Through a series of iterative surveys or meetings, the group comes to a consensus. Opinions are gathered, synthesized, and given to the group for further consideration in each iteration (Hutchins et al., 2019).

3.2.1 Participant selection

The ideal number of participants in a study using the Delphi method is between six and 12 (Hogarth, 1978), especially if experts with different professional backgrounds are invited to participate (Clayton, 1997). For this study, 43 experts were invited to participate in the Delphi study, which included specialists from different universities and consultancy firms.

The academic experts were selected considering two criteria: first, the area of expertise, which was fundamentally linked to the topics of Industry 4.0 and sustainable supply chain; and second, their research was significant in terms of academic contributions to international journals dealing with these topics. Industry experts were professionals with practical experience in the area of Circular Economy and Sustainability and who took part as experts in the "From linear to Circular Economy" course organized by the Ellen MacArthur Foundation (EMF, 2021b).

In total, 15 experts agreed to participate in the study (35% acceptance rate), which involved 11 academic experts and four practitioners. The experts work in different countries: Spain, England, India, Italy, USA, Sweden, Austria, Germany, Namibia, and the Netherlands. Of the initial 15 participants, only 11 completed the two rounds, as time constraints prevented four participants from finishing the Delphi rounds. The experts were informed of the goal as soon as they confirmed their participation and were given instructions on how to reply to the Delphi rounds online.

3.2.2 **Delphi structure**

The objective of the experts' panel was to evaluate and reach a consensus on the initial proposal of principles, fulfilling the following evaluation criteria (Fawcett, 2005): significance, internal consistency, parsimony and empirical adequacy. The significance criterion required justifying the importance of defining the principles for the production area. The parsimony criterion meant that the fewer principles needed to fully explain the phenomena of interest, the better. The criterion of internal consistency required all principles to be congruent, reflecting semantic clarity and coherence. The criterion of empirical adequacy required the definitions to be consistent with the empirical evidence. The data used to determine the empirical adequacy of a theory could come from multiple personal experiences of an individual or similar personal experiences of several individuals (Fawcett, 2005).

To achieve the evaluation of the principles the experts were asked the following questions:

i. Are the SP principles stated clearly and concisely? Do you think that any principle is missing or surplus? Justify your response (parsimony criterion)

ii. Do you consider that all criteria are semantically clear and consistent (different terms are not used for the same concept nor are different meanings attributed to the same concept) with the theory and concepts of sustainability and Circular Economy? (criterion of internal consistency)

To evaluate the empirical adequacy criterion, the experts were asked to answer the previous questions considering that the assertions of each principle had to be congruent both with their knowledge about the topic and with their empirical evidence.

Two online Delphi rounds were performed. The Delphi process ended when consensus was reached. The updated set of principles for Sustainable Production from the experts' consensus is discussed in the following section.

3.3 Phase 3: ISM Model and MICMAC analysis

To address the second research question, the Interpretive Structural Modeling (ISM) method was employed. This technique is used to depict the system structure in terms of element relationships (Sushil, 2012). A MICMAC analysis was also performed, which included a graph that categorizes the factors under study according to their driving and dependent power. MICMAC analysis was utilized to classify the components and validate the interpretative structural model factors (Ahmad et al., 2019).

The ISM technique was selected above other methods since it offers a distinctive method for building the structural hierarchy and exploring the dynamic relationship within a complex problem (Vimal et al., 2022) such as the one under study in this research. ISM analyzes the ordered relationship between the various aspects of a system and interprets the particular relationships between the elements that are based on the judgements of a group of experts who determine the correlation between them (Vimal et al., 2022).

J.N. Warfield developed ISM as a computer-assisted process for studying complex issues and organizing them into clearly understandable phrases and directed graphs (Poduval et al., 2015). In the extant literature, the ISM approach for analyzing systems and problems in various fields (such as TQM, supply chain management, knowledge management, logistics, and productivity improvement) is well documented (Attri et al., 2013). Recently this technique has been used to map interrelationships between variables such as barriers regarding sustainability adoption (Ghobakhloo and Fathi, 2021; Sarkar et al., 2021; Zayed and Yaseen, 2021).

The ISM technique was used to develop a model that structures the relationships of the principles encountered during the Delphi process. Therefore, the experts from the Delphi Panel who agreed to participate in this phase of the study were asked the following question:

To what extent will principle (i) help achieve principle (j)? (Sushil, 2012)

This technique should be implemented by following a set of well-defined steps in a specified order. Each step is important and related to the previous step, and therefore none can be bypassed. The steps followed for the ISM method are as follows (Gani et al., 2022):

Step I: Based on the experts' comments, the Initial Reachability Matrix (IRM) was completed. The IRM shows the possibility of interaction between the principles, which was scaled in this study with a 0- if no interaction exists, 2- low interaction, and 4- high interaction. The matrix was then transformed into a new matrix having 0s and 1s.

Step II: Modify IRM by checking it for transitivity, (i.e., if A leads to B and B leads to C, then A leads to C). Once the transitive links were checked, the IRM was transformed into a Final Reachability Matrix (FRM).

Step III: For each principle, antecedent sets and reachability sets were derived. Through a series of revisions based on antecedent and reachability sets, the FRM was partitioned into several levels.

Step IV: Based on the level portioning of the principles, a digraph plot was prepared by removing transitive links.

Step V: Finally, the digraph was converted into an ISM model by adding statements in place of nodes.

4. Results

This section presents the initial proposal of the Sustainable Production Principles, followed by the results from the Delphi Panel and the ISM analysis.

4.1 Initial Proposal of SP Principles

The principles in the present study set out to govern Sustainable Production operations in the mindset of the transition toward a Circular Economy and smart industry model. These principles should reflect the basic characteristics of Sustainable Production considering the following dimensions: (1) energy and material use (resources), (2) natural environment, (3) social justice and community development, (4) economic performance, (5) workers, and (6) products (Veleva and Ellenbecker, 2001). These six dimensions were considered while proposing the initial proposal of 11 principles. Based on a literature review and the experience of the research team, the nine principles in Veleva and Ellenbecker (2001) were enhanced, integrating some and adding new ones (see Table 2). A more detailed explanation of this for the updated principles is presented below.

Veleva and Ellenbecker's (2011) principles were used as a starting point for developing a new set of principles based on the definition of Sustainable Production (Veleva and Ellenbecker, 2001). Some of the principles were adapted and new principles were added as a result of integrating the SP principles into the context of Circular Economy and Industry 4.0. For example, Veleva and Ellenbecker's (2001) environmental principles promoted the reduction, reuse and/or recycling of energy and materials (3R strategy). These principles have been the most frequent strategies to address Sustainable Production in the first years of the 21st century (Barreiro-Gen and Lozano, 2020). However, these 3R strategies were considered to be insufficient to address sustainability in a Circular Economy context. Therefore, one of the principles already stated in the proposal by Veleva and Ellenbecker (2001) was adapted to include the broader 9R strategies (Potting et al., 2017), which also include the possibility of Refusing some products and Rethinking the product and/or processes to achieve a more intensive use, (see principles 1,2,3 in the initial proposal).

Moreover, the social dimension of sustainability is not only about employee health care and capacity building, but also the importance of strengthening the criteria of inclusion and diversity in organizations, considering social class, gender, age group, cultural identity, disability, etc. across all areas of the company (Stock et al., 2018) (see principle 5 and 6 in the initial proposal).

At the same time, the concept of Sustainable Circular Economy is understood from a holistic, whole-system perspective, taking into account the environmental, social and human aspects of the local context (Velenturf and Purnell, 2021). Production or manufacturing are part of the value chain of a product or service and, therefore, should never be seen as a system isolated from the rest of the value chain. This idea was included as a part of a new principle of SP (see principle 8 in the initial proposal).

Furthermore, the successful transition to a CE paradigm requires an industrial metabolism to close loops across different value chains (Prieto-Sandoval et al., 2018). Chertow (2000) defines Industrial Symbiosis (IS) as "*the activity that engages traditionally separate industries in a collective approach to gain a competitive advantage involving the physical exchange of materials, energy, water and/or by-products*" (Chertow, 2000, p. 313). IS, which is part of the so-called industrial ecology, contributes to sustainability with environmental, economic and social benefits (Neves et al., 2020). In a review of scientific articles on IS, these same authors identify manufacturing as one of the sectors with the greatest presence in these studies. According to Neves et al. (2020), this is "*due to the waste that this sector generates but also to its capacity to integrate by-products and waste into its production cycle*". In accordance with these ideas, we consider that promoting inter-industry relations that involve a physical exchange of water, materials, energy, and by-products should be considered as a further principle of SP (see principle 9 in the initial proposal).

Moreover, the evolutionary perspective of the sustainability concept makes it necessary to monitor, evaluate, control and continuously adapt production operations to keep them sustainable (Dubey et al., 2017; Velenturf and Purnell, 2021) (see principle 10 in the initial proposal). Industry 4.0 boosts digitizing transversal and vertical processes, capturing, analyzing and processing data for explanatory and predictive purposes, tracking, monitoring and controling production systems, and communicating and exchanging information between different stakeholders. To this end, it is considered necessary to establish as a principle the need for the digitalization of production processes consistent with the objectives of sustainability through the use of green computer systems and green algorithms (Tyurin and Kamenskih, 2017; Lannelongue et al., 2021) (see principle 11 in the initial proposal). The adoption of other I4.0 technologies will need to be carefully evaluated to analyze their impact on sustainability in each case (Bai et al., 2020).

4.2 Results from the Delphi Panel

Based on the experts' comments, the Principles of Sustainable Production initially proposed were modified as shown in Table 2. Two rounds were carried out to reach a consensus.

Table 2. Results from the Delphi Panel

Phases	Methodology	Phases	Methodology	Phases	Methodology	Phases
Veleva and Ellenbecker (2001)	**Literature review & Research Team experience**	**Initial proposal**	**Delphi results, Literature review & Research Team experience**	**First round results**	**Delphi results, Literature review & Research Team experience**	**Second round results**
Products and packaging are designed to be safe and ecologically sound throughout their life cycles; services are designed to be safe and ecologically sound.	Enhanced	**(1) Design for circularity**	Enhanced	**(1) Design for circularity**	Maintained	**(1) Design for circularity**
Energy and materials are conserved, and the forms of energy and materials used are most appropriate for the desired ends.	Enhanced	**(2) Conserve flows of resources**	Enhanced	**(2) Conserve resources and preserve their value**	Maintained	**(2) Conserve resources and preserve their value.**
Wastes and ecologically incompatible byproducts are continuously reduced, eliminated, or recycled.	Enhanced	**(3) Follow a sustainable management of waste**	Enhanced	**(3) Manage waste sustainably**	Maintained	**(3) Manage waste sustainably**
Chemical substances, physical agents, technologies, and work	Integrated	**(4) Ensure a risk-free environment**	Divided into two	**(4) Pursue a risk-free environment**	Maintained	**(4) Pursue a risk-free environment**

practices that present hazards to human health or the environment are continuously reduced or eliminated.						
Workplaces are designed to minimize or eliminate physical, chemical, biological, and ergonomic hazards.				**(5) Prioritize employees' well-being**	Enhanced	**(5) Prioritize employees' well-being**
Management is committed to an open, participatory process of continuous evaluation and improvement, focused on the long-term economic performance of the firm.	Enhanced	**(5) Develop a sustainable organizational culture**	Integrated	**(6) Enhance management commitment to sustainability**	Enhanced	**(6) Enhance management commitment to sustainability**
Work is organized to conserve and enhance the efficiency and creativity of employees.	Integrated	**(6) Enhance a sustainable work environment**				
The security and well-being of all employees are a priority, as is the continuous development of their talents and capacities.						
The communities around workplaces are respected and enhanced economically, socially, culturally, and physically; equity and fairness are promoted.	Enhanced	**(7) Pursue a corporate social responsibility to surroundings**	Enhanced	**(7) Engage in Corporate Social Responsibility**	Enhanced	**(7) Make a positive contribution to the community**
New principles added		**(8) Embrace the value chain vision**	Enhanced	**(8) Promote value chain stakeholder collaboration**	Maintained	**(8) Promote value chain stakeholder collaboration**
		(9) Foster industrial symbiosis	Included in new principle 2			

	(10) Monitorization and control of the sustainability of processes	Enhanced	**(9) Measure and optimize sustainable processes**	Enhanced	**(9) Measure and optimize sustainable processes**
	(11) Boost the use of sustainable technologies	Enhanced	**(10) Boost the use of sustainable technologies**	Maintained	**(10) Boost the use of sustainable technologies**

During these two rounds, the principles were adjusted to meet the comments and suggestions of the experts. Some principles were integrated into one, while others were separated into new principles for better understanding.

4.2.1 First Round of the Delphi Panel:

Figure 3 summarizes the performance of the first round of the Delphi Panel. The columns represent the % of experts that agree with the statement presented in questions 1 (Q1) and question 2 (Q2) for each principle and the lines represent the percentage of experts who make comments on each principle. Once all the experts' comments were collected, the research team identified the main points to address in order to reformulate the principles and tried to integrate the new ideas suggested by the experts. Table 2 shows that all the principles were changed. However, there were some in which deeper changes were made. As shown in Figure 3, Principles 3 ("*Follow sustainable management of waste"*) and 4 ("*Ensure a risk-free environment"*) were the less clear (concerning question 1). Therefore, Principle 4 was divided into two new principles ("Pursue a risk-free environment") & ("*Prioritize employees' well-being*"). Principles 5 ("*Develop a sustainable organizational culture*") and 6 ("*Enhance a sustainable work environment*") were integrated into a new principle (*"Enhance management commitment with sustainability"*). Furthermore, Principle 9 ("*Foster industrial symbiosis"*) was eliminated because the idea of industrial symbiosis was considered a way to achieve Principle 2 (*"Conserve resources and preserve their value"*).

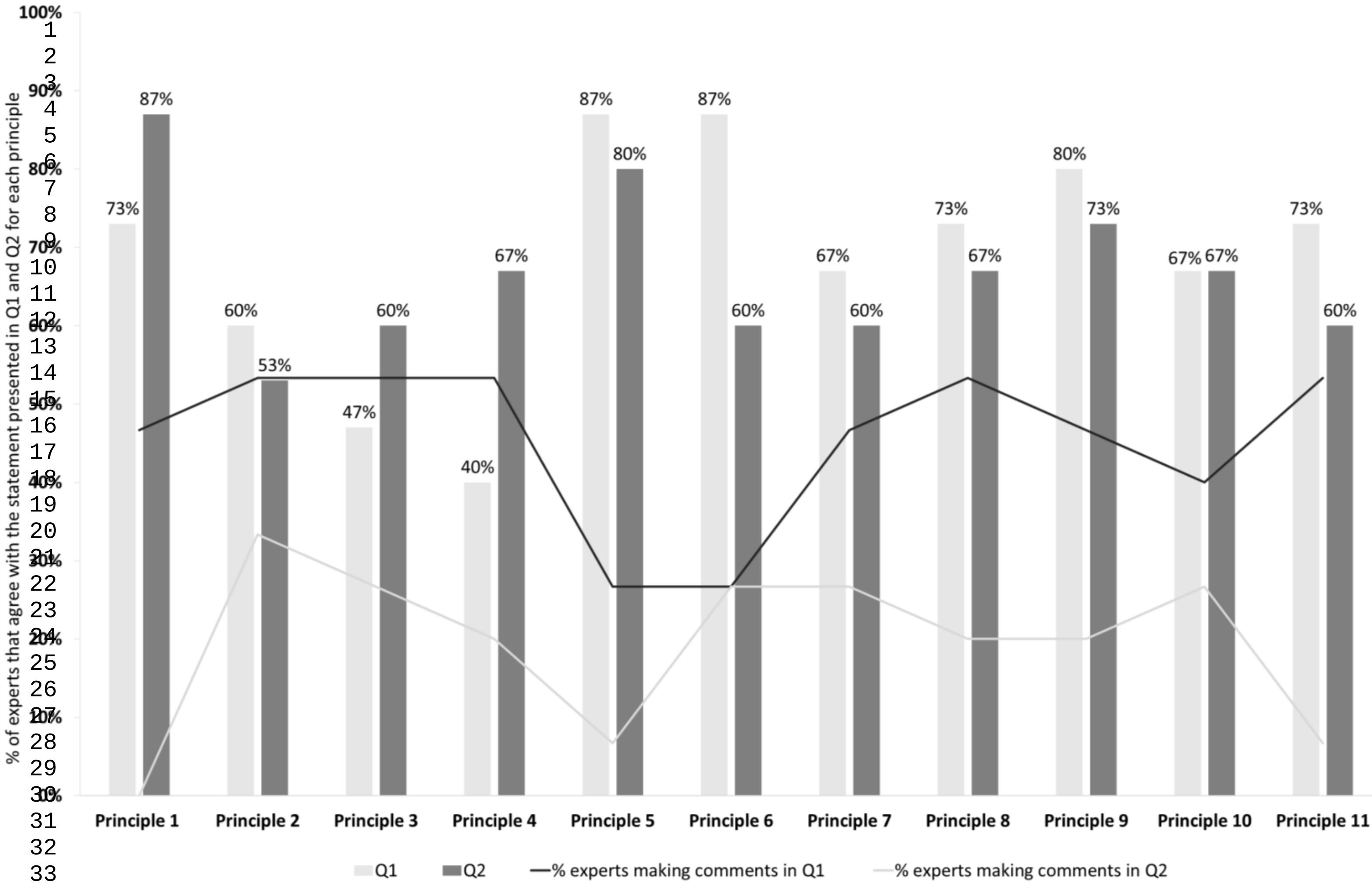

Figure 3. First round of Delphi Panel

According to the experts, most of the principles were consistent with the theory and concepts about sustainability and Circular Economy (second question).

4.2.2 Second Round of the Delphi Panel:

In the second round, the participants were asked the question *"Do you consider that this principle is stated clearly and concisely and covers all the relevant aspects regarding its definition?"* Since the majority of the experts agreed on the question proposed (Figure 4), only minor changes were made to the final proposal of principles.

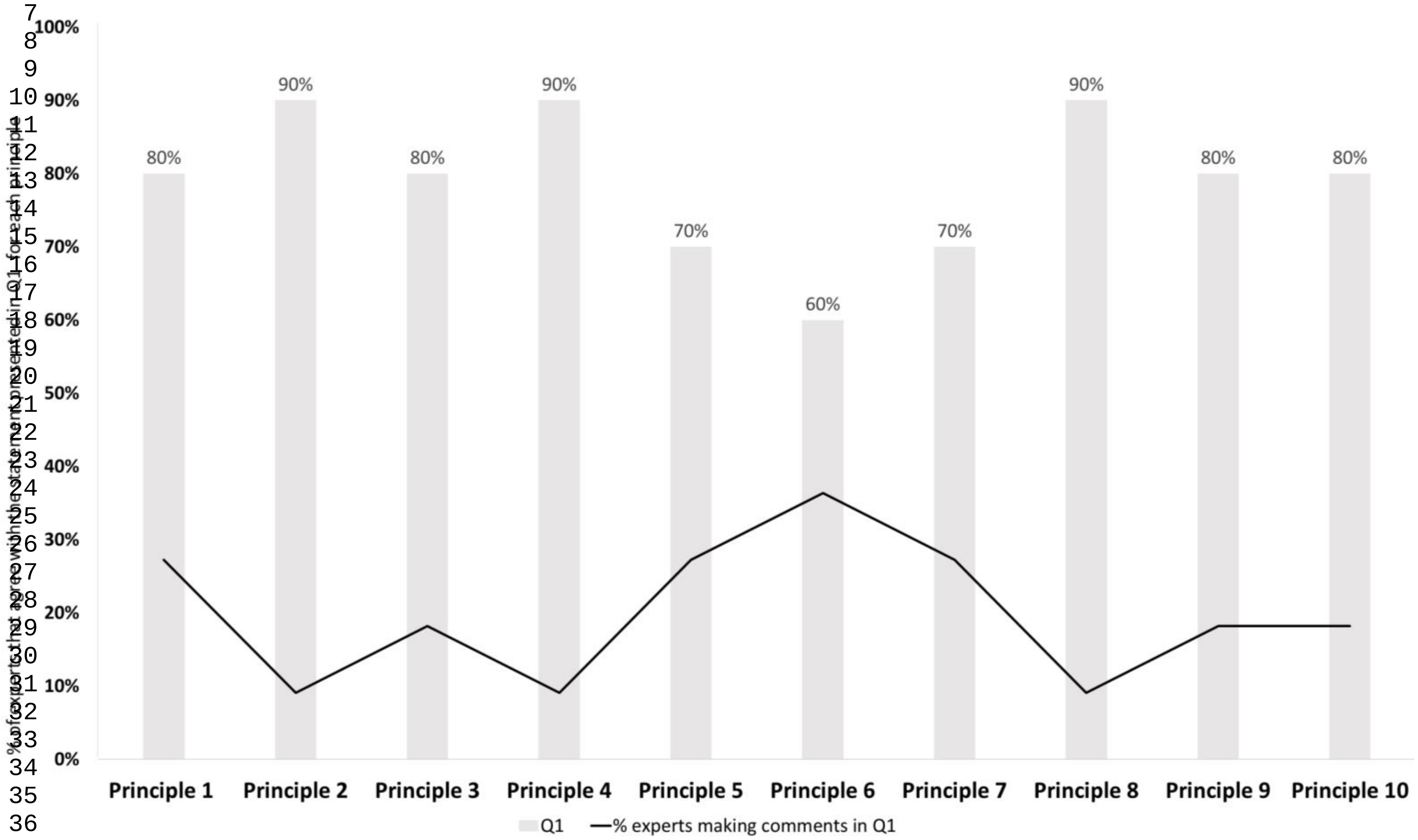

Figure 4. Second round of the Delphi Panel

Principle 6 (*"Enhance management commitment with sustainability"*) received various comments from the experts, as shown in Figure 4. Thus, this principle was reformulated to adjust the definition to the suggestions proposed. Minor changes were made in this second round to Principles 5 ("Prioritize employees' well-being"), 7 (*"Engage in Corporate Social Responsibility"*) and 9 (*"Measure and optimize sustainable processes"*). Therefore, since the majority of experts agreed with the statement presented in the question, the Delphi study was considered completed in this second round.

As shown in Table 3, the final version of the principles consisted of ten principles of Sustainable Production that were considered for the ISM analysis.

Table 3. Principles of Sustainable Production

Final version of Sustainable Production Principles
(1) Design for circularity. Design processes, products, and packing to consume minimum natural resources and energy to sustain the ecosystem's regenerative capacities. Follow design for disassembly to allow - if possible - for recycling, repairing, reconditioning, refurbishing, or remanufacturing.
(2) Conserve resources and preserve their value. Use the appropriate natural resources and energy for the desired sustainable goals. Preserve the value of resources for as long as possible within production facilities (internal recirculation) and consider the concept of industrial symbiosis to circulate resources (external recirculation).
(3) Manage waste sustainably. Emphasize waste-prevention activities by reintroducing resources within the intended flow. For resources that reach the waste management stage, use the waste management hierarchy following these strategies: reduce waste, then reuse and recycle, minimizing all disposal routes, including landfilling and waste to energy.
(4) Pursue a risk-free environment. Reduce or eliminate chemical substances, physical agents, and technologies that present a risk to the environment. Reduce GHGs emissions to reach net-zero emissions.
(5) Prioritize employees' well-being. Embed employee safety and well-being in the day-to-day work. Choose practices and workplaces that preserve the physical, functional, and psychological comfort of employees.
(6) Enhance management commitment to sustainability. Establish an organizational culture enabling high sustainability performance. Empower employees and develop their talents. Promote diversity, equity and inclusion in the workplace.
(7) Make a positive contribution to the community. Contribute to better economic, environmental, social, cultural, and physical outcomes of the communities in which the company operates and in those where its decisions can have an impact.
(8) Promote value chain stakeholder collaboration. Establish fluid communication and collaboration with all the stakeholders of your value chain to make processes and products more sustainable.
(9) Measure and optimize sustainable processes. Define a set of "Key Performance Indicators" to optimize production processes. Monitor short- and long-term sustainability performance of the production system by encouraging digitalization.
(10) Boost the use of sustainable technologies. Improve existing technologies with more sustainable alternatives, and provide information on both the potential benefits and risks to Sustainable Production. Consider Best Available Techniques; these techniques involve both the technology used and the design, construction, maintenance, and operation of the installation.

4.3 ISM analysis and results

Based on the IRM (Table A1, Appendix A) completed by the experts, the ISM method was applied, and a digraph plot was created as shown in Figure 5. The arrows further link the principles based on the relations derived from the IRM (Gani et al., 2022). It is important to highlight that three pair relationships, PR4-PR5, PR6-PR5 and PR8-PR1, were eliminated at this stage since the ISM follows a bottom-up approach, and the presence of these links would have generated top-down links in the final ISM model (Vimal et al., 2022).

The bottom-up approach that the ISM follows is based on the Level Partition done in the Reachability Matrix. The elements are arranged graphically in levels and the directed links are drawn as per the relationships shown in the reachability matrix (Sushil, 2012). The elements in the top level of the hierarchy will not reach any elements above their own level.

Figure 5 shows the ISM model, which indicates the significant impact of Principles 5 ("*Prioritize employees' well-being*"), 6 ("*Enhance management commitment to sustainability*"), 9 ("M*easure and optimize sustainable processes*"), and 10 ("*Boost the use of sustainable technologies*") on the others.

The IRM was transformed into an FRM (Table A2, Appendix A) after checking the transitive links. From this matrix, the reachability and antecedents set were performed as presented in Table 4. For a given principle, the "reachability set" included the principle itself and the principles it may affect, whereas the "antecedent set" consisted of the principle itself and the principles affecting it.

Subsequently, the intersection of both sets was obtained for all principles and the level of each principle was determined. The principles with the same reachability and intersection set occupy the first level (Poduval et al., 2015). To assess the next level, the first-level principles were then isolated from the other principles for the next stage-iteration. The method was then repeated to assign a level to each principle. Table 4 also shows the level partitioning of the principles to be placed in the ISM model.

Table 4. Level partitioning of Sustainable Production Principles

Principles	Reachability set	Antecedent set	Intersection set	Levels
PR 1	[1,2,3,7,8]	[1,6,7,8,9,10]	[1]	II
PR 2	[2,3,7,8]	[1,2,3,4,6,7,8,9,10]	[2,3,7,8]	I
PR 3	[2,3,7,8]	[1,2,3,4,5,6,7,8,9,10]	[2,3,7,8]	I
PR 4	[2,3,4,5,6,7,8]	[4,5,6,9,10]	[4,5,6]	II
PR 5	[3,4,5,6,7,8,9,10]	[4,5,6,9]	[5]	IV
PR 6	[1,2,3,4,5,6,7,8,9,10]	[4,5,6,9,10]	[5,6,9,10]	III
PR 7	[1,2,3,7,8]	[1,2,3,4,5,6,7,8,9,10]	[1,2,3,7,8]	I
PR 8	[1,2,3,7,8]	[1,2,3,4,5,6,7,8,9,10]	[1,2,3,7,8]	I
PR 9	[1,2,3,4,5,6,7,8,9,10]	[5,6,9,10]	[5,6,9,10]	III
PR 10	[1,2,3,4,6,7,8,9,10]	[5,6,9,10]	[6,9,10]	III

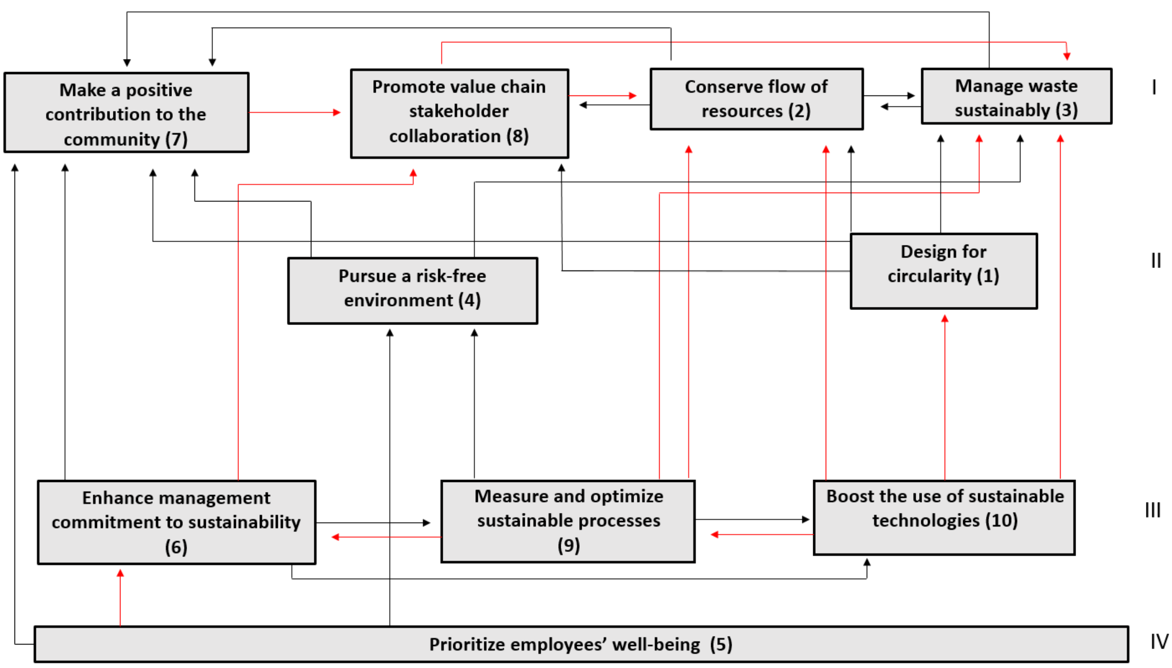

Figure 5. ISM for Sustainable Production. Interesting relationships are highlighted in red.

The ISM model (Figure 5) shows that the level partitioning resulted in a digraph consisting of four levels, where the topmost level indicates the most dependent principles and the bottommost level, the most driving principle (independent). The structural model presented in Figure 5 represents the ten principles in the four levels. In level I, Principles 7 (“*Make a positive contribution to the community”), 8 (“Promote value chain stakeholder collaboration”, 2 (“Conserve resources and preserve their value”), and 3 (Manage waste sustainably)* are dependent on the other principles. The lowest level (level IV) represents the principle that leads to achieving the principles in level I, through mediating principles (the ones in levels II and III). For this study, Principle 5 (“*Prioritize employees’ well-being”)* is located at the lowest level and Principle 6 (“*Enhance management commitment to sustainability”);* Principle 9 *(“Measure and optimize sustainable processes”);* Principle 10 *(Boost the use of sustainable technologies);* Principle 1 *(“Design for circularity”);* and Principle 4 *(“Pursue a risk-free environment”)* constitute the mediating principles.

4.3.1 Categorization of Principles using MICMAC analysis:

The ISM methodology was followed by a MICMAC (Cross Impact Multiplication Matrix) analysis to classify the principles and determine their relative influencing power. First, the driving power and dependence power of each variable were calculated by summing up the 0s and 1s in the columns and rows corresponding to each variable. Then, the principles were classified into four quadrants based on their driving power (along the y-axis) and dependence power (along the x-axis), as shown in Figure 6.

The principles located in the first quadrant are termed autonomous principles. However, none of the principles fell within this category (considering transitive links). The principles located in the second quadrant are termed dependent principles, which means that they have a strong dependence power but a weak driving power. This result can be interpreted to mean that these principles have a substantial influence on the system but are not influenced by it and that they are sensitive to the actions of the influencing principles. Principles 2 *(“Conserve resources and preserve their value”)* and 3 *(Manage waste sustainably)* are dependent, as also presented in Figure 5.

The principles located in the fourth quadrant are known as independent principles, which means that they have a strong driving power and weak dependence power. This suggests that these principles strongly influence the system but are not influenced by the system. Any action on these principles will affect other principles, which are dependent on them. Principles 5 (“*Prioritize employees’ well-being*”), 9 (“M*easure and optimize sustainable processes*”), and 10 (“*Boost the use of sustainable technologies*”) fall into this category.

The MICMAC analysis shows that there is a discrepancy in Principles (1), (4), (6), (7) and (8). This discrepancy arises due to the presence of transitive links from these principles. If the transitive links are removed and the direct links presented in the digraph considered, Principles 1 (*“Design for circularity”*) and 4 *(“Pursue a risk-free environment”)* are autonomous factors, which means that due to their weak driving and dependence power they do not affect the system to a great extent. Principles 7 (“*Make a positive contribution to the community*”) and 8 (“*Promote value chain stakeholder collaboration*”) are dependent, while Principle 6 (*“Enhance management commitment to sustainability”*) is independent.

Table 5. Driving and Dependence power

	PR1	PR1	PR3	PR4	PR5	PR6	PR7	PR8	PR9	PR10
Driving Power	5	4	4	7	8	10	5	5	10	9
Dependence Power	6	9	10	5	4	5	10	10	4	4

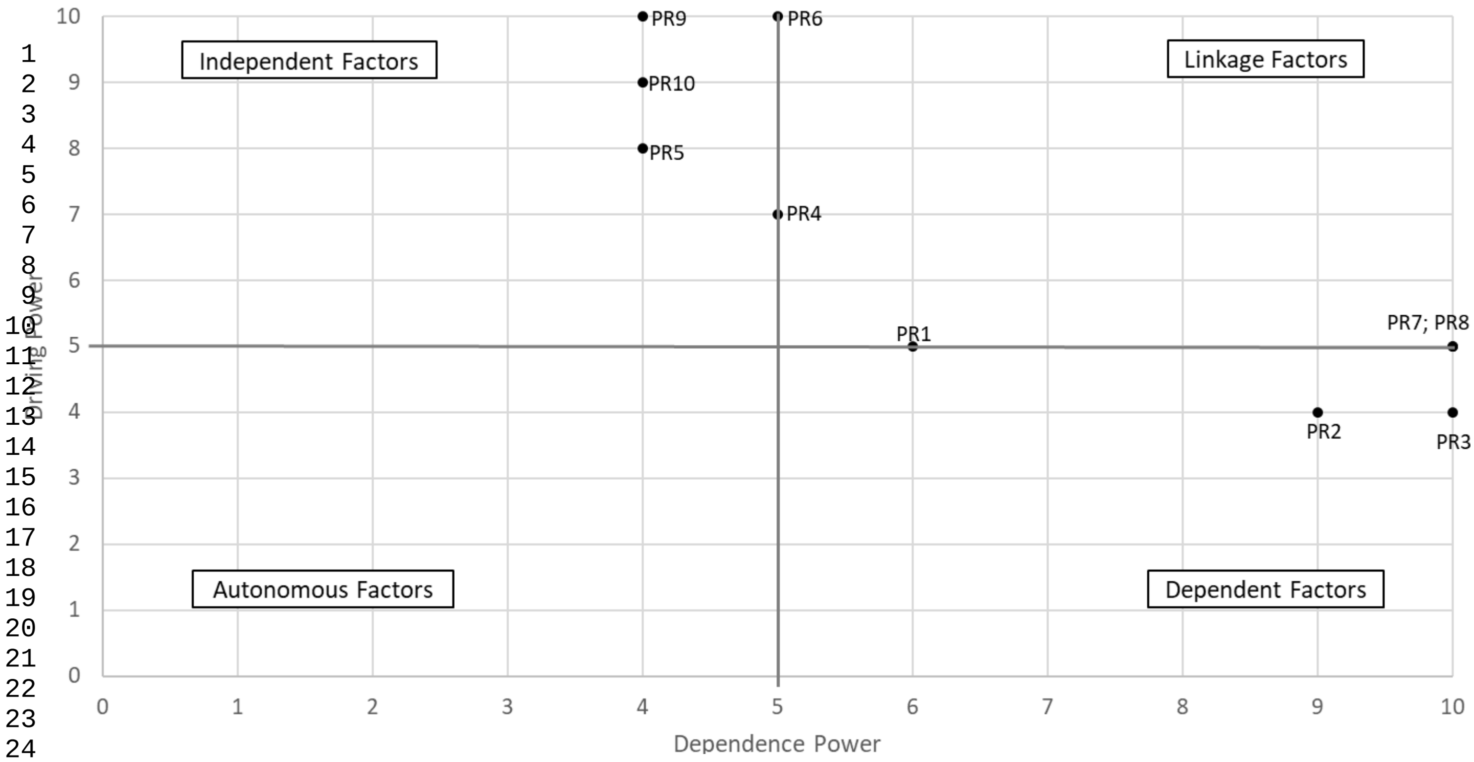

Figure 6. MICMAC Analysis

5 Discussion

More than 20 years ago, Veleva and Ellenbecker (2001) enunciated nine principles of Sustainable Production, which consider in their definition the three dimensions of sustainability (Alayón et al., 2017). Over the past 20 years, the definition of these principles has not been questioned, but industry and the economy in which production is framed have evolved significantly towards a more Circular Economy (Prieto-Sandoval et al., 2018a) and smarter industry (Nakayama et al., 2020). Thus, what are the principles governing Sustainable Production in the current context?

Considering that both industry and the economy are immersed in profound changes, we took Veleva and Ellenbecker's (2001) nine principles of Sustainable Production and proposed 11 updated principles that help understand how Sustainable Production should work in the current context of Circular Economy and Industry 4.0. After applying the Delphi method with 11 experts, a consensus was reached on ten principles governing Sustainable Production, thus contributing to some of the targets proposed in SDG 12.

5.1 Updated Principles of Sustainable Production

The results indicate that the updated principles maintain the essence of most of the initiatives expressed in Veleva and Ellenbecker (2001) (Principles 1-7) while incorporating important nuances in their definitions. These nuances arise fundamentally from the theoretical and practical progress made in these 20 years by the Circular Economy and the commitment of institutions to Sustainable Development by encouraging, among other things, investment in environmentally friendly technologies (Schöggl et al., 2020; Commission, 2018, page 773). Principles 1-3 are mostly aligned with the principles proposed by Suárez-Eiroa et al. (2019):

Sensitivity: Internal

Designing for circular economy, Maintaining resource value within the system, and Closing the system.

The principles most closely related to the social dimension of sustainability (5-7) have also been nuanced. The inclusion of these principles covers the social gap associated with achieving ecological objectives, and with concerns such as equity, gender equality, and access to education mentioned by Suárez-Eiroa et al. (2019) in their study. At an organizational level, diversity, equity, and inclusion are promoted in the workplace. At a community level, it is made explicit that companies must contribute to social, economic and environmental development not only in the place where they operate but also in places where their decisions have an impact.

The definition of three new principles (Principles 8-10) is confirmed as a result of analyzing Sustainable Production in an economic context increasingly concerned with the environment and biodiversity, as is the Circular Economy (EMF, 2021c), and taking into account the rapid development of technologies associated with Industry 4.0.

In recent years, various authors have argued that green manufacturing and integrating sustainability in the sustainable value chain provide competitive advantages to organizations (Khan et al., 2021; Raut et al., 2019). Wolf and Seuring (2010) define sustainable supply chains as "cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development." Principle 8 ("*Promote value chain stakeholder collaboration*") explicitly expresses the need for organizations to inculcate communication and coordination with the rest of the actors in the value chain that promotes increasingly sustainably production within the framework of the Circular Economy (Velenturf and Purnell, 2021).

Some of the Industry 4.0 technologies are being developed to achieve more Sustainable Production. However, technology is not sustainable by merely serving to achieve or improve the circularity of a product or process or trying to reduce resource consumption. Sustainable technology must comply with the fundamental aspects of the concept of sustainability at all stages (creation, implementation, use and end of use). While the economic dimension of technologies in the framework of Industry 4.0 has been widely analyzed, there is still a lack of research and analysis on the environmental and social dimensions in the development of these technologies (Birkel and Müller, 2021). Principle 10 ("*Boost the use of sustainable technologies*") promotes the incorporation of new sustainable techniques in the fields of facility design, construction, maintenance and operation, whose positive effects on the three axes of sustainability have already been tested and evaluated.

Furthermore, the difficulty of specifying the definition of sustainability in clear objectives discourages company managers who have traditionally focused on measuring economic and operational results (Henao and Sarache, 2022). Principle 9 ("*Measure and optimize sustainable processes*") considers it essential to monitor, measure and control production processes in the three aspects of sustainability. The exponential growth of new technologies linked to data science should lead to the use of metrics and indicators that enable managers to incorporate sustainability criteria in decision-making. However, in some cases, monitoring and measurement may require greater sensorization and digitalization of production processes. This should be implemented as long as the balance of Sustainable Production is not upset due to an energy increase in smart production systems (Birkel and Müller, 2021; Birkel et al., 2019). A prior analysis of the real monitoring needs should also be carried out to adjust the number of sensors deployed to only those necessary to collect the information required to control or improve processes and minimize the environmental impact of their installation. In this regard, principle 9 is aligned with principle 10: “Whole system assessment” presented in Velenturf and Purnell (2021), which highlights the importance of utilizing a whole system approach through a process of continuous improvement driven by whole system assessments using holistic indicators before, during, and after the implementation of circular economy practices.

Ultimately, the principles of Sustainable Production encompass not only design and production operations but also the adoption and management of technologies, people care and management, interaction and communication among manufacturers and other value chain stakeholders, and contribution to the community. The speed in the development of new technological innovations and the progression of climate change, together with the new economic, political and social context, demonstrate the need for flexible production systems that facilitate and accelerate the development of sustainable initiatives that may result from applying the principles. Achieving flexibility throughout the entire value chain is one of the current priorities in the framework of sustainable value chains (Dwivedi et al., 2021).

5.2 Relationships between the Principles

The ISM analysis has made it possible to identify relationships between the principles, a novelty not yet addressed in the literature. These relationships can help to understand certain connections between the principles that are of interest for further in-depth study and implementation. As seen in Figure 5, the ISM methodology makes it possible to identify from these relationships which principles can be considered independent, and which can be considered dependent. This identification, linked to a certain extent to Levels I, II, II and IV in Figure 5, should not be understood as a message of prioritization in applying these principles, but rather that the development of some principles can be enhanced by the development of others.

On the one hand, according to Figure 5, the principles of Sustainable Production that appear as independent (i.e., none of the other principles helps to fulfil these principles) are Principles 5 ("*Prioritize employees' well-being*"), 6 ("*Enhance management commitment to sustainability*"), 9 ("*Measure and optimize sustainable processes*") and 10 ("*Boost the use of sustainable technologies*"). However, these four principles act as drivers of Sustainable Production and help to establish an ideal context to enhance the development of the rest of the principles. On the other hand, the principles whose application benefits most from the development of other principles are Principle 2 ("*Conserve resources and preserve their value*"), Principle 3 ("*Manage waste sustainably*") and Principle 7 ("*Make a positive contribution to the community*").

It is worth highlighting that some of the principles aligned with the social dimension of sustainability (Principles 5 and 6) appear as enhancers of others when traditionally the study of sustainability in the field of production has been more oriented to the economic and environmental dimension (Birkel et al., 2019). Identifying this relationship can serve as a starting point for further research on how the development of the social aspect of sustainability in the field of production helps to achieve the development of principles more closely linked to the environmental dimension.

By going deeper into the relationships between principles, 30 strong relationships have been identified, as seen in Figure 5. Of these 30 relationships, some have been widely discussed in the literature, such as the relationships between Principle 1 ("*Design for circularity*") and its positive effect on Principles 2 ("*Conserve resources and preserve their value*"), 3 ("*Manage waste sustainably*"), and 8 ("*Promote value chain stakeholder collaboration*"), and on the relationship between Principle 6 ("*Enhance management commitment to sustainability*") and Principle 7 ("*Make a positive contribution to the community*"). Therefore, in this discussion, we focused on analyzing the relationships obtained from the three new principles added in relation to the ones presented in Veleva and Ellenbecker (2001). Figure 5 also shows in red the relationships that will be discussed below.

A recent literature review on sustainable supply chain management of 362 articles published from 2004-2019 (Khan et al., 2021) collected information about different authors who have identified various drivers of a sustainable value chain. These drivers are the creation of organizational culture (Khan and Qianli, 2017, 2016; Brandenburg et al., 2014 cited in Khan et al., 2021) and the involvement of leaders (Govindan et al., 2015 cited in Khan et al., 2021). Employee training and coaching (Yadav et al., 2018 cited in Khan et al., 2021) and employee health and safety aspects (Distelhorst et al., 2015; Mathiyazhagan et al., 2015 cited in Khan et al., 2021) were also identified as drivers of a sustainable value chain. These references, among others, are compatible with the relationship obtained in this study, which shows that promoting Principles 6 ("*Enhance management commitment to sustainability*") and 5 ("*Prioritize employees' well-being*") helps promote the development of Principle 8 ("*Promote value chain stakeholder collaboration*").

This study also suggests that Principle 7 ("*Make a positive contribution to the community*") can help to achieve Principle 8 ("*Promote value chain stakeholder collaboration*"), something that has not been previously established in the literature. One possible explanation for this relationship is that Principle 7 makes explicit the importance of contributing positively to sustainable development both in the place where the company operates and in places that are also impacted by its strategic and operational decisions. This second fact can help producers to promote closer collaboration with supply chain stakeholders in these other places.

Figure 5 also shows that the development of Principle 8 ("*Promote value chain stakeholder collaboration*") can help to comply with Principles 2 ("*Conserve resources and preserve their value*") and 3 ("*Manage waste sustainably*"). These results are aligned with the evidence shown by some authors in relation to how evaluation and active collaboration with suppliers have a positive effect on the environmental performance of organizations (Gimenez and Tachizawa, 2012). It also coincides with other authors who argue the importance of collaborating between organizations in the framework of Circular Economy practices (Dora, 2020; Mishra et al., 2019), while recognizing the real difficulty of achieving this (Khan et al., 2021).

In relation to Principle 9 ("*Measure and optimize sustainable processes*"), from the study conducted with the experts, it can be deduced that being able to measure processes helps to comply with Principles 2 ("*Conserve resources and preserve their value*"), 3 ("*Manage waste sustainably*") and 6 ("*Enhance management commitment to sustainability*"). Principle 6 promotes the establishment of a clear strategy and objectives for the entire organization in relation to the three dimensions of sustainability. This is a key principle since the lack of management support is considered a barrier when it comes to the implementation of sustainable practices (Tanco et al., 2021). Without a set of key metrics and indicators, it is not possible to monitor compliance with the objectives. Currently, many indicators are proposed to do such monitoring on a general or sectoral basis (Waltersmann et al., 2019; GRI, 2016; Veleva and Ellenbecker, 2001). According to Swarnakar et al. (2021) and Roos Lindgreen et al. (2022) the assessment of sustainability in production processes helps to identify and recognize opportunities for improvement and, therefore, to make continuous progress towards Sustainable Production.

Principle 10 ("*Boost the use of sustainable technologies*") arises from identifying that the great technological development of recent years can accelerate the transition to Sustainable Production systems. From this study, it can be deduced that introducing new sustainable technologies in the field of production can help to comply with Principles 1 ("*Design for circularity*"), 2 ("*Conserve resources and preserve their value*"), 3 ("*Manage waste sustainably*"), and 9 ("*Measure and optimize sustainable processes*"). As an example of these relationships, several authors who recognize the importance of smart technologies as a basis for the development of Sustainable Production were identified. For example, Ghobakhloo and Fathi (2021) suggested that the digitization of the energy sector, the digitalization of the manufacturing industry, and the introduction of new, smarter and more sustainable products are the main opportunities for achieving sustainable energy (that which offers the most effective and balanced combination of economic, social and environmental impacts). Research in the field of technology applied to waste management focuses on the significant efforts being made to solve the problems of separating different types of waste (plastic waste, electronic waste, polymer waste, etc.) to convert them into useful resources (new building materials, regeneration of valuable metals, production and hydrogen, etc.) (Nižetić et al., 2019). In the social dimension, we also found authors who analyzed the potential of Industry 4.0 to help improve the health and workplace of employees, as well as improve employee empowerment and help them develop their talents (Birkel et al., 2019). However, most of the new proposals raise a concern about the amount of energy required by the new technologies under development and which, in some cases, makes them unfeasible for the time being. It is also deemed necessary to promote the development of sustainable technological research that incorporates sustainability criteria from design. In this way, the challenges to be addressed can be identified in the early stages of development and, once resolved, incorporated into production systems.

Finally, it is interesting to see how the model of relationships that has emerged from this study is in line with what the European Commission has recently begun to promote as a new approach to industry (called Industry 5.0). In this new approach, "the well-being of the worker is placed at the heart of the production process and uses new technologies to deliver prosperity beyond employment and growth while respecting the production limits of the planet" (European Commission, 2021).

5.3 Contribution to SDG 12

SDG 12 is meant to "ensure good use of resources, improving energy efficiency, sustainable infrastructure, and providing access to green products and services, decent jobs and ensuring a better quality of life for all" (United Nations General Assembly, 2017).

According to the definition of the ten SP principles, their contribution to SDG 12 is noticeable. Specifically, the declaration and updating of the SP principles aim to inform people in general, and company managers in particular, about what it means to contribute to sustainable development from productive systems (target 12.8). Furthermore, providing this information and clarifying it also aims to encourage businesses of all sizes to adopt sustainable practices (target 12.6).

Therefore, deploying business strategies aligned with the principles of Sustainable Production presented here will contribute to achieving sustainable management and efficient use of natural resources by manufacturing companies (target 12.2); reducing the release of pollutants, especially chemicals (target 12.4); and reducing waste (target 12.5) by promoting the application of circular and sustainable design strategies and waste management following the waste hierarchy. In addition, the SP principles applied to agri-food industry enterprises will help to make better use of harvested products entering the food production chains and thus reduce food losses along production chains (target 12.3).

Finally, as can be deduced from the SP principles, production should not be seen as an activity isolated from the rest of the value chain; rather, production should promote active collaboration with all the stakeholders in the value chain in order to advance sustainability with a more holistic vision and commit to making a positive contribution to the communities in which production companies operate. Therefore, the monitoring of production models based on the SP principles of companies in developed countries can contribute to promoting Sustainable Production models in developing countries through their trade agreements (target 12.1), helping them to move towards more Sustainable Production methods (target 12.A).

5.4 Limitations

This study is not free from limitations. First, it is important to highlight that consumers are relevant actors in the field of sustainability and Circular Economy. This study has been undertaken from the production perspective, assuming environmentally responsible and sustainable consumption and not questioning the quality of the resulting products.

Furthermore, the limitations of the method used in this study are linked to the use of the Delphi method since the Delphi-study group was relatively small.

6. Conclusions

The main objective of this paper is to shed light and clarity on the definition of the principles that characterize Sustainable Production. These principles will also help manufacturing companies primarily to identify different strategies to help them move toward more Sustainable Production.

As a result of this study, ten principles evaluated by experts according to criteria of significance, parsimony, semantic consistency, and empirical adequacy have been proposed. Moreover, this study has made it possible to identify which principles are more independent and which are more dependent on the others and to establish relationships between them. According to this study, Principle 5 ("*Prioritize employees' well-being*"), Principle 6 ("*Enhance management commitment to sustainability*"), Principle 9 ("*Measure and optimize sustainable processes*"), and Principle 10 ("*Boost the use of sustainable technologies*") help to establish an ideal context to enhance the development of the rest of the principles. This study also suggests that Principle 7 ("*Make a positive contribution to the community*") can help to achieve Principle 8 ("*Promote value chain stakeholder collaboration*"), an observation that has not been previously established in the literature.

In terms of its theoretical value, the study contributes to the definition of SP principles and the analysis of the relationships among them with the aim of clarifying the organizational, human, and technological implications associated with Sustainable Production in the context of Circular Economy and Industry 4.0. Furthermore, the ISM analysis has made it possible to identify relationships between the principles, which is a novelty not yet addressed in the literature. These relationships can help to understand certain connections between the principles that are of interest for further in-depth study and implementation, which constitutes the main contribution of the present study.

In terms of practical implications, this study reveals that having clearly defined the principles governing SP operations and knowing how these principles interact could contribute to companies developing an orderly transition of their production processes towards Sustainable Production. Therefore, the presentation of the updated principles opens up new research possibilities, while helping producers to better understand such an abstract concept as sustainability, contributing in this way to achieving SDG 12. Additionally, the declaration of the principles of SP within the framework of a circular economy can facilitate the integration of circular and sustainability principles into EMS.

Further studies, from an operational perspective, would be needed to assess whether the actions based on the defined principles are compatible with the expectations for which they have been formulated, thus verifying the usefulness of the principles. This is not a simple task. All the principles should be established as standard practice in an organization in order to evaluate them over time. However, due to the advancement and promotion of Sustainable Production in recent years, successful practical results of the partial application of some of the principles can be found in the literature. In addition, the definition of these principles opens the door to aligning and classifying different business practices according to their contribution to these principles, which will help practitioners to promote the dissemination of well-founded success stories.

It is, therefore, necessary to move forward in the search for the most appropriate way to measure the progress of production systems towards more sustainable models. Aligning sustainability-related metrics and indicators in relation to these principles can result in a new framework for assessing Sustainable Production.

Furthermore, recent studies suggest that efforts made by companies today should be more focused on understanding whether the consumer is willing to recognize (with consistent purchasing behavior) the commitment of producers to both the circular and green dimensions. As stated earlier, the role of the consumer as part of the production system has not been analyzed in this paper. However, the incorporation of new principles that serve to enhance the co-responsibility of consumers and manufacturers in terms of Sustainable Production and consumption could be addressed in future studies.

Finally, as we can observe in this study, not all Sustainable Production principles act independently. It would be worthwhile to further understand the relationships obtained as a result of the ISM and to support them empirically to get the most out of the contribution of this research.

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Appendix

This section shows the results after implementing Step I (Initial Reachability Matrix) and Step II (Final Reachability Matrix) of the ISM technique. Based on the experts' comments, Table A1 shows the Initial Reachability Matrix. After checking transitivity links, Table A2 shows the Final Reachability Matrix.

Table A1. Initial Reachability Matrix

	1	2	3	4	5	6	7	8	9	10
1	0	**1**	**1**	0	0	0	**1**	**1**	0	0
2	0	0	**1**	0	0	0	**1**	**1**	0	0
3	0	**1**	0	0	0	0	**1**	0	0	0
4	0	0	**1**	0	1	0	**1**	0	0	0
5	0	0	0	**1**	0	**1**	**1**	0	0	0
6	0	0	0	0	1	0	**1**	**1**	**1**	**1**
7	0	0	0	0	0	0	0	**1**	0	0
8	1	**1**	**1**	0	0	0	0	0	0	0
9	0	**1**	**1**	**1**	0	**1**	0	0	0	**1**
10	**1**	**1**	**1**	0	0	0	0	0	**1**	0

Table A2. Final Reachability Matrix

	1	2	3	4	5	6	7	8	9	10
1	1	1	1	0	0	0	1	1	0	0
2	0	1	1	0	0	0	1	1	0	0
3	0	1	1	0	0	0	1	1	0	0
4	0	1	1	1	1	1	1	1	0	0
5	0	0	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1
7	1	1	1	0	0	0	1	1	0	0
8	1	1	1	0	0	0	1	1	0	0
9	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	0	1	1	1	1	1

Theorizing the Principles of Sustainable Production in the context of Circular Economy and Industry 4.0.

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Abstract:

The concept of Sustainable Production is evolving with changes triggered by the emergence of new economic and industrial models such as Circular Economy and Industry 4.0. However, most studies that currently link these concepts are based on the principles of Sustainable Production defined 20 years ago. Therefore, the primary aim of this study is to redefine the principles that should govern Sustainable Production operations in the transition towards a Circular Economy and smart industry models. To this end, an initial proposal of 11 principles was shared with 11 world-class experts (academics and practitioners) and a consensus proposal was sought through a Delphi Panel. Ten principles emerged from this study, which were evaluated by experts according to criteria of significance, parsimony, semantic consistency and empirical adequacy. Additionally, to study the relationships between the ten principles, the Interpretative Structural Model (ISM) technique was applied. The ISM technique identified which principles are independent of or dependent on each other and established relationships between the principles. The findings suggest that Principle 5 ("*Prioritize employees' well-being*"), Principle 6 ("*Enhance management commitment to sustainability*"), Principle 9 ("*Measure and optimize sustainable processes*") and Principle 10 ("*Boost the use of sustainable technologies*") help to establish an ideal context to enhance the development of the rest of the principles that characterize Sustainable Production. The presentation of the ten principles opens new possibilities for researchers while helping managers to better understand sustainability in terms of production and, therefore contribute to achieving SDG 12.

Keywords: Sustainable Production; Principles; Circular Economy; Industry 4.0; Interpretive Structural Modeling; Delphi Panel.

1. Introduction

Although the environmental performance of industries has improved in recent years, industrial activities continue to generate large amounts of waste and pollution, damaging the environment (European Environmental Agenda, 2019; Tanco et al., 2021). However, most companies have not yet made the transformational changes needed to truly integrate environmental and social sustainability into the way they do business (Bocken and Short, 2021). Therefore, ensuring patterns of sustainable consumption and production is one of the 17 Sustainable Development Goals (SDG) adopted by the United Nations as part of the 2030 Agenda for Sustainable Development (United Nations. General Assembly, 2015). The concept of Sustainable Development (SD) was defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987).

Industrial Ecology (IE) emerged in the late 1980s as one approach to the green economy to serve as a guide for the transformation of industrial systems towards SD (Gunasekaran and Spalanzani, 2012; Saavedra et al., 2018); i.e., to guide production strategies towards Sustainable Production (SP). Nowadays, the concept of Circular Economy (CE) is understood as a continuity and extension of the IE concept (Saavedra et al., 2018; Suárez-Eiroa et al., 2019). “The objective of the Circular Economy is to maintain the values and manage stocks of assets from natural, cultural, human, manufactured to financial stocks” (Walter R. Stahel and MacArthur, 2019). CE has been proposed as a very promising concept to guide the achievement of sustainability (Betancourt Morales and Zartha Sossa, 2020), especially for manufacturers (Acerbi and Taisch, 2020).

Furthermore, the implementation of sustainable practices could be enhanced by the implementation of Industry 4.0 technologies, also called "the fourth industrial revolution" (Kagermann and Wahlster, 2013). This concept proposes a new scenario for production that combines information and communication technologies with digital manufacturing technologies (Kang et al., 2016).

Both Industry 4.0 and CE have grown significantly in the last decade, with many studies analyzing their relationship (Laskurain-Iturbe et al., 2021; Nascimento et al., 2019). In general, these studies discuss how the different technologies help to implement different CE strategies; i.e., reducing material, energy, and waste flows. In particular, technologies are investigated to support either the physical implementation of circular strategies in manufacturing or the decision-making process to determine the most appropriate strategy (Acerbi and Taisch, 2020). Many studies have concluded that the implementation of CE strategies in production, i.e., remanufacturing and recycling, can be enhanced by adopting I4.0 technologies (Acerbi and Taisch, 2020).

Additionally, there are numerous examples in the literature that study the link between CE and sustainability concepts (Bertassini et al., 2021; Schöggl et al., 2020) and the relationship between Industry 4.0 and sustainability (Gollavilli et al., 2020; Yadav et al., 2020). A survey carried out in Brazilian companies (Satyro et al., 2022) concluded that, in general, the first motivation for the implementation of Industry 4.0 is linked more closely to productivity and competitive improvements than to improvements related to sustainability (more specifically concerning its social dimension). These same authors warn of the need to better understand the role of promoting and incorporating new technologies in the context of Sustainable Production.

Despite recent exponential growth in the literature on sustainability in production, the concept of Sustainable Production is more than 20 years old (Lowell Center for Sustainable Production, 1998; O’Brien, 1999; Veleva and Ellenbecker, 2001). More definitions of this same concept have recently been proposed (EPA, 2018; Moldavska and Welo, 2017). Moldavska and Welo (2017) concluded that a unified understanding of the concept of sustainable manufacturing had not yet been reached, which demonstrates the intrinsic complexity of this concept (Ciliberto et al. 2021). It also helps us to understand why it is difficult for organizations to make progress in terms of sustainability (Alayón et al., 2017).

Recent studies consider Green-circular premium and Sustainability certifications as effective organizational approaches to leverage sustainability as a competitive advantage factor (Appolloni et al., 2022). Currently, environmental management systems (EMSs) are used by most organizations to fulfill national and/or international environmental standards and ensure a comprehensive assessment of their processes and their impact on the environment. While the latest revision of ISO 14001 (2015) offers opportunities to align and manage initiatives such as the use of a life cycle perspective, circular economy strategies or stakeholder interactions that go beyond operational optimizations, it is still unclear how companies can integrate circular and sustainability principles into EMSs (Kristensen et al., 2021).

The concept of SP goes beyond setting and assessing environmental, economic, and social objectives for processes and products (Bonvoisin et al. 2017); it also involves the interaction between production systems. From this perspective, it is easy to understand that summarizing the meaning of Sustainable Production in a few sentences is complicated. This can give rise to multiple interpretations with academic and practical consequences (difficulty in understanding and applying the concept, difficulty in carrying out comparative case studies related to SP, and lack of alignment and focus in the way of evaluating SP, among others). For manufacturing firms, it is not clear how companies can adequately adapt their production systems to sustainability requirements (Waltersmann et al., 2019), constituting a gap that needs to be addressed.

Veleva and Ellenbecker (2001) wrote nine principles of Sustainable Production, describing the characteristics of SP in detail. These principles included sustainable attributes for product, materials, work tasks, management style and people management. However, they are based on a definition of SP that was built under a linear mode of production. More recently, Suárez-Eiroa et al. (2019) proposed a set of seven principles of circular economy for sustainable development. The core principles presented by the authors are closing the system, maintaining resource value within the system and reducing the system size. However, the role of social goals for CE was not considered while defining the principles. In the same context, Velenturf and Purnell (2021) defined principles for a sustainable circular economy. The list consists of ten principles, but only two are mentioned regarding production, i.e. design for circularity and circular business models. Additionally, these studies are focused on CE, with no reference to the new technologies proposed in Industry 4.0.

Consequently, the concept of Sustainable Production is evolving, immersed in a changing context and with the emergence of new paradigms (Hussain and Jahanzaib, 2018). However, to the best of our knowledge, most studies linking the concepts of Circular Economy, Industry 4.0 and Sustainability are based on the definitions of Sustainable Production principles identified 20 years ago. While these definitions are quite conceptual, they constitute an important guide to help companies move steadily towards more Sustainable Production (Alayón et al., 2017). In this new context of CE and Industry 4.0, a common understanding of Sustainable Production principles is essential as a point of departure for studying how manufacturers can make their operations more sustainable (Alayón et al. 2017). Additionally, the potential relationships between the principles of SP are under-represented in literature.

In order to address the above-mentioned gaps in the academic literature, this study contributes to the field of production by addressing the following research questions:

RQ1. *What are the principles of Sustainable Production in the context of Circular Economy and Industry 4.0?*

RQ2. *How are these principles interrelated?*

Therefore, this study analyzes the information available in the literature on Sustainable Production and proposes ten principles for SP in the context of Circular Economy and Industry 4.0 derived from an update of the nine principles of SP presented by Veleva and Ellenbecker (2001). Eleven principles were initially proposed and subsequently validated by 11 experts (academics and practitioners) from around the world following the Delphi Panel method (Okoli and Pawlowski, 2004). Moreover, an Interpretative Structural Model (ISM) was used to study the possible relationships between the principles. This work has allowed us to review the existing principles and reach a consensus on principles for Sustainable Production operations in the current economic and industrial context as well as understand the interrelations among them.

One of the limitations of this study is that while defining these principles, we realized that the sustainable management of production operations should not be treated independently from the rest of the value chain. However, consumer and end-of-life issues have not been addressed because currently, they have less influence on the internal manufacturing activities and procedures used by companies (Acerbi and Taisch, 2020).

From both theoretical and managerial perspectives, this research provides three major contributions.

i. From a conceptual point of view, the definition of SP principles and the analysis of the relationships among them aim to clarify the organizational, human, and technological implications associated with Sustainable Production in the context of Circular Economy and Industry 4.0. A clear understanding of the key aspects that define SP will help researchers delve deeper into the study of how organizations can adequately adapt their production systems to sustainability requirements and even how to measure whether they are meeting those requirements.
ii. From a regulatory perspective, defining the principles of SP within the framework of a circular economy can help integrate circular and sustainability principles into EMSs. By doing so, Sustainable Production is expressed in a more visionary manner and makes it possible to identify which operational and production processes sustainability and circularity objectives should be applied.
iii. From a practical viewpoint, having clearly defined principles governing SP operations will contribute to achieving the SDG 12 target 12.8: "By 2030 ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature." In addition, knowing how these principles interact could contribute to the orderly transition of a company’s production processes to Sustainable Production.

The layout of this article is as follows. Section 2 takes a deeper look at the concept of Sustainable Production, Circular Economy, and Industry 4.0. Section 3 presents the three-step methodology used in the present study: the initial proposal of principles, the Delphi Panel process carried out, and the ISM technique. Section 4 presents an initial proposal of the principles adapted from Veleva and Ellenbecker (2001). The main results from the Delphi Panel and the ISM model are also presented in Section 4. Section 5 discusses the results, the contribution of the study to SDG 12, and the limitations of the study. Finally, Section 6 presents the conclusions and suggestions for future work.

2. Theoretical background

The literature review consists of three subsections. The first two provide the context in which the principles of Sustainable Production are defined in the present study. The third subsection reviews and discusses the prior knowledge of Sustainable Production and its principles.

2.1 Sustainable Circular Economy

Production, together with distribution and consumption, is one of the main activities of an economic system. The economic system of 20 years ago was based on a linear model, which means creating, using, and discarding everything that has been produced when no longer useful. Since the earliest definition of the concept of SP, the search for more sustainable products and processes has promoted innovations aimed at reducing the use of natural resources and reusing or recycling used materials or resources (3Rs Sustainable Production strategies). Subsequently, another three Rs were added (Recover, Redesign, Remanufacture), extending the scope of action from 3Rs to 6Rs to achieve more Sustainable Production (Joshi, K., Venkatachalam, A., Jawahir, 2006). Currently, the scientific community refers to the 9Rs strategies (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover) as the way to produce in the context of Circular Economy (Potting et al., 2017).

The term 'Circular Economy' was first coined by Pearce and Turner in 1990 (Prieto-Sandoval et al., 2018), but since 2012 has gained popularity in civil society through the work carried out by Ellen MacArthur Foundation (Loiseau et al., 2016). Today, CE is presented as an alternative to the traditional linear economic model to help society become more sustainable (Velenturf and Purnell, 2021). Korhonen et al. (2018a) are among the authors who most clearly define the Circular Economy from the perspective of sustainability. From the perspective of SD, they defined the concept of CE scientifically as follows: *"Circular Economy is an economy constructed from societal production-consumption systems that maximizes the service produced from the linear nature-society-nature material and energy throughput flow. This is achieved by using cyclical materials flows, renewable energy sources and cascading-type energy flows."*

Some recent studies have defined CE principles for sustainable development (Suárez-Eiroa et al., 2019; Velenturf and Purnell, 2021). In these articles, the principles are defined for the three main economic activities: production, distribution and consumption. Overall, the principles defined by these authors are based on the three main principles defined by the Ellen MacArthur Foundation (2021), namely: eliminate waste and pollution, circulate products and materials by closing production cycles, and regenerate nature. These principles are all driven by design (EMF, 2021a) since the design for circularity constitutes one of the main principles for transforming production (Velenturf and Purnell, 2021; Suárez-Eiroa et al., 2019).

The studies mentioned before offer some practical strategies related to circular design, such as designing new business models, designing transparent, reproducible, scalable products to build the same products in other places from local resources, designing new methodologies to ensure continuous improvement, and thinking about practical utilities and consumer preferences. In this study, the definition of CE proposed by Korhonen et al. (2018b) and the principles of CE from the articles by Velenturf and Purnell (2021) and Suárez-Eiroa et al. (2019) serve to contextualize the economy in which the updated principles of SP should be deployed.

2.2 Contribution of Industry 4.0 to Sustainable Circular Economy

Since 2011, the so-called "Fourth Industrial Revolution," or Industry 4.0 (Kagermann and Wahlster, 2013), has been proposing a new scenario for manufacturing that combines information and communication technologies with digital manufacturing technologies (Kang et al., 2016). In recent years, authors have identified this new manufacturing approach as an enabling scenario for a more sustainable industry (Machado et al., 2020; Gupta et al., 2021).

The central idea of Industry 4.0 is to use emerging technologies so that all industrial processes are integrated, thus making production work flexible, efficient and intelligent with high quality and low cost (Machado et al., 2020). The major Industry 4.0 technologies include Additive Manufacturing (AM), Cyber-Physical Systems (CPS), Blockchain, Artificial Intelligence, Artificial Vision, Big Data & Advanced Analytics, Cybersecurity, Internet of Things, Robotics, and Virtual and Augmented Reality (Laskurain-Iturbe et al., 2021). These technologies help companies to improve circularity since they contribute to reducing material and energy consumption and the generation of waste and emissions (Laskurain-Iturbe et al., 2021). In this vein, a literature review conducted by Acerbi and Taisch (2020) concluded that Additive Manufacturing constitutes one of the most diffused I4.0 technologies. AM has been studied by recycling materials such as plastic, metal and organic waste. Additionally, it has been implemented to design circular products to facilitate resource circularity at products end-of-life. Comparing AM to conventional production, it has been shown to be more energy and cost-efficient (Acerbi and Taisch, 2020). Other CE strategies in production such as resource recovery, recycling and waste minimization (Fisher et al., 2018) have been also supported by the implementation of digital technologies.

Regarding the link between Industry 4.0 and sustainability, Lopes de Sousa Jabbour et al. (2018) suggested that Industry 4.0 technologies contribute to the decision-making process regarding sustainable operations management and the development of new business models by integrating value chains through data collection and sharing. Machado et al. (2020) presented evidence that corroborates that reinforcing the integration of horizontal and vertical systems and real-time data management favors the closing of circles in productive processes and product life-cycle management. The same authors also highlighted that modelling and simulating the activities that occur throughout the product value chain are methods that can help decision-making for sustainable process improvements.

However, not everything related to Industry 4.0 technologies seems to favor sustainability. For example, Rejeski et al. (2018) argued that Additive Manufacturing had the potential to contribute to sustainability through its combination with IoT technology, but the full implications of its realization were still difficult to assess. More recently, some authors identified gaps in the contribution of these technologies to the social dimension of sustainability (Machado et al., 2020). There is still a lack of knowledge and uncertainty in the relationship between Industry 4.0 technologies and sustainability (Bai et al., 2020; Satyro et al., 2022).

2.3 Sustainable Production

Already in 1999, O'Brien recognized the need to develop SP systems that minimized the pressing environmental issues at the time. O'Brien (1999) described generic characteristics that he considered SP should meet. "*Environmental consciousness throughout the culture of the whole organization, both product and process design addressing sustainable issues, maximum use and reuse of recycled components and materials, product life-cycle concepts applied to the whole manufacturing system, factories reconfigurable to respond flexibly to changes in products, volumes, process technologies etc., organization lean as well as clean, re-engineering addressing environmental and sustainable issues, Kaizen activities addressing environmental issues, metrics according sustainability issues and use of clean technologies* (O'Brien 1999)."

Veleva and Ellenbecker (2001) presented a framework and a methodology for measuring SP by introducing the principles that would govern the concept of SP. They based their SP definition on an earlier definition by the Lowell Center for Sustainable Production (LCSP), University of Massachusetts Lowell (Lowell Center for Sustainable Production, 1998). LCSP defines Sustainable Production as *"the creation of goods and services using processes and systems that are non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for employees, communities and consumers; and socially and creatively rewarding for all working people".* They also presented nine principles that would determine the basis for the development of SP (Veleva and Ellenbecker, 2001). These principles are shown in Table 1.

Table 1. Principles of Sustainable Production (Extracted from Veleva and Ellenbecker (2001))

	Principles of Sustainable Production
1	Products and packaging are designed to be safe and ecologically sound throughout their life cycles; services are designed to be safe and ecologically sound.
2	Wastes and ecologically incompatible byproducts are continuously reduced, eliminated, or recycled.
3	Energy and materials are conserved, and the forms of energy and materials used are most appropriate for the desired ends.
4	Chemical substances, physical agents, technologies, and work practices that present hazards to human health or the environment are continuously reduced or eliminated.
5	Workplaces are designed to minimize or eliminate physical, chemical, biological, and ergonomic hazards.
6	Management is committed to an open, participatory process of continuous evaluation and improvement, focused on the long-term economic performance of the firm.
7	Work is organized to conserve and enhance the efficiency and creativity of employees.
8	The security and well-being of all employees are a priority, as is the continuous development of their talents and capacities.
9	The communities around workplaces are respected and enhanced economically, socially, culturally and physically; equity and fairness are promoted.

Recently, more definitions of this same concept of SP have been proposed (EPA, 2018; Bonvoisin et al., 2017). Specifically, in 2017, Moldavska and Welo (2017) analyzed different definitions of "sustainable manufacturing," as a concept similar to SP. In their article, Moldavska and Welo (2017) concluded that a unified understanding of the concept of sustainable manufacturing had not yet been reached and that there was a lack of unity in the terminology and vocabulary used to define this concept. They further argued that it is important to differentiate between an organization's actual contribution to sustainability and the existence of sustainability-oriented organizational structures and management instruments, which in itself is no guarantee of sustainability (Moldavska and Welo, 2017).

As observed in the present literature review, the movement of industry towards sustainability requires important changes that range from behavior to technology. These changes must be considered from a holistic perspective, even if acting locally (Despeisse et al., 2013). The evolution of the concept and operationalization of green economy and green production over the last 20 years, together with a manufacturing scenario that has been moving towards greater factory digitalization and more efficient and intelligent manufacturing in the last ten years, suggests the need to adapt the principles governing Sustainable Production to the new economic and industrial context.

Consequently, we consider it pertinent to analyze, adapt and update the principles of SP identified by Veleva and Ellenbecker in 2001 to fit the current economic and industrial context and to study the potential relationships between the new defined principles of Sustainable Production.

Figure 1 represents the relationship between the three pillars of sustainability. It suggests that the economy and society are embedded into the environment, which means that any decision towards sustainability should be considered holistically. In this scenario, companies are part of this embedded system and therefore should adapt their production processes to fit the principles of a sustainable and circular economy. To achieve this, today's organisations are increasingly using smart technologies.

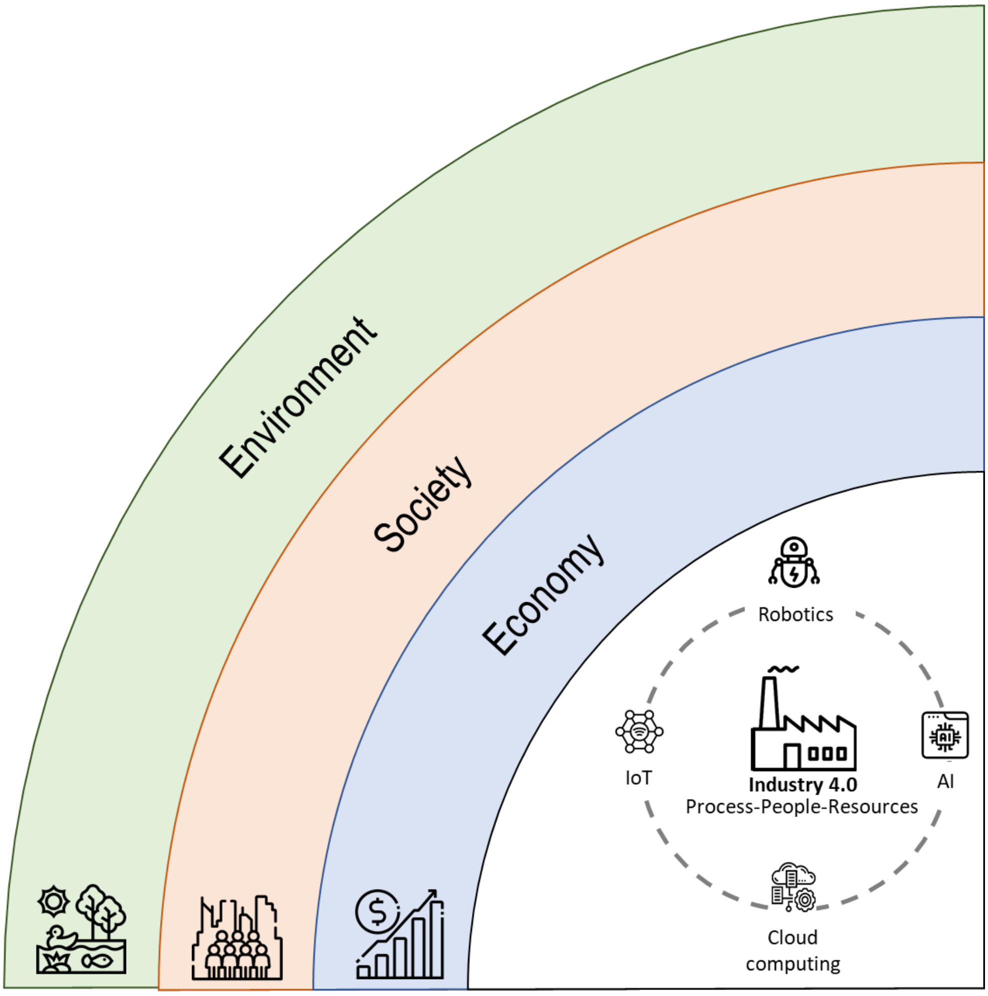

Figure 1. Sustainability-related concepts in a CE and Industry 4.0 context (icons extracted from www.flaticon.com)

3. Methodology

The main objective of this study is to identify the principles of Sustainable Production in the context of Circular Economy and Industry 4.0. It also proposes a theoretical model that establishes the relationships between these principles. To address these two objectives, we followed a three-phase research methodology which included an extensive review of the extant literature on Sustainable Production, a Delphi study, and an ISM and MICMAC analysis. The methodology used to present an updated version of the SP principles is presented in Figure 2.

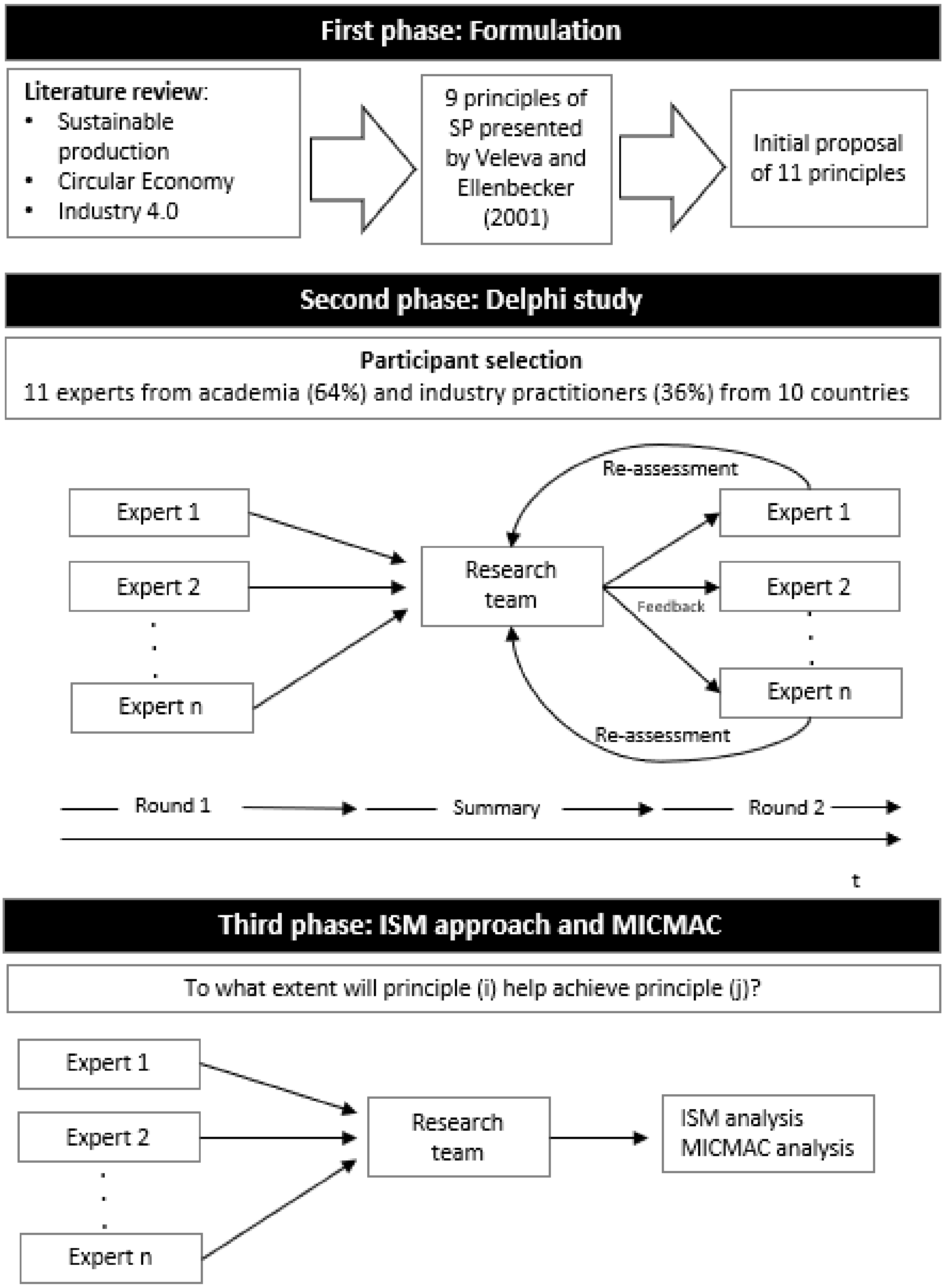

Figure 2. Phases followed by the present study (adapted from Gebhardt et al., 2022).

3.1 Phase 1: Literature review

According to Suárez-Eiroa et al. (2019), the principles of a system are understood as a set of basic characteristics necessary to understand and operate the system. An operational principle could be used to describe theoretical strategies that explain how a system operates. In this article, we consider the definition of principle to encompass both ideas.

To develop the SP principles, we first conducted a literature review based on the snowball strategy focused on the research already carried out on Sustainable Production and the new economic and industrial context related to production.

Firstly, the keywords "Sustainable Production" and "sustainable manufacturing" were used to search for papers in the Web of Science and Scopus database. Subsequently, the 'snowball' technique was applied since it allows citations to be traced backwards and forward to locate leads to other related articles (Lim et al., 2018).

The snowball strategy was selected since it involved reviewing all bibliographical references cited in the literature specific to the research topic being addressed (Wohlin, 2014). This way of conducting the literature review benefited not only from examining the initial list of references but also from complementing it by examining where the documents were cited (Suárez-Eiroa B. et al., 2019). Snowballing constitutes a better method for expanding systematic literature investigations than a database search (Wohlin, 2014).

Initially, a proposal of 11 SP principles was presented based on the nine principles of SP defined by Veleva and Ellenbecker (2001). These principles were defined by applying a critical analysis of the literature and the knowledge and experience of the authors, trying to coherently integrate what was already known with the latest scientific approaches to the subject in question.

3.2 Phase 2: Delphi method

To validate the initial proposal of principles, a Delphi study was conducted. In comparison with other methods that could have been implemented for this research, i.e survey, the Delphi method is a stronger methodology for a rigorous query of experts (Okoli and Pawlowski, 2004).

In the absence of prior knowledge, experts' assessments and opinions can be gathered using the Delphi method to evaluate a phenomenon (Garza-Reyes et al., 2019). Furthermore, in this study, the Delphi method makes it possible to collect richer data, which leads to a deeper understanding of the topics (Okoli and Pawlowski, 2004). It also provides access to the opinion of multiple experts from diverse professional backgrounds with reasonable effort (Prieto-Sandoval et al., 2018b). It is characterized by iteration, statistical group response, controlled feedback, and anonymity (Habibi et al., 2015). This anonymous participation avoids group thinking; therefore, it gives experts the freedom to express their views. Another advantage is that the iterations allow specialists to reassess their initial opinions on the proposed topic. Through a series of iterative surveys or meetings, the group comes to a consensus. Opinions are gathered, synthesized, and given to the group for further consideration in each iteration (Hutchins et al., 2019).

3.2.1 Participant selection

The ideal number of participants in a study using the Delphi method is between six and 12 (Hogarth, 1978), especially if experts with different professional backgrounds are invited to participate (Clayton, 1997). For this study, 43 experts were invited to participate in the Delphi study, which included specialists from different universities and consultancy firms.

The academic experts were selected considering two criteria: first, the area of expertise, which was fundamentally linked to the topics of Industry 4.0 and sustainable supply chain; and second, their research was significant in terms of academic contributions to international journals dealing with these topics. Industry experts were professionals with practical experience in the area of Circular Economy and Sustainability and who took part as experts in the "From linear to Circular Economy" course organized by the Ellen MacArthur Foundation (EMF, 2021b).

In total, 15 experts agreed to participate in the study (35% acceptance rate), which involved 11 academic experts and four practitioners. The experts work in different countries: Spain, England, India, Italy, USA, Sweden, Austria, Germany, Namibia, and the Netherlands. Of the initial 15 participants, only 11 completed the two rounds, as time constraints prevented four participants from finishing the Delphi rounds. The experts were informed of the goal as soon as they confirmed their participation and were given instructions on how to reply to the Delphi rounds online.

3.2.2 Delphi structure

The objective of the experts' panel was to evaluate and reach a consensus on the initial proposal of principles, fulfilling the following evaluation criteria (Fawcett, 2005): significance, internal consistency, parsimony and empirical adequacy. The significance criterion required justifying the importance of defining the principles for the production area. The parsimony criterion meant that the fewer principles needed to fully explain the phenomena of interest, the better. The criterion of internal consistency required all principles to be congruent, reflecting semantic clarity and coherence. The criterion of empirical adequacy required the definitions to be consistent with the empirical evidence. The data used to determine the empirical adequacy of a theory could come from multiple personal experiences of an individual or similar personal experiences of several individuals (Fawcett, 2005).

To achieve the evaluation of the principles the experts were asked the following questions:

i. Are the SP principles stated clearly and concisely? Do you think that any principle is missing or surplus? Justify your response (parsimony criterion)

ii. Do you consider that all criteria are semantically clear and consistent (different terms are not used for the same concept nor are different meanings attributed to the same concept) with the theory and concepts of sustainability and Circular Economy? (criterion of internal consistency)

To evaluate the empirical adequacy criterion, the experts were asked to answer the previous questions considering that the assertions of each principle had to be congruent both with their knowledge about the topic and with their empirical evidence.

Two online Delphi rounds were performed. The Delphi process ended when consensus was reached. The updated set of principles for Sustainable Production from the experts' consensus is discussed in the following section.

3.3 Phase 3: ISM Model and MICMAC analysis

To address the second research question, the Interpretive Structural Modeling (ISM) method was employed. This technique is used to depict the system structure in terms of element relationships (Sushil, 2012). A MICMAC analysis was also performed, which included a graph that categorizes the factors under study according to their driving and dependent power. MICMAC analysis was utilized to classify the components and validate the interpretative structural model factors (Ahmad et al., 2019).

The ISM technique was selected above other methods since it offers a distinctive method for building the structural hierarchy and exploring the dynamic relationship within a complex problem (Vimal et al., 2022) such as the one under study in this research. ISM analyzes the ordered relationship between the various aspects of a system and interprets the particular relationships between the elements that are based on the judgements of a group of experts who determine the correlation between them (Vimal et al., 2022).

J.N. Warfield developed ISM as a computer-assisted process for studying complex issues and organizing them into clearly understandable phrases and directed graphs (Poduval et al., 2015). In the extant literature, the ISM approach for analyzing systems and problems in various fields (such as TQM, supply chain management, knowledge management, logistics, and productivity improvement) is well documented (Attri et al., 2013). Recently this technique has been used to map interrelationships between variables such as barriers regarding sustainability adoption (Ghobakhloo and Fathi, 2021; Sarkar et al., 2021; Zayed and Yaseen, 2021).

The ISM technique was used to develop a model that structures the relationships of the principles encountered during the Delphi process. Therefore, the experts from the Delphi Panel who agreed to participate in this phase of the study were asked the following question:

To what extent will principle (i) help achieve principle (j)? (Sushil, 2012)

This technique should be implemented by following a set of well-defined steps in a specified order. Each step is important and related to the previous step, and therefore none can be bypassed. The steps followed for the ISM method are as follows (Gani et al., 2022):

<u>Step I:</u> Based on the experts' comments, the Initial Reachability Matrix (IRM) was completed. The IRM shows the possibility of interaction between the principles, which was scaled in this study with a 0- if no interaction exists, 2- low interaction, and 4- high interaction. The matrix was then transformed into a new matrix having 0s and 1s.

<u>Step II:</u> Modify IRM by checking it for transitivity, (i.e., if A leads to B and B leads to C, then A leads to C). Once the transitive links were checked, the IRM was transformed into a Final Reachability Matrix (FRM).

<u>Step III:</u> For each principle, antecedent sets and reachability sets were derived. Through a series of revisions based on antecedent and reachability sets, the FRM was partitioned into several levels.

<u>Step IV</u>: Based on the level portioning of the principles, a digraph plot was prepared by removing transitive links.

<u>Step V:</u> Finally, the digraph was converted into an ISM model by adding statements in place of nodes.

4. Results

This section presents the initial proposal of the Sustainable Production Principles, followed by the results from the Delphi Panel and the ISM analysis.

4.1 Initial Proposal of SP Principles

The principles in the present study set out to govern Sustainable Production operations in the mindset of the transition toward a Circular Economy and smart industry model. These principles should reflect the basic characteristics of Sustainable Production considering the following dimensions: (1) energy and material use (resources), (2) natural environment, (3) social justice and community development, (4) economic performance, (5) workers, and (6) products (Veleva and Ellenbecker, 2001). These six dimensions were considered while proposing the initial proposal of 11 principles. Based on a literature review and the experience of the research team, the nine principles in Veleva and Ellenbecker (2001) were enhanced, integrating some and adding new ones (see Table 2). A more detailed explanation of this for the updated principles is presented below.

Veleva and Ellenbecker's (2011) principles were used as a starting point for developing a new set of principles based on the definition of Sustainable Production (Veleva and Ellenbecker, 2001). Some of the principles were adapted and new principles were added as a result of integrating the SP principles into the context of Circular Economy and Industry 4.0. For example, Veleva and Ellenbecker's (2001) environmental principles promoted the reduction, reuse and/or recycling of energy and materials (3R strategy). These principles have been the most frequent strategies to address Sustainable Production in the first years of the 21st century (Barreiro-Gen and Lozano, 2020). However, these 3R strategies were considered to be insufficient to address sustainability in a Circular Economy context. Therefore, one of the principles already stated in the proposal by Veleva and Ellenbecker (2001) was adapted to include the broader 9R strategies (Potting et al., 2017), which also include the possibility of Refusing some products and Rethinking the product and/or processes to achieve a more intensive use, (see principles 1,2,3 in the initial proposal).

Moreover, the social dimension of sustainability is not only about employee health care and capacity building, but also the importance of strengthening the criteria of inclusion and diversity in organizations, considering social class, gender, age group, cultural identity, disability, etc. across all areas of the company (Stock et al., 2018) (see principle 5 and 6 in the initial proposal).

At the same time, the concept of Sustainable Circular Economy is understood from a holistic, whole-system perspective, taking into account the environmental, social and human aspects of the local context (Velenturf and Purnell, 2021). Production or manufacturing are part of the value chain of a product or service and, therefore, should never be seen as a system isolated from the rest of the value chain. This idea was included as a part of a new principle of SP (see principle 8 in the initial proposal).

Furthermore, the successful transition to a CE paradigm requires an industrial metabolism to close loops across different value chains (Prieto-Sandoval et al., 2018). Chertow (2000) defines Industrial Symbiosis (IS) as "*the activity that engages traditionally separate industries in a collective approach to gain a competitive advantage involving the physical exchange of materials, energy, water and/or by-products*" (Chertow, 2000, p. 313). IS, which is part of the so-called industrial ecology, contributes to sustainability with environmental, economic and social benefits (Neves et al., 2020). In a review of scientific articles on IS, these same authors identify manufacturing as one of the sectors with the greatest presence in these studies. According to Neves et al. (2020), this is "*due to the waste that this sector generates but also to its capacity to integrate by-products and waste into its production cycle*". In accordance with these ideas, we consider that promoting inter-industry relations that involve a physical exchange of water, materials, energy, and by-products should be considered as a further principle of SP (see principle 9 in the initial proposal).

Moreover, the evolutionary perspective of the sustainability concept makes it necessary to monitor, evaluate, control and continuously adapt production operations to keep them sustainable (Dubey et al., 2017; Velenturf and Purnell, 2021) (see principle 10 in the initial proposal). Industry 4.0 boosts digitizing transversal and vertical processes, capturing, analyzing and processing data for explanatory and predictive purposes, tracking, monitoring and controling production systems, and communicating and exchanging information between different stakeholders. To this end, it is considered necessary to establish as a principle the need for the digitalization of production processes consistent with the objectives of sustainability through the use of green computer systems and green algorithms (Tyurin and Kamenskih, 2017; Lannelongue et al., 2021) (see principle 11 in the initial proposal). The adoption of other I4.0 technologies will need to be carefully evaluated to analyze their impact on sustainability in each case (Bai et al., 2020).

4.2 Results from the Delphi Panel

Based on the experts' comments, the Principles of Sustainable Production initially proposed were modified as shown in Table 2. Two rounds were carried out to reach a consensus.

Table 2. Results from the Delphi Panel

Phases	Methodology	Phases	Methodology	Phases	Methodology	Phases
Veleva and Ellenbecker (2001)	**Literature review & Research Team experience**	**Initial proposal**	**Delphi results, Literature review & Research Team experience**	**First round results**	**Delphi results, Literature review & Research Team experience**	**Second round results**
Products and packaging are designed to be safe and ecologically sound throughout their life cycles; services are designed to be safe and ecologically sound.	Enhanced	**(1) Design for circularity**	Enhanced	**(1) Design for circularity**	Maintained	**(1) Design for circularity**
Energy and materials are conserved, and the forms of energy and materials used are most appropriate for the desired ends.	Enhanced	**(2) Conserve flows of resources**	Enhanced	**(2) Conserve resources and preserve their value**	Maintained	**(2) Conserve resources and preserve their value.**
Wastes and ecologically incompatible byproducts are continuously reduced, eliminated, or recycled.	Enhanced	**(3) Follow a sustainable management of waste**	Enhanced	**(3) Manage waste sustainably**	Maintained	**(3) Manage waste sustainably**
Chemical substances, physical agents, technologies, and work	Integrated	**(4) Ensure a risk-free environment**	Divided into two	**(4) Pursue a risk-free environment**	Maintained	**(4) Pursue a risk-free environment**

practices that present hazards to human health or the environment are continuously reduced or eliminated.						
Workplaces are designed to minimize or eliminate physical, chemical, biological, and ergonomic hazards.				**(5) Prioritize employees' well-being**	Enhanced	**(5) Prioritize employees' well-being**
Management is committed to an open, participatory process of continuous evaluation and improvement, focused on the long-term economic performance of the firm.	Enhanced	**(5) Develop a sustainable organizational culture**	Integrated	**(6) Enhance management commitment to sustainability**	Enhanced	**(6) Enhance management commitment to sustainability**
Work is organized to conserve and enhance the efficiency and creativity of employees.	Integrated	**(6) Enhance a sustainable work environment**				
The security and well-being of all employees are a priority, as is the continuous development of their talents and capacities.						
The communities around workplaces are respected and enhanced economically, socially, culturally, and physically; equity and fairness are promoted.	Enhanced	**(7) Pursue a corporate social responsibility to surroundings**	Enhanced	**(7) Engage in Corporate Social Responsibility**	Enhanced	**(7) Make a positive contribution to the community**
New principles added		**(8) Embrace the value chain vision**	Enhanced	**(8) Promote value chain stakeholder collaboration**	Maintained	**(8) Promote value chain stakeholder collaboration**
		(9) Foster industrial symbiosis	Included in new principle 2			

	(10) Monitorization and control of the sustainability of processes	Enhanced	**(9) Measure and optimize sustainable processes**	Enhanced	**(9) Measure and optimize sustainable processes**
	(11) Boost the use of sustainable technologies	Enhanced	**(10) Boost the use of sustainable technologies**	Maintained	**(10) Boost the use of sustainable technologies**

During these two rounds, the principles were adjusted to meet the comments and suggestions of the experts. Some principles were integrated into one, while others were separated into new principles for better understanding.

4.2.1 First Round of the Delphi Panel:

Figure 3 summarizes the performance of the first round of the Delphi Panel. The columns represent the % of experts that agree with the statement presented in questions 1 (Q1) and question 2 (Q2) for each principle and the lines represent the percentage of experts who make comments on each principle. Once all the experts' comments were collected, the research team identified the main points to address in order to reformulate the principles and tried to integrate the new ideas suggested by the experts. Table 2 shows that all the principles were changed. However, there were some in which deeper changes were made. As shown in Figure 3, Principles 3 ("*Follow sustainable management of waste"*) and 4 ("*Ensure a risk-free environment"*) were the less clear (concerning question 1). Therefore, Principle 4 was divided into two new principles ("Pursue a risk-free environment") & ("*Prioritize employees' well-being*"). Principles 5 ("*Develop a sustainable organizational culture*") and 6 ("*Enhance a sustainable work environment*") were integrated into a new principle (*"Enhance management commitment with sustainability"*). Furthermore, Principle 9 ("*Foster industrial symbiosis"*) was eliminated because the idea of industrial symbiosis was considered a way to achieve Principle 2 (*"Conserve resources and preserve their value"*).

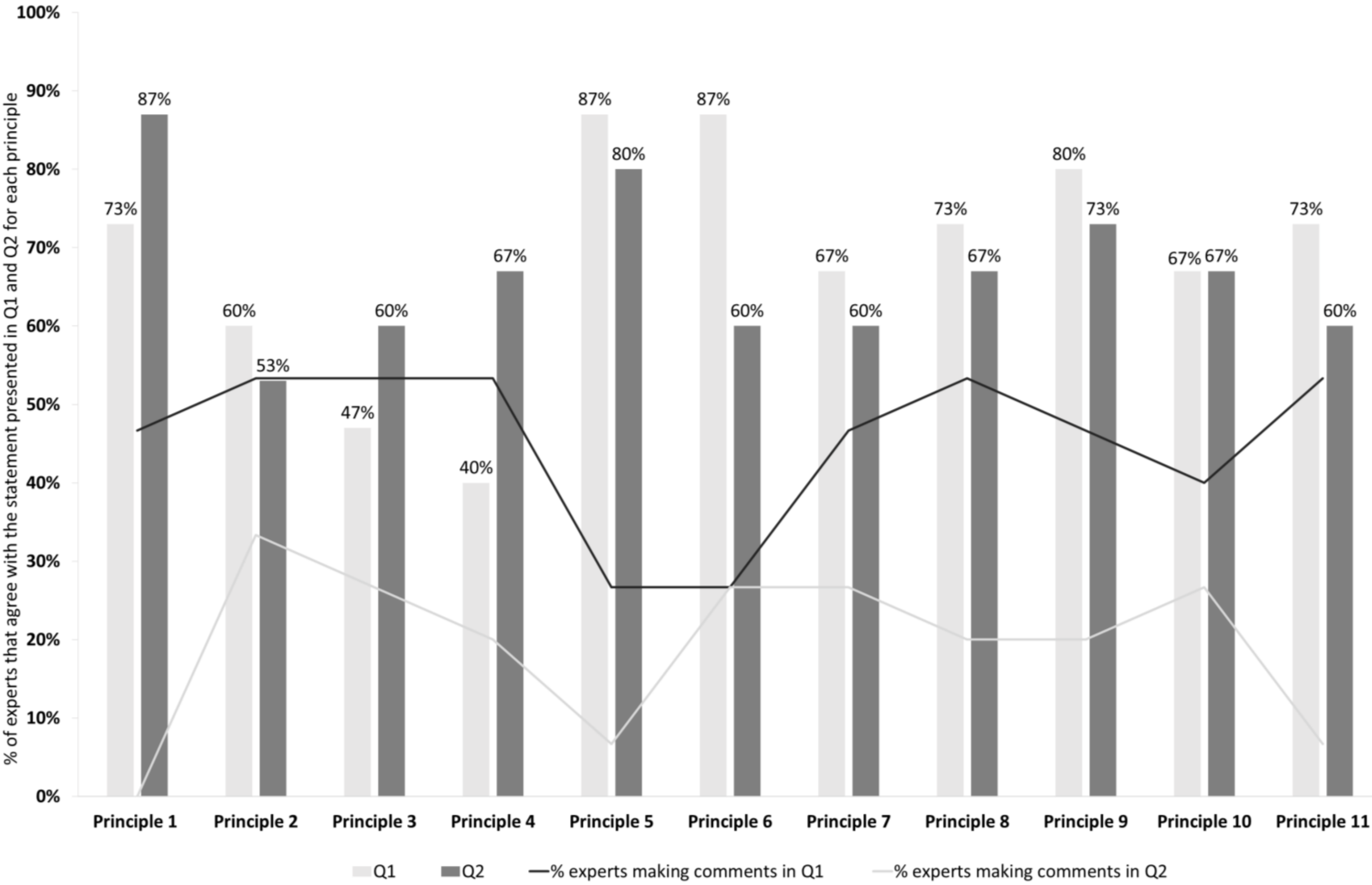

Figure 3. First round of Delphi Panel

According to the experts, most of the principles were consistent with the theory and concepts about sustainability and Circular Economy (second question).

4.2.2 Second Round of the Delphi Panel:

In the second round, the participants were asked the question *"Do you consider that this principle is stated clearly and concisely and covers all the relevant aspects regarding its definition?*" Since the majority of the experts agreed on the question proposed (Figure 4), only minor changes were made to the final proposal of principles.

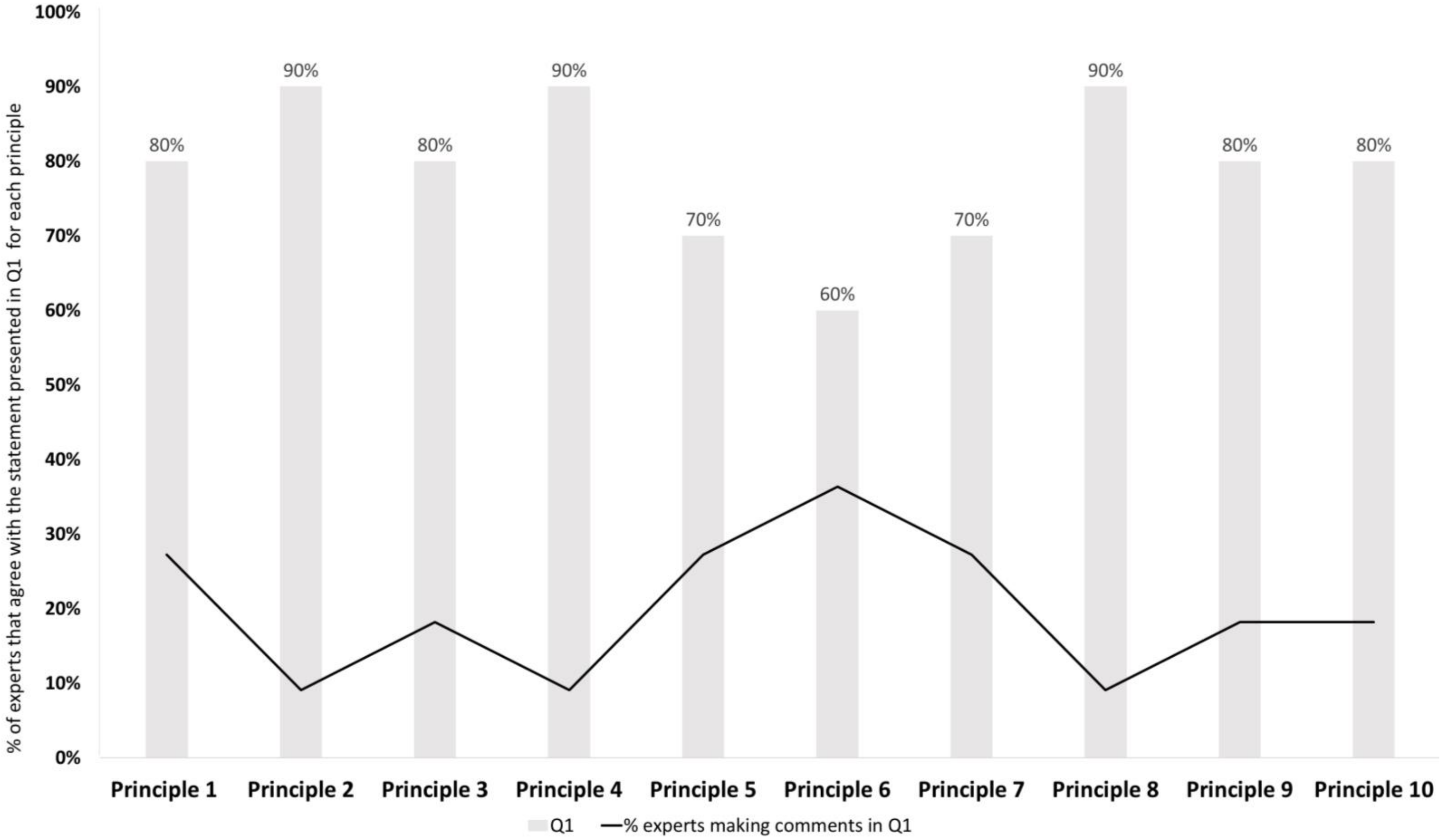

Figure 4. Second round of the Delphi Panel

Principle 6 (*"Enhance management commitment with sustainability"*) received various comments from the experts, as shown in Figure 4. Thus, this principle was reformulated to adjust the definition to the suggestions proposed. Minor changes were made in this second round to Principles 5 ("Prioritize employees' well-being"), 7 ("*Engage in Corporate Social Responsibility"*) and 9 (*"Measure and optimize sustainable processes"*). Therefore, since the majority of experts agreed with the statement presented in the question, the Delphi study was considered completed in this second round.

As shown in Table 3, the final version of the principles consisted of ten principles of Sustainable Production that were considered for the ISM analysis.

Table 3. Principles of Sustainable Production

Final version of Sustainable Production Principles
(1) Design for circularity. Design processes, products, and packing to consume minimum natural resources and energy to sustain the ecosystem's regenerative capacities. Follow design for disassembly to allow - if possible - for recycling, repairing, reconditioning, refurbishing, or remanufacturing.
(2) Conserve resources and preserve their value. Use the appropriate natural resources and energy for the desired sustainable goals. Preserve the value of resources for as long as possible within production facilities (internal recirculation) and consider the concept of industrial symbiosis to circulate resources (external recirculation).
(3) Manage waste sustainably. Emphasize waste-prevention activities by reintroducing resources within the intended flow. For resources that reach the waste management stage, use the waste management hierarchy following these strategies: reduce waste, then reuse and recycle, minimizing all disposal routes, including landfilling and waste to energy.
(4) Pursue a risk-free environment. Reduce or eliminate chemical substances, physical agents, and technologies that present a risk to the environment. Reduce GHGs emissions to reach net-zero emissions.
(5) Prioritize employees' well-being. Embed employee safety and well-being in the day-to-day work. Choose practices and workplaces that preserve the physical, functional, and psychological comfort of employees.
(6) Enhance management commitment to sustainability. Establish an organizational culture enabling high sustainability performance. Empower employees and develop their talents. Promote diversity, equity and inclusion in the workplace.
(7) Make a positive contribution to the community. Contribute to better economic, environmental, social, cultural, and physical outcomes of the communities in which the company operates and in those where its decisions can have an impact.
(8) Promote value chain stakeholder collaboration. Establish fluid communication and collaboration with all the stakeholders of your value chain to make processes and products more sustainable.
(9) Measure and optimize sustainable processes. Define a set of "Key Performance Indicators" to optimize production processes. Monitor short- and long-term sustainability performance of the production system by encouraging digitalization.
(10) Boost the use of sustainable technologies. Improve existing technologies with more sustainable alternatives, and provide information on both the potential benefits and risks to Sustainable Production. Consider Best Available Techniques; these techniques involve both the technology used and the design, construction, maintenance, and operation of the installation.

4.3 ISM analysis and results

Based on the IRM (Table A1, Appendix A) completed by the experts, the ISM method was applied, and a digraph plot was created as shown in Figure 5. The arrows further link the principles based on the relations derived from the IRM (Gani et al., 2022). It is important to highlight that three pair relationships, PR4-PR5, PR6-PR5 and PR8-PR1, were eliminated at this stage since the ISM follows a bottom-up approach, and the presence of these links would have generated top-down links in the final ISM model (Vimal et al., 2022).

The bottom-up approach that the ISM follows is based on the Level Partition done in the Reachability Matrix. The elements are arranged graphically in levels and the directed links are drawn as per the relationships shown in the reachability matrix (Sushil, 2012). The elements in the top level of the hierarchy will not reach any elements above their own level.

Figure 5 shows the ISM model, which indicates the significant impact of Principles 5 ("*Prioritize employees' well-being*"), 6 ("*Enhance management commitment to sustainability*"), 9 ("M*easure and optimize sustainable processes*"), and 10 ("*Boost the use of sustainable technologies*") on the others.

The IRM was transformed into an FRM (Table A2, Appendix A) after checking the transitive links. From this matrix, the reachability and antecedents set were performed as presented in Table 4. For a given principle, the "reachability set" included the principle itself and the principles it may affect, whereas the "antecedent set" consisted of the principle itself and the principles affecting it.

Subsequently, the intersection of both sets was obtained for all principles and the level of each principle was determined. The principles with the same reachability and intersection set occupy the first level (Poduval et al., 2015). To assess the next level, the first-level principles were then isolated from the other principles for the next stage-iteration. The method was then repeated to assign a level to each principle. Table 4 also shows the level partitioning of the principles to be placed in the ISM model.

Table 4. Level partitioning of Sustainable Production Principles

Principles	Reachability set	Antecedent set	Intersection set	Levels
PR 1	[1,2,3,7,8]	[1,6,7,8,9,10]	[1]	II
PR 2	[2,3,7,8]	[1,2,3,4,6,7,8,9,10]	[2,3,7,8]	I
PR 3	[2,3,7,8]	[1,2,3,4,5,6,7,8,9,10]	[2,3,7,8]	I
PR 4	[2,3,4,5,6,7,8]	[4,5,6,9,10]	[4,5,6]	II
PR 5	[3,4,5,6,7,8,9,10]	[4,5,6,9]	[5]	IV
PR 6	[1,2,3,4,5,6,7,8,9,10]	[4,5,6,9,10]	[5,6,9,10]	III
PR 7	[1,2,3,7,8]	[1,2,3,4,5,6,7,8,9,10]	[1,2,3,7,8]	I
PR 8	[1,2,3,7,8]	[1,2,3,4,5,6,7,8,9,10]	[1,2,3,7,8]	I
PR 9	[1,2,3,4,5,6,7,8,9,10]	[5,6,9,10]	[5,6,9,10]	III
PR 10	[1,2,3,4,6,7,8,9,10]	[5,6,9,10]	[6,9,10]	III

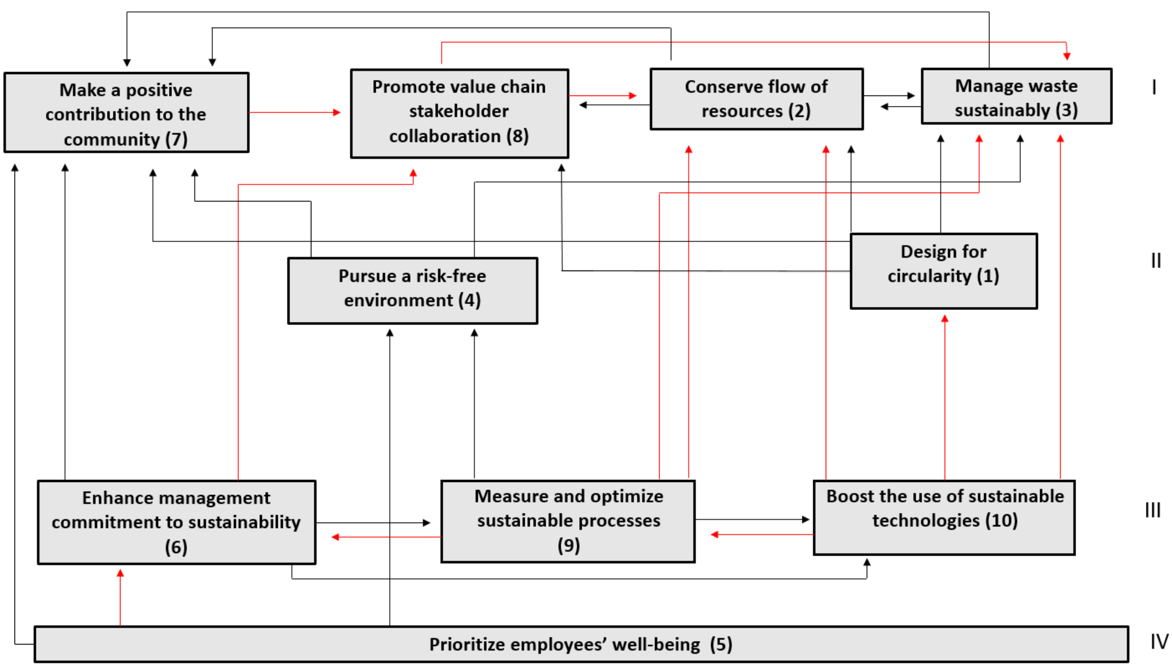

Figure 5. ISM for Sustainable Production. Interesting relationships are highlighted in red.

The ISM model (Figure 5) shows that the level partitioning resulted in a digraph consisting of four levels, where the topmost level indicates the most dependent principles and the bottommost level, the most driving principle (independent). The structural model presented in Figure 5 represents the ten principles in the four levels. In level I, Principles 7 (*"Make a positive contribution to the community"), 8 ("Promote value chain stakeholder collaboration", 2 ("Conserve resources and preserve their value"), and 3 (Manage waste sustainably)* are dependent on the other principles. The lowest level (level IV) represents the principle that leads to achieving the principles in level I, through mediating principles (the ones in levels II and III). For this study, Principle 5 (*"Prioritize employees' well-being")* is located at the lowest level and Principle 6 (*"Enhance management commitment to sustainability");* Principle 9 *("Measure and optimize sustainable processes");* Principle 10 *(Boost the use of sustainable technologies);* Principle 1 *("Design for circularity");* and Principle 4 *("Pursue a risk-free environment")* constitute the mediating principles.

4.3.1 Categorization of Principles using MICMAC analysis:

The ISM methodology was followed by a MICMAC (Cross Impact Multiplication Matrix) analysis to classify the principles and determine their relative influencing power. First, the driving power and dependence power of each variable were calculated by summing up the 0s and 1s in the columns and rows corresponding to each variable. Then, the principles were classified into four quadrants based on their driving power (along the y-axis) and dependence power (along the x-axis), as shown in Figure 6.

The principles located in the first quadrant are termed autonomous principles. However, none of the principles fell within this category (considering transitive links). The principles located in the second quadrant are termed dependent principles, which means that they have a strong dependence power but a weak driving power. This result can be interpreted to mean that these principles have a substantial influence on the system but are not influenced by it and that they are sensitive to the actions of the influencing principles. Principles 2 *("Conserve resources and preserve their value")* and 3 *(Manage waste sustainably)* are dependent, as also presented in Figure 5.

The principles located in the fourth quadrant are known as independent principles, which means that they have a strong driving power and weak dependence power. This suggests that these principles strongly influence the system but are not influenced by the system. Any action on these principles will affect other principles, which are dependent on them. Principles 5 ("*Prioritize employees' well-being*"), 9 ("M*easure and optimize sustainable processes*"), and 10 ("*Boost the use of sustainable technologies*") fall into this category.

The MICMAC analysis shows that there is a discrepancy in Principles (1), (4), (6), (7) and (8). This discrepancy arises due to the presence of transitive links from these principles. If the transitive links are removed and the direct links presented in the digraph considered, Principles 1 (*"Design for circularity"*) and 4 *("Pursue a risk-free environment")* are autonomous factors, which means that due to their weak driving and dependence power they do not affect the system to a great extent. Principles 7 ("*Make a positive contribution to the community*") and 8 ("*Promote value chain stakeholder collaboration*") are dependent, while Principle 6 (*"Enhance management commitment to sustainability"*) is independent.

Table 5. Driving and Dependence power

	PR1	PR1	PR3	PR4	PR5	PR6	PR7	PR8	PR9	PR10
Driving Power	5	4	4	7	8	10	5	5	10	9
Dependence Power	6	9	10	5	4	5	10	10	4	4

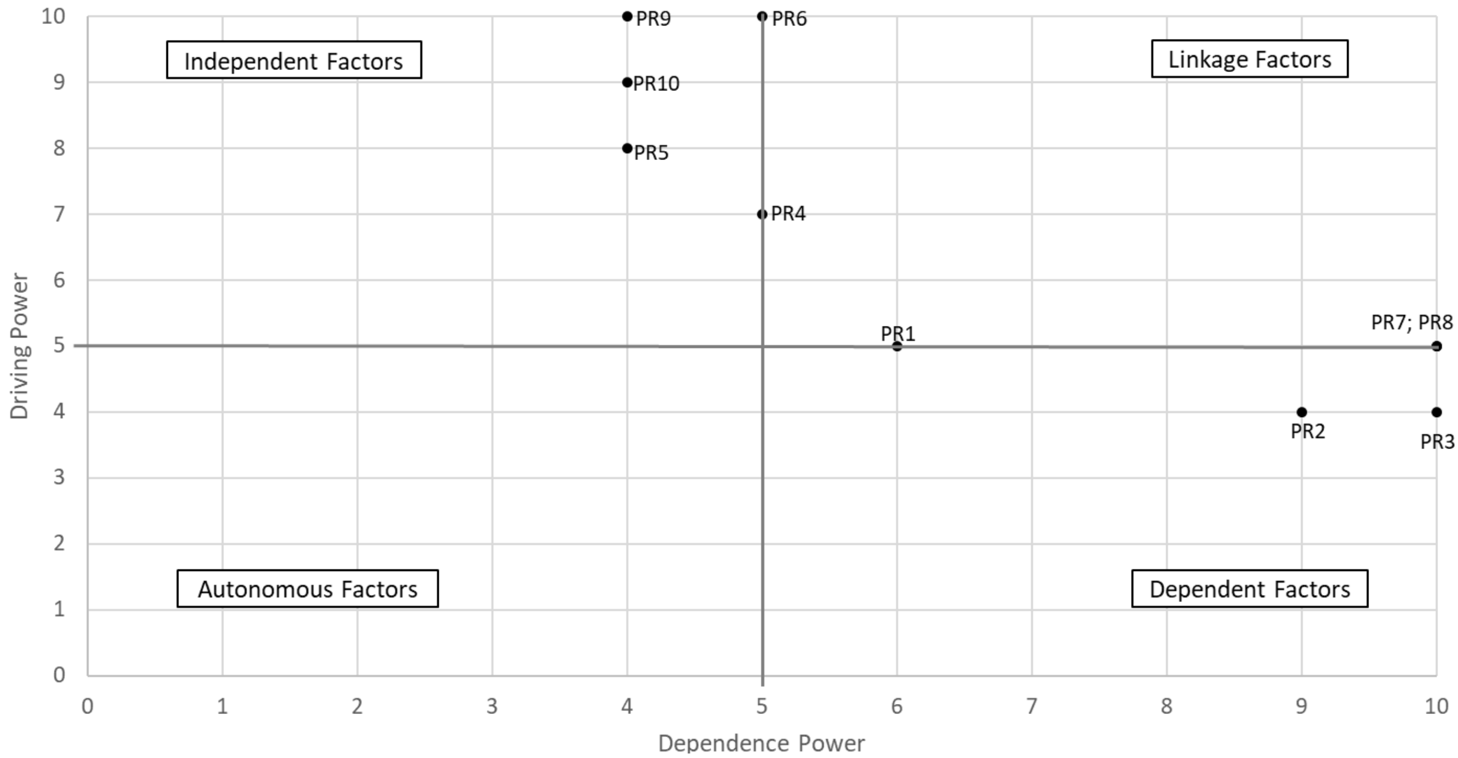

Figure 6. MICMAC Analysis

5 Discussion

More than 20 years ago, Veleva and Ellenbecker (2001) enunciated nine principles of Sustainable Production, which consider in their definition the three dimensions of sustainability (Alayón et al., 2017). Over the past 20 years, the definition of these principles has not been questioned, but industry and the economy in which production is framed have evolved significantly towards a more Circular Economy (Prieto-Sandoval et al., 2018a) and smarter industry (Nakayama et al., 2020). Thus, what are the principles governing Sustainable Production in the current context?

Considering that both industry and the economy are immersed in profound changes, we took Veleva and Ellenbecker's (2001) nine principles of Sustainable Production and proposed 11 updated principles that help understand how Sustainable Production should work in the current context of Circular Economy and Industry 4.0. After applying the Delphi method with 11 experts, a consensus was reached on ten principles governing Sustainable Production, thus contributing to some of the targets proposed in SDG 12.

5.1 Updated Principles of Sustainable Production

The results indicate that the updated principles maintain the essence of most of the initiatives expressed in Veleva and Ellenbecker (2001) (Principles 1-7) while incorporating important nuances in their definitions. These nuances arise fundamentally from the theoretical and practical progress made in these 20 years by the Circular Economy and the commitment of institutions to Sustainable Development by encouraging, among other things, investment in environmentally friendly technologies (Schöggl et al., 2020; Commission, 2018, page 773). Principles 1-3 are mostly aligned with the principles proposed by Suárez-Eiroa et al. (2019):

Designing for circular economy, Maintaining resource value within the system, and Closing the system.

The principles most closely related to the social dimension of sustainability (5-7) have also been nuanced. The inclusion of these principles covers the social gap associated with achieving ecological objectives, and with concerns such as equity, gender equality, and access to education mentioned by Suárez-Eiroa et al. (2019) in their study. At an organizational level, diversity, equity, and inclusion are promoted in the workplace. At a community level, it is made explicit that companies must contribute to social, economic and environmental development not only in the place where they operate but also in places where their decisions have an impact.

The definition of three new principles (Principles 8-10) is confirmed as a result of analyzing Sustainable Production in an economic context increasingly concerned with the environment and biodiversity, as is the Circular Economy (EMF, 2021c), and taking into account the rapid development of technologies associated with Industry 4.0.

In recent years, various authors have argued that green manufacturing and integrating sustainability in the sustainable value chain provide competitive advantages to organizations (Khan et al., 2021; Raut et al., 2019). Wolf and Seuring (2010) define sustainable supply chains as "cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development." Principle 8 ("*Promote value chain stakeholder collaboration*") explicitly expresses the need for organizations to inculcate communication and coordination with the rest of the actors in the value chain that promotes increasingly sustainably production within the framework of the Circular Economy (Velenturf and Purnell, 2021).

Some of the Industry 4.0 technologies are being developed to achieve more Sustainable Production. However, technology is not sustainable by merely serving to achieve or improve the circularity of a product or process or trying to reduce resource consumption. Sustainable technology must comply with the fundamental aspects of the concept of sustainability at all stages (creation, implementation, use and end of use). While the economic dimension of technologies in the framework of Industry 4.0 has been widely analyzed, there is still a lack of research and analysis on the environmental and social dimensions in the development of these technologies (Birkel and Müller, 2021). Principle 10 ("*Boost the use of sustainable technologies*") promotes the incorporation of new sustainable techniques in the fields of facility design, construction, maintenance and operation, whose positive effects on the three axes of sustainability have already been tested and evaluated.

Furthermore, the difficulty of specifying the definition of sustainability in clear objectives discourages company managers who have traditionally focused on measuring economic and operational results (Henao and Sarache, 2022). Principle 9 ("*Measure and optimize sustainable processes*") considers it essential to monitor, measure and control production processes in the three aspects of sustainability. The exponential growth of new technologies linked to data science should lead to the use of metrics and indicators that enable managers to incorporate sustainability criteria in decision-making. However, in some cases, monitoring and measurement may require greater sensorization and digitalization of production processes. This should be implemented as long as the balance of Sustainable Production is not upset due to an energy increase in smart production systems (Birkel and Müller, 2021; Birkel et al., 2019). A prior analysis of the real monitoring needs should also be carried out to adjust the number of sensors deployed to only those necessary to collect the information required to control or improve processes and minimize the environmental impact of their installation. In this regard, principle 9 is aligned with principle 10: “Whole system assessment” presented in Velenturf and Purnell (2021), which highlights the importance of utilizing a whole system approach through a process of continuous improvement driven by whole system assessments using holistic indicators before, during, and after the implementation of circular economy practices.

Ultimately, the principles of Sustainable Production encompass not only design and production operations but also the adoption and management of technologies, people care and management, interaction and communication among manufacturers and other value chain stakeholders, and contribution to the community. The speed in the development of new technological innovations and the progression of climate change, together with the new economic, political and social context, demonstrate the need for flexible production systems that facilitate and accelerate the development of sustainable initiatives that may result from applying the principles. Achieving flexibility throughout the entire value chain is one of the current priorities in the framework of sustainable value chains (Dwivedi et al., 2021).

5.2 Relationships between the Principles

The ISM analysis has made it possible to identify relationships between the principles, a novelty not yet addressed in the literature. These relationships can help to understand certain connections between the principles that are of interest for further in-depth study and implementation. As seen in Figure 5, the ISM methodology makes it possible to identify from these relationships which principles can be considered independent, and which can be considered dependent. This identification, linked to a certain extent to Levels I, II, II and IV in Figure 5, should not be understood as a message of prioritization in applying these principles, but rather that the development of some principles can be enhanced by the development of others.

On the one hand, according to Figure 5, the principles of Sustainable Production that appear as independent (i.e., none of the other principles helps to fulfil these principles) are Principles 5 ("*Prioritize employees' well-being*"), 6 ("*Enhance management commitment to sustainability*"), 9 ("*Measure and optimize sustainable processes*") and 10 ("*Boost the use of sustainable technologies*"). However, these four principles act as drivers of Sustainable Production and help to establish an ideal context to enhance the development of the rest of the principles. On the other hand, the principles whose application benefits most from the development of other principles are Principle 2 ("*Conserve resources and preserve their value*"), Principle 3 ("*Manage waste sustainably*") and Principle 7 ("*Make a positive contribution to the community*").

It is worth highlighting that some of the principles aligned with the social dimension of sustainability (Principles 5 and 6) appear as enhancers of others when traditionally the study of sustainability in the field of production has been more oriented to the economic and environmental dimension (Birkel et al., 2019). Identifying this relationship can serve as a starting point for further research on how the development of the social aspect of sustainability in the field of production helps to achieve the development of principles more closely linked to the environmental dimension.

By going deeper into the relationships between principles, 30 strong relationships have been identified, as seen in Figure 5. Of these 30 relationships, some have been widely discussed in the literature, such as the relationships between Principle 1 ("*Design for circularity*") and its positive effect on Principles 2 ("*Conserve resources and preserve their value*"), 3 ("*Manage waste sustainably*"), and 8 ("*Promote value chain stakeholder collaboration*"), and on the relationship between Principle 6 ("*Enhance management commitment to sustainability*") and Principle 7 ("*Make a positive contribution to the community*"). Therefore, in this discussion, we focused on analyzing the relationships obtained from the three new principles added in relation to the ones presented in Veleva and Ellenbecker (2001). Figure 5 also shows in red the relationships that will be discussed below.

A recent literature review on sustainable supply chain management of 362 articles published from 2004-2019 (Khan et al., 2021) collected information about different authors who have identified various drivers of a sustainable value chain. These drivers are the creation of organizational culture (Khan and Qianli, 2017, 2016; Brandenburg et al., 2014 cited in Khan et al., 2021) and the involvement of leaders (Govindan et al., 2015 cited in Khan et al., 2021). Employee training and coaching (Yadav et al., 2018 cited in Khan et al., 2021) and employee health and safety aspects (Distelhorst et al., 2015; Mathiyazhagan et al., 2015 cited in Khan et al., 2021) were also identified as drivers of a sustainable value chain. These references, among others, are compatible with the relationship obtained in this study, which shows that promoting Principles 6 ("*Enhance management commitment to sustainability*") and 5 ("*Prioritize employees' well-being*") helps promote the development of Principle 8 ("*Promote value chain stakeholder collaboration*").

This study also suggests that Principle 7 ("*Make a positive contribution to the community*") can help to achieve Principle 8 ("*Promote value chain stakeholder collaboration*"), something that has not been previously established in the literature. One possible explanation for this relationship is that Principle 7 makes explicit the importance of contributing positively to sustainable development both in the place where the company operates and in places that are also impacted by its strategic and operational decisions. This second fact can help producers to promote closer collaboration with supply chain stakeholders in these other places.

Figure 5 also shows that the development of Principle 8 ("*Promote value chain stakeholder collaboration*") can help to comply with Principles 2 ("*Conserve resources and preserve their value*") and 3 ("*Manage waste sustainably*"). These results are aligned with the evidence shown by some authors in relation to how evaluation and active collaboration with suppliers have a positive effect on the environmental performance of organizations (Gimenez and Tachizawa, 2012). It also coincides with other authors who argue the importance of collaborating between organizations in the framework of Circular Economy practices (Dora, 2020; Mishra et al., 2019), while recognizing the real difficulty of achieving this (Khan et al., 2021).

In relation to Principle 9 ("*Measure and optimize sustainable processes*"), from the study conducted with the experts, it can be deduced that being able to measure processes helps to comply with Principles 2 ("*Conserve resources and preserve their value*"), 3 ("*Manage waste sustainably*") and 6 ("*Enhance management commitment to sustainability*"). Principle 6 promotes the establishment of a clear strategy and objectives for the entire organization in relation to the three dimensions of sustainability. This is a key principle since the lack of management support is considered a barrier when it comes to the implementation of sustainable practices (Tanco et al., 2021). Without a set of key metrics and indicators, it is not possible to monitor compliance with the objectives. Currently, many indicators are proposed to do such monitoring on a general or sectoral basis (Waltersmann et al., 2019; GRI, 2016; Veleva and Ellenbecker, 2001). According to Swarnakar et al. (2021) and Roos Lindgreen et al. (2022) the assessment of sustainability in production processes helps to identify and recognize opportunities for improvement and, therefore, to make continuous progress towards Sustainable Production.

Principle 10 ("*Boost the use of sustainable technologies*") arises from identifying that the great technological development of recent years can accelerate the transition to Sustainable Production systems. From this study, it can be deduced that introducing new sustainable technologies in the field of production can help to comply with Principles 1 ("*Design for circularity*"), 2 ("*Conserve resources and preserve their value*"), 3 ("*Manage waste sustainably*"), and 9 ("*Measure and optimize sustainable processes*"). As an example of these relationships, several authors who recognize the importance of smart technologies as a basis for the development of Sustainable Production were identified. For example, Ghobakhloo and Fathi (2021) suggested that the digitization of the energy sector, the digitalization of the manufacturing industry, and the introduction of new, smarter and more sustainable products are the main opportunities for achieving sustainable energy (that which offers the most effective and balanced combination of economic, social and environmental impacts). Research in the field of technology applied to waste management focuses on the significant efforts being made to solve the problems of separating different types of waste (plastic waste, electronic waste, polymer waste, etc.) to convert them into useful resources (new building materials, regeneration of valuable metals, production and hydrogen, etc.) (Nižetić et al., 2019). In the social dimension, we also found authors who analyzed the potential of Industry 4.0 to help improve the health and workplace of employees, as well as improve employee empowerment and help them develop their talents (Birkel et al., 2019). However, most of the new proposals raise a concern about the amount of energy required by the new technologies under development and which, in some cases, makes them unfeasible for the time being. It is also deemed necessary to promote the development of sustainable technological research that incorporates sustainability criteria from design. In this way, the challenges to be addressed can be identified in the early stages of development and, once resolved, incorporated into production systems.

Finally, it is interesting to see how the model of relationships that has emerged from this study is in line with what the European Commission has recently begun to promote as a new approach to industry (called Industry 5.0). In this new approach, "the well-being of the worker is placed at the heart of the production process and uses new technologies to deliver prosperity beyond employment and growth while respecting the production limits of the planet" (European Commission, 2021).

5.3 Contribution to SDG 12

SDG 12 is meant to "ensure good use of resources, improving energy efficiency, sustainable infrastructure, and providing access to green products and services, decent jobs and ensuring a better quality of life for all" (United Nations General Assembly, 2017).

According to the definition of the ten SP principles, their contribution to SDG 12 is noticeable. Specifically, the declaration and updating of the SP principles aim to inform people in general, and company managers in particular, about what it means to contribute to sustainable development from productive systems (target 12.8). Furthermore, providing this information and clarifying it also aims to encourage businesses of all sizes to adopt sustainable practices (target 12.6).

Therefore, deploying business strategies aligned with the principles of Sustainable Production presented here will contribute to achieving sustainable management and efficient use of natural resources by manufacturing companies (target 12.2); reducing the release of pollutants, especially chemicals (target 12.4); and reducing waste (target 12.5) by promoting the application of circular and sustainable design strategies and waste management following the waste hierarchy. In addition, the SP principles applied to agri-food industry enterprises will help to make better use of harvested products entering the food production chains and thus reduce food losses along production chains (target 12.3).

Finally, as can be deduced from the SP principles, production should not be seen as an activity isolated from the rest of the value chain; rather, production should promote active collaboration with all the stakeholders in the value chain in order to advance sustainability with a more holistic vision and commit to making a positive contribution to the communities in which production companies operate. Therefore, the monitoring of production models based on the SP principles of companies in developed countries can contribute to promoting Sustainable Production models in developing countries through their trade agreements (target 12.1), helping them to move towards more Sustainable Production methods (target 12.A).

5.4 Limitations

This study is not free from limitations. First, it is important to highlight that consumers are relevant actors in the field of sustainability and Circular Economy. This study has been undertaken from the production perspective, assuming environmentally responsible and sustainable consumption and not questioning the quality of the resulting products.

Furthermore, the limitations of the method used in this study are linked to the use of the Delphi method since the Delphi-study group was relatively small.

6. Conclusions

The main objective of this paper is to shed light and clarity on the definition of the principles that characterize Sustainable Production. These principles will also help manufacturing companies primarily to identify different strategies to help them move toward more Sustainable Production.

As a result of this study, ten principles evaluated by experts according to criteria of significance, parsimony, semantic consistency, and empirical adequacy have been proposed. Moreover, this study has made it possible to identify which principles are more independent and which are more dependent on the others and to establish relationships between them. According to this study, Principle 5 ("*Prioritize employees' well-being*"), Principle 6 ("*Enhance management commitment to sustainability*"), Principle 9 ("*Measure and optimize sustainable processes*"), and Principle 10 ("*Boost the use of sustainable technologies*") help to establish an ideal context to enhance the development of the rest of the principles. This study also suggests that Principle 7 ("*Make a positive contribution to the community*") can help to achieve Principle 8 ("*Promote value chain stakeholder collaboration*"), an observation that has not been previously established in the literature.

In terms of its theoretical value, the study contributes to the definition of SP principles and the analysis of the relationships among them with the aim of clarifying the organizational, human, and technological implications associated with Sustainable Production in the context of Circular Economy and Industry 4.0. Furthermore, the ISM analysis has made it possible to identify relationships between the principles, which is a novelty not yet addressed in the literature. These relationships can help to understand certain connections between the principles that are of interest for further in-depth study and implementation, which constitutes the main contribution of the present study.

In terms of practical implications, this study reveals that having clearly defined the principles governing SP operations and knowing how these principles interact could contribute to companies developing an orderly transition of their production processes towards Sustainable Production. Therefore, the presentation of the updated principles opens up new research possibilities, while helping producers to better understand such an abstract concept as sustainability, contributing in this way to achieving SDG 12. Additionally, the declaration of the principles of SP within the framework of a circular economy can facilitate the integration of circular and sustainability principles into EMS.

Further studies, from an operational perspective, would be needed to assess whether the actions based on the defined principles are compatible with the expectations for which they have been formulated, thus verifying the usefulness of the principles. This is not a simple task. All the principles should be established as standard practice in an organization in order to evaluate them over time. However, due to the advancement and promotion of Sustainable Production in recent years, successful practical results of the partial application of some of the principles can be found in the literature. In addition, the definition of these principles opens the door to aligning and classifying different business practices according to their contribution to these principles, which will help practitioners to promote the dissemination of well-founded success stories.

It is, therefore, necessary to move forward in the search for the most appropriate way to measure the progress of production systems towards more sustainable models. Aligning sustainability-related metrics and indicators in relation to these principles can result in a new framework for assessing Sustainable Production.

Furthermore, recent studies suggest that efforts made by companies today should be more focused on understanding whether the consumer is willing to recognize (with consistent purchasing behavior) the commitment of producers to both the circular and green dimensions. As stated earlier, the role of the consumer as part of the production system has not been analyzed in this paper. However, the incorporation of new principles that serve to enhance the co-responsibility of consumers and manufacturers in terms of Sustainable Production and consumption could be addressed in future studies.

Finally, as we can observe in this study, not all Sustainable Production principles act independently. It would be worthwhile to further understand the relationships obtained as a result of the ISM and to support them empirically to get the most out of the contribution of this research.

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Appendix

This section shows the results after implementing Step I (Initial Reachability Matrix) and Step II (Final Reachability Matrix) of the ISM technique. Based on the experts' comments, Table A1 shows the Initial Reachability Matrix. After checking transitivity links, Table A2 shows the Final Reachability Matrix.

Table A1. Initial Reachability Matrix

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	0	**1**	**1**	0	0	0	**1**	**1**	0	0
2	0	0	**1**	0	0	0	**1**	**1**	0	0
3	0	**1**	0	0	0	0	**1**	0	0	0
4	0	0	**1**	0	1	0	**1**	0	0	0
5	0	0	0	**1**	0	**1**	**1**	0	0	0
6	0	0	0	0	1	0	**1**	**1**	**1**	**1**
7	0	0	0	0	0	0	0	**1**	0	0
8	1	**1**	**1**	0	0	0	0	0	0	0
9	0	**1**	**1**	**1**	0	**1**	0	0	0	**1**
10	**1**	**1**	**1**	0	0	0	0	0	**1**	0

Table A2. Final Reachability Matrix

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	1	1	1	0	0	0	1	1	0	0
2	0	1	1	0	0	0	1	1	0	0
3	0	1	1	0	0	0	1	1	0	0
4	0	1	1	1	1	1	1	1	0	0
5	0	0	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1
7	1	1	1	0	0	0	1	1	0	0
8	1	1	1	0	0	0	1	1	0	0
9	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	0	1	1	1	1	1

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:
