Pontifícia Universidade Católica do Rio de Janeiro

Nathália Geronazzo Franco

A Strategic Measurement Model to Monitor and Evaluate Circularity Performance in Organizations from a Transition Perspective

Dissertação de Mestrado

Dissertation presented to the Programa de Pós-graduação em Metrologia of PUC-Rio in partial fulfillment of the requirements for the degree of Mestre em Metrologia.

Advisor: Prof. Maria Fatima Ludovico de Almeida

Co-advisor: Prof. Rodrigo Flora Calili

Rio de Janeiro
April 2021

PONTIFÍCIA UNIVERSIDADE CATÓLICA
DO RIO DE JANEIRO

Nathália Geronazzo Franco

A Strategic Measurement Model to Monitor and Evaluate Circularity Performance in Organizations from a Transition Perspective

Dissertation presented to the Programa de Pós-graduação em Metrologia of PUC-Rio in partial fulfillment of the requirements for the degree of Mestre em Metrologia. Approved by the Examination Committee:

Prof. Maria Fatima Ludovico de Almeida
Advisor
Programa de Pós-Graduação em Metrologia – PUC-Rio

Prof. Rodrigo Flora Calili
Co-advisor
Programa de Pós-Graduação em Metrologia – PUC-Rio

Prof. Simone Sehnem
Universidade do Oeste de Santa Catarina – UNOESC

Dr. Victoria Emilia Neves Santos
Centro de Tecnologia da Indústria Química e Têxtil

Prof. Helder Gomes Costa
Universidade Federal Fluminense – UFF

Rio de Janeiro, April 23rd, 2021

Nathália Geronazzo Franco

Environmental Scientist by the Federal University of the State of Rio de Janeiro. Member of the ABNT /CEE-323 Circular Economy Special Study Commission, a mirror of ISO/TC 323 – Circular economy, and Content Coordinator of the Brazilian Circular Economy Hub (NEC).

Bibliographic data

Franco, Nathália Geronazzo

A Strategic Measurement Model to Monitor and Evaluate Circularity Performance in Organizations from a Transition Perspective / Nathália Geronazzo Franco ; advisor: Maria Fatima Ludovico de Almeida ; co-advisor: Rodrigo Flora Calili. – 2021.

102 f. : il. color. ; 30 cm

Dissertação (mestrado)–Pontifícia Universidade Católica do Rio de Janeiro, Centro Técnico Científico, Programa de Pós-Graduação em Metrologia, 2021.

Inclui bibliografia

1. Metrologia – Teses. 2. Economia circular. 3. Medição de circularidade. 4. Teoria da transição sociotécnica. 5. Métodos multicritério de apoio à decisão. I. Almeida, Maria Fatima Ludovico de. II. Calili, Rodrigo Flora. III. Pontifícia Universidade Católica do Rio de Janeiro. Centro Técnico Científico. Programa de Pós-Graduação em Metrologia. IV. Título.

CDD: 389.1

Acknowledgements

To my advisors Prof. Maria Fatima Ludovico de Almeida and Prof. Rodrigo Flora Calili, whose expertise was invaluable in formulating the research questions and for choosing a hybrid methodological approach. Both presented me with such rich tools and encouraged me to overcome significant learning challenges. Their insightful feedback pushed me to sharpen my thinking and brought my work to a higher level.

To the women who inspired me in my scientific path through sustainability and circular economy: Ana Maria Oestreich, Ana Rúbia Carvalho, Beatriz Luz, Camila Carreiro, Dalia Ibrahim, Daniela Fontana, Dilma Pimentel, Efigênia Rossi, Fosca Poltronieri, Glaucia Terreo, Joana Alvarez, Josepha Potting, Juliana Veloso, Ladeja Košir, Marcela Tavares, Natália Chaves, Patricia Broers, Peggy De Rop, Priscilla Gomes, Raísa Moesch, Simone Lisboa, Simone Sehnem, Victoria Santos and, Wanda Alves. Thank you, ladies!

To my beloved family: Epaminondas Franco Neto, Viviane, Manoela, and João Carlos Geronazzo Franco, for a life of support; and to Lucas de Castelo, my partner of love and life, who shares with me the dream and the struggle for a fair, inclusive, and sustainable future.

To the participants of the second and third phases of the framework development, for their constructive discussions and judgments. As well, to my classmates in PósMQI, especially Manuel Calçada, for pushing me forward in rich debates and discussion!

I am grateful to Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (Capes) for the financial support.

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

Abstract

Franco, Nathalia Geronazzo; Almeida, Maria Fatima Ludovico de (Advisor); Calili, Rodrigo Flora (Co-advisor). **A Strategic Measurement Model to Monitor and Evaluate Circularity Performance in Organizations from a Transition Perspective.** Rio de Janeiro, 2021. 102p. Dissertação de Mestrado – Programa de Pós-Graduação em Metrologia, Pontifícia Universidade Católica do Rio de Janeiro.

The concept of a circular economy (CE) transition requires multi-level frameworks regarding the definition of goals and targets for different time horizons, desired change timeframes, sectoral circularity guidelines, and national and regional public policies, among other factors. Aiming to provide consistent frameworks for evidence-based business decisions with implications for the meso and macro levels of CE, the objective of this dissertation is to propose a strategic measurement model to monitoring and evaluating the circularity performance at the micro level by integrating GMA and two multicriteria decision-making methods. The main findings of this study are: (i) a generic morphological matrix comprising eight parameters and their possible states to define and visually represent possible CE transition scenarios for a given organization that aims to evolve through CE transitions; (ii) the potential use of a hybrid methodological approach (that combines GMA with two MCDM methods) for selecting the most relevant C-indicators for each R-strategy could be highlighted; (iii) an initial list of 58 C-indicators and metrics associated to ten R-strategies and a set of 38 selected C-indicators by adopting the hybrid AHP-TOPSIS method; (iv) definition of ten composite C-indicators associated with the R-strategies, as well as an overall Circularity Performance Index (CPI), and a step-by-step procedure to calculate them in different CE transition scenarios. From a CE transition perspective, the results highlighted practical implications for organizations and value chains, once the proposed model is designed to be applied in different business contexts, especially in those organizations that will define their circularity targets and respective agendas concerning CE transitions.

Keywords

Metrology; circular economy; circularity measurement; sociotechnical transition theory; morphological analysis; multicriteria decision-making methods.

Resumo

Franco, Nathalia Geronazzo; Almeida, Maria Fatima Ludovico de (Orientadora); Calili, Rodrigo Flora (Co-orientador). **Modelo estratégico de medição para monitorar e avaliar o desempenho em circularidade nas organizações, segundo uma perspectiva de transição.** Rio de Janeiro, 2021. 102p. Dissertação de Mestrado – Programa de Pós-Graduação em Metrologia, Pontifícia Universidade Católica do Rio de Janeiro.

A transição para uma economia circular (EC) requer modelos multidimensionais para a definição de objetivos e metas de circularidade em diferentes horizontes temporais, prazos, diretrizes circulares setoriais, políticas públicas nacionais e regionais, entre outros. Visando fornecer estruturas consistentes para decisões de negócios baseadas em evidências, com implicações para os níveis meso e macro de CE, o objetivo desta dissertação é propor um modelo de mensuração estratégica para monitorar e avaliar o desempenho da circularidade no nível micro, integrando GMA e dois métodos multicritério de tomada de decisão. Os principais resultados deste estudo envolvem: (i) uma matriz morfológica genérica composta por oito parâmetros e seus possíveis estados para definir e representar visualmente possíveis cenários de transição de CE para uma determinada organização que pretende evoluir através de transições de CE; (ii) o uso potencial de uma abordagem metodológica híbrida (que combina GMA com dois métodos MCDM) para selecionar os indicadores C mais relevantes para cada estratégia-R pode ser destacado; (iii) uma lista inicial de 58 C-indicadores e métricas associadas a dez estratégias-R e um conjunto de 38 C-indicadores selecionados por meio da adoção do método híbrido AHP-TOPSIS; (iv) definição de dez indicadores de circularidade compostos associados às estratégias R, bem como um Índice de Performance de Circularidade (IPC) geral, e um procedimento passo a passo para calculá-los em diferentes cenários de transição de CE. De uma perspectiva de transição circular, os resultados destacam implicações práticas para organizações e cadeias de valor, uma vez que o modelo foi concebido para ser aplicado em diferentes contextos de negócio, especialmente em organizações que irão definir seus objetivos de circularidade e respectivas agendas relativas à transição para uma economia circular.

Palavras-chave

Metrologia; economia circular; medição de circularidade; teoria da transição sociotécnica; análise morfológica; métodos multicritério de apoio à decisão.

Table of contents

List of figures

List of tables

"What's measured improves"
Peter Drucker

1
Introduction

Circular economy (CE) has been understood as a model in which economic growth practices are dissociated from the use and exploitation of natural resources (UNEP, 2006, 2011; EMF, 2013a, 2013b, 2014). The adoption of a circular economy framework by globally recognized institutions and the inclusion of the theme in public policies in some countries (WBCSD, 2018 OECD, 2019; UNEPFI, 2020) reinforces the consensus on the approach as a megatrend and on the need for appropriate ways of measuring and evaluating different organizational circularity strategies (Kristensen and Mosgaard, 2020; Moraga *et al.*, 2019).

Circular economy (CE) has been understood as a systemic approach to the design of business models in which economic growth practices are dissociated from using and exploiting natural resources (UNEP, 2006; EMF, 2013a, 2013b, 2014; BSI, 2017). According to the Circularity Gap Report 2020, the world is now only 8.6% circular. Of all the minerals, fossil fuels, metals, and biomass that enter it each year, just 8.6% are cycled back (CGRi, 2020).

1.1.
Context and motivation

The circular economy has been associated with the effective evolution of sustainable economic models respecting the planetary limits. The CE systemic approach has been addressed to extend the lifecycle for materials, design out waste, increase resource efficiency, and achieve a better balance between economic growth, environmental protection, and social well-being. Within the United Nations 2030 Agenda framework, CE practices can be associated with a significant number of Sustainable Development Goals (SDGs) (Schroeder *et al.*, 2019; Rodriguez-Anton *et al.*, 2019; Netherlands Enterprise Agency, 2020).

In this context, CE transitions require the capability to measure and evaluate progress on circularity performance in different contexts and levels (Ruggieri *et al.*, 2016; Ghisellini *et al.*, 2016; Kirchherr *et al.*, 2017; Potting *et al.*, 2017; Saidani *et al.*, 2019). For this, three levels of indicators and metrics have been considered by researchers and practitioners: (i) micro; (ii) meso; and (iii) macro level. The micro level comprises products, companies, and consumers. The meso level refers to developing an eco-industrial network, which benefits regional production systems and the environment. Finally, the macro level means circular economy development in global, national, regional, or local contexts.

In particular, at the micro level, the CE paradigm introduces a new perspective to look at business ecosystems. In this regard, organizations must prepare themselves for CE transitions based on insights into their circularity performance. Accordingly, organizations need measurement frameworks addressed to assess their circularity from a transition perspective. The lack of standard indicators to track progress on circularity at the micro level is generating misunderstanding and contradiction, which can be translated into a challenge to the implementation of CE strategies per se (Saidani *et al.*, 2017, 2019; Iacovidou *et al.*, 2017; Corona *et al.*, 2019), partly because the multiplicity of metrics that have emerged to meet this demand created a competitive and often conflicting environment as to the real progress towards circularity (WBCSD, 2018).

Current attempts to develop standardized metrics have been adopting different types of units (e.g., mass-flow analysis, energy) to quantify product-level circularity (EMF, 2015; Sassanelli *et al.*, 2019; Parchomenko *et al.*, 2019; Janik and Ryszko, 2019). The existing circularity measurement systems are not adequate to measure performance on every CE strategy at the organizational level (Rincon-Moreno *et al.*, 2021; Corona *et al.*, 2019).

Moraga *et al.* (2019) argue that C-indicators (as the indicators and metrics related to circular economy are known) developed until now could not assess the implementation of CE strategies at the micro level. In their words, "most indicators focus on the preservation of materials. Strategies focusing on materials, especially recycling, are well-developed, but they are some of the existing options to promote CE: recycling even being essential to the economy is not the only aspect of a sustainable CE" (Moraga *et al.*, 2019, p.460). In this regard, Potting *et al.* (2017) recognize that a strong focus on recycling remains remarkable. Nevertheless, a more ambitious CE transition towards substantially lower resource and material consumption and less waste generation will preferably be based on high-circularity strategies.

1.2. Research problem and objectives

Although considerable research has been devoted to circularity measurement, gaps are evident concerning the selection of proper indicators to measure circularity in decision-making processes, particularly at the micro level.

A systematic literature review covering the last two decades indicated that the previous studies on CE performance measurement systems had not considered a CE transition perspective for designing these systems at the micro level yet.

Another critical issue is how to apply and combine different theoretical approaches and tools to provide consistent frameworks for evidence-based business decisions with managerial and policy implications. Linked to these concerns, three research questions arise:

- How to calculate composite C-indicators to monitor and evaluate the implementation of circularity strategies in organizations, from a CE transition perspective?;
- How to calculate the overall circularity of an organization committed to foster and promote a circular economy as a business model value proposition?; and
- To what extent the application of a strategic measurement framework that combines morphological analysis with multicriteria decision-making methods can help organizations to monitor and evaluate their circularity performance towards a circular economy?.

With an attempt to answer these research questions, this dissertation aims to propose a strategic measurement framework to monitor and evaluate circularity performance in organizations from a transition perspective by integrating general morphological analysis (GMA) and multicriteria decision-making (MCDM) methods. In order to fulfil the general objective, five specific objectives were defined, as follows:

- To identify and compare the existing circularity measurement models and indicators to highlight substantial gaps in the existing knowledge on the interconnections between value proposition, circularity strategic choices, and circularity indicators (C-indicators);
- To build CE transition scenarios for a given organization that aims to evolve through CE transitions, based on a generic morphological matrix comprising parameters and their possible states to define and visually represent these scenarios;
- To investigate the potential use of a hybrid methodological approach that combines general morphological analysis (GMA) with two MCDM methods for selecting the most relevant C-indicators for each R-strategy;

- To identify and analyze existing C-indicators and their classification by R-strategy, according to the framework proposed by Potting *et al.* (2007);
- To define ten composite C-indicators associated with the R-strategies, as well as an overall Circularity Performance Index (CPI), and a step-by-step procedure to calculate them in different CE transition scenarios.

1.3.
Research design

This research follows a procedural framework of analysis based on Franco *et al.* (2021) to provide an underlying structure and an approved course of action (Table 1.1). A conceptual research map complements the research design presented below (Figure 2.1).

Table 1.1 – Research design

Phase	**Stage**	**Research question**	**Chapter**
Motivation (Why?)	Research problem definition	Why should be developed a strategic framework for monitoring and evaluating the circularity performance of organizations (micro level), from a CE transition perspective?	Chapter 1
Conceptualization and research gaps (What?)	State of research on central themes and identification of research gaps and unsolved problems	Which theoretical and methodological approaches and tools have been employed for defining measurement systems of circularity at the micro level? Which are the substantial gaps in the existing knowledge on the interconnections between value proposition, circularity strategic choices, and C-indicators?	Chapters 2 and 3
Research design and development (How?)	Definition of the research methodology	How can a strategic framework for monitoring and evaluating the circularity performance of organizations at the microlevel, from a CE transition perspective, be developed and validated?	Chapter 4
	Development of the systemic and contextual framework	Which methods should be combined to overcome limitations of current research on the circularity measurement at the micro level? What are the benefits of integrating general morphological analysis (GMA) and multicriteria decision-making (MCDM) methods to fill the research gaps pointed out in Chapter 3? Which criteria should be considered for selecting C-Indicators associated with each R-strategy? How to calculate the composite C-indicators for monitoring and evaluating the implementation of the R-Strategies adopted by an organization? Furthermore, how to measure its overall Circularity Performance Index by aggregating those composite C-indicators?	Chapter 5
Results discussion (What are the implications of this research?)	Differentials of the proposed framework. Managerial and policy implications	What are the main differentials of the proposed framework compared to the current circularity measurement systems at the micro level? Which are the main managerial and policy implications of this research from the transition perspective?	Chapter 5

Source: Based on Franco *et al.* (2021).

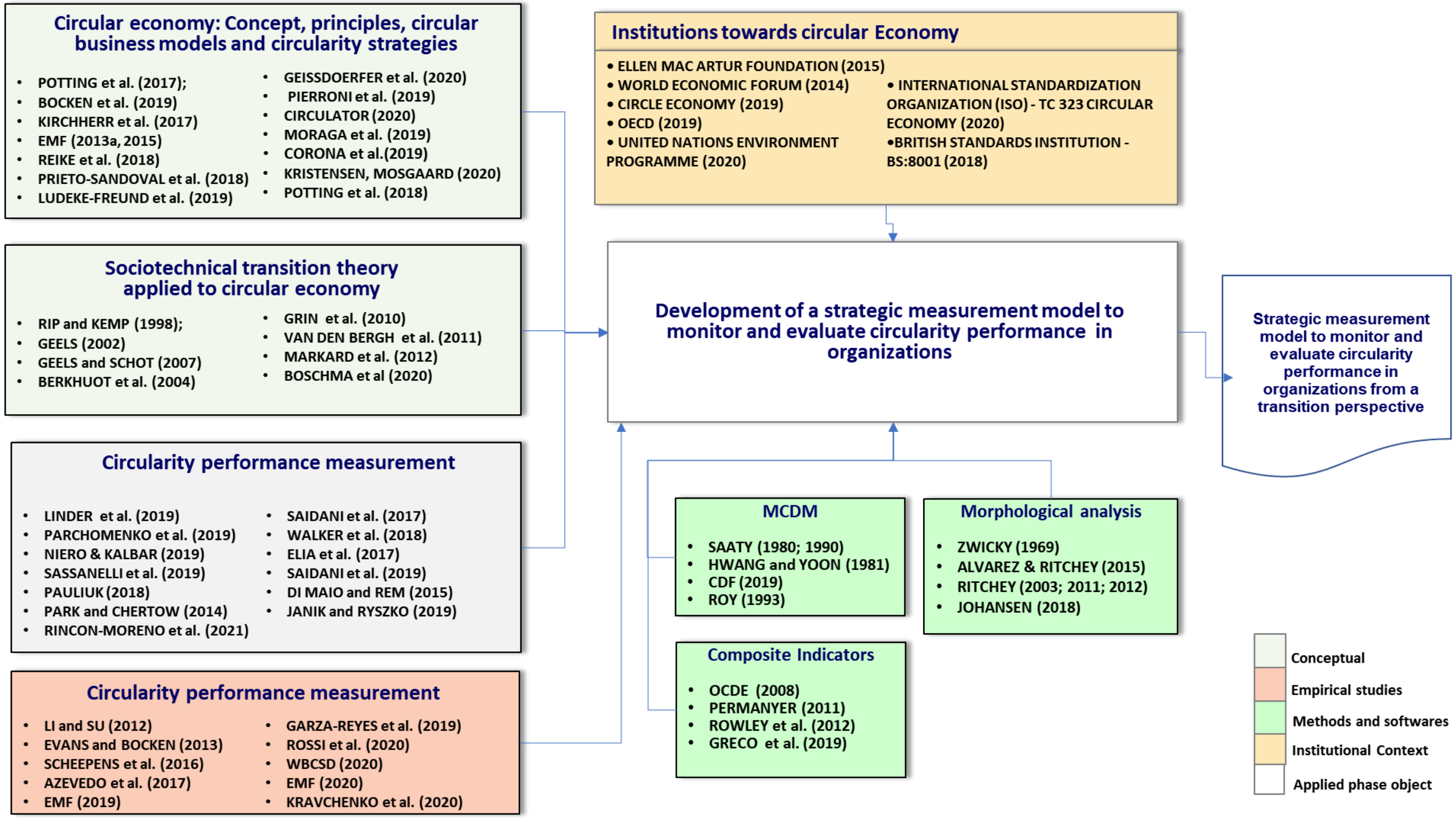

Figure 1.1 – Research conceptual map

1.4.
Structure of the dissertation

According to the research design presented in Table 1.1, this dissertation is structured in six chapters.

Following the introduction, presents the state of existing knowledge on the circular economy, focusing on CE definitions and principles, circular business models, and circularity strategies, as theoretical background for developing a strategic framework for monitoring and evaluating the circularity performance of organizations (micro level). In sequence, the contributions of the sociotechnical transition theory for CE transitions at the micro level. This multi-level approach can help organizations understand the continuous development and dissemination of innovations in alignment with the CE principles. At the interface between the micro and meso levels, new circular markets and business models emerge.

Chapter 3 is addressed to answer two questions posed in Table 1.1: "Which theoretical and methodological approaches have been employed for defining measurement systems of circularity at the micro level?"; and "Which are the substantial gaps in the existing knowledge on the interconnections between value proposition, circularity strategic choices, and C-indicators?. Thus, ten circularity measurement models and indicators published in the last decade are described. From the CE transition perspective, substantial gaps in the existing knowledge on the interconnections between value proposition, circularity strategic choices, and circularity indicators could be highlighted.

Chapter 4 details the methods adopted in each phase of this research, as follows: (i) literature review and documentary analysis on the central research themes; (ii) conceptual modelling for complex sociotechnical systems, integrating general morphological analysis (GMA) and multicriteria decision-making (MCDM) methods; and (iii) definition and calculation of composite circularity indicators and overall circularity performance index at the micro level.

Chapter 5 presents the main result of this research – a strategic measurement framework proposed for monitoring and evaluating organizations' circularity performance from a CE transition perspective. The benefits of integrating general morphological analysis (GMA) and multicriteria decision-making (MCDM) methods to fill the research gaps pointed out in Chapter 3 are highlighted and discussed.

Finally, Chapter 6 synthesizes the conclusions and suggestions for replicating the proposed framework in other business contexts.

This dissertation is totally aligned with the research line “Strategic Management of Innovation and Sustainability” of the Programa de Pós-graduação em Metrologia (PósMQI) at Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio).

The research was financially supported part by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and part by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (Capes) - Finance Code 001.

2
Circular economy and sociotechnical transition theory

In the last decades, different conceptual approaches were proposed to guide organizations towards sustainable economic development as the 'Ecological Economy' (Georgescu-Roegen, 1971); the 'Performance Economy and the Economy of Cycles' (Stahel and Reday-Mulvey, 1976); 'Regenerative Economy' (Lyle, 1994); 'Blue Economy' (Pauli, 2010), and the 'Green Economy' (UNEP, 2011). All of them are based on the idea of decreasing the exploitation of natural resources and reducing impacts on human health and the environment in our production model. Analogous to the predecessor's schools of thought, the circular economy approach seeks to develop products and services that reduce the generation of waste, the use of resources, and the toxicology associated with the materials they employ (Shamiyeh, 2010).

Various definitions have been stated, and many articles reviewing CE concepts have been published (e.g., Accenture, 2014; UNIDO, 2016; Kirchherr *et al.*, 2017; Korhonen *et al.*, 2018; EMF, 2013a; 2019).

More generally, a circular economic model has been defined as one in which economic growth practices are dissociated from the use and exploitation of natural resources. What makes the circular economy different and mature for widespread adoption is the development of disruptive technologies, which allow change to occur quickly and massively (Accenture, 2014). However, critics claim that there is great variation in the perception of the concept, which was evidenced by Kirchherr *et al.* (2017) in the quest to create transparency regarding the general understanding of the circular economy. A set of 114 definitions identified in the literature was reviewed and codified in 17 dimensions to propose a harmonized definition:

> "We defined CE within our iteratively developed coding framework as an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and

social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers"

(Kirchherr *et al.*, 2017, p. 229).

Other definitions are commonly seen in the main forums of discussion on circular economy:

> "The circular economy is a concept that promotes the reuse and recycling of goods with a goal of 'zero waste'. This in turn saves resources, reduces adverse effects on the environment, and promotes (green) jobs and economic growth" (UNIDO, 2016).

> "A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models"
> (EMF., 2013a).

> "A circular economy is a global economic model that decouples economic growth and development from the consumption of finite resources. It relies on three principles: designing out waste and pollution; keeping products and materials in use; and regenerating natural systems" (EMF, 2019).

Although the relevance of circular economy has been a central topic in the current political and economic debate, the concept of a CE remains open to interpretations (Ghisellini *et al.*, 2016; Kirchherr *et al.*, 2017; Kalmykova *et al.*, 2018; Laurenti *et al.*, 2018; Reike *et al.*, 2018; Korhonen *et al.*, 2018).

To avoid deviation from the research design presented in Table 1.1, this research assumes the definition given by Ellen MacArthur Foundation (2019). The following sections presented (i) the principles and characteristics of a circular economy, (ii) circular business models, (iii) circularity strategies that can be adopted in CE transitions; and (iv) business archetypes in a circular economy transition process.

2.1.
CE principles and characteristics

The Ellen MacArthur Foundation (2013a, 2015) defines three principles of a circular economy, which will be incorporated in the concept of EC published in 2019 and are commonly used in the literature.

The first principle says that it is necessary to 'Preserve and increase natural capital, controlling finite stocks and balancing the flow of renewable resources' (EMF, 2015). The maintenance of natural capital begins with the reduction of resource extraction and, when needed, renewable and biodegradable resources must be prioritized, and technologies and processes that present better performance, when compared to traditional ones, should be chosen.

To meet the second principle 'Optimize the production of resources, circulating products, components, and materials at the highest level of utility at all times, both in the technical and biological cycle' (EMF, 2013), it is necessary design for remanufacturing, reform and recycling. Products must be able to be recovered or, in case of disposal, re-inserted into the production chain, thus contributing to the economy as well. Circular systems also extend to the maximum the use of biological materials already used, extracting valuable biochemical raw materials and destining them for applications in lower degrees (EMF, 2013). Also important are the models of the sharing economy, which increases the use of products.

In addition to the search for efficiency, it is necessary to consider the socio-environmental impacts throughout the life cycle of materials and products, so that the third principle can be met: "Foster the system's effectiveness, revealing the negative externalities generated and excluding them from projects" (EMF, 2013). Damages to the ecosystem services and society generated using land, air, water, and several resources must be reduced.

EMF complemented the definition of the concept, establishing five characteristics that should be presented in a CE model: (i) design without residue; (ii) creating resilience through diversity; (iii) transition to the use of energy from renewable sources; (iv) systemic thinking, and (v) value cascading. They are significant mainly in terms of their differentiation from other schools of economic thought focused on sustainable development. Thinking about value cascades is about the gradation of value associated with products and their materials. In its primary origin, the value of the resource is at its maximum. As it loses characteristics that add value to it, it cascaded to another manufacturing level that better takes advantage of its properties. In a circular economy, maintaining the value of products and components is prioritized. By way of illustration, a tree going to the furnace waives the value that could be used through the stages of decomposition through successive uses of wood and wood products before degradation and eventual incineration (EMF, 2013).

Technological materials have high added value and must be cascaded to maintain their value at the highest possible level, from the noblest applications to the recycling process, which should only occur when it is no longer reusable. For organic origin materials, the essence of creating value lies in the possibility of extracting additional value from products and materials in cascade through other applications, such as the production of biogas and the production of agricultural inputs.

2.2. Circular business models

Transitioning to a circular economy demands the creation of new modes of production, and consumption and involves the management of the environmental liability of the current linear model, through the reinsertion of materials in the production chain. Using principles of the circular economy in the innovation process and the design of new business models is particularly ambitious, once the concept claims for changes in the production system, maximizing the useful life of products, minimizing waste and loss of valuable and/or scarce materials, and improving the economic performance of agents in the system.

For Teece (2010), a business model describes the design or architecture of the mechanisms for creating, delivering, and capturing value, and all companies, explicitly or implicitly, employ a specific business model. As the author mentions, a business model is more generic than a business strategy, since the definition of a strategy requires segmenting the market, creating a value proposition for each segment, configuring the apparatus to deliver that value and, then discover several "isolation mechanisms" that can be used to prevent the business model/strategy from being harmed through imitation by competitors or disintermediation by customers. It is necessary to couple the analysis of the strategy with the analysis of the business model, and unless the business model survives the filters imposed by the analysis of the strategy, it is unlikely to be viable, as many features of the business model are easily imitated.

This direction, in the field of circular economy, would occur through the application of different circularity strategies (Potting *et al.*, 2018; Blomsma *et al.*, 2019), requiring adaptation of the business models and a review of the relationships between agents the productive chain (B2B models - business to business) and between industry and the consumer (B2C models - business to consumer). Teece (2010) argues that the essence of a business model is to define how the company adds value to customers and encourages customers to pay for value and converts them into profit, and the market aspects must not be disregarded, although the proposal of a circular economy.

The Organization for Economic Cooperation and Development (OECD), defines five typical circular business models aligned with the circular economy principles (OECD, 2019). They are:

- Circular Supply: Business models in which traditional raw materials are substituted by renewable, biobased, or recovered materials. Business that prioritizes the usage or offer renewable resources contribute to the reduction of the exploitation of natural resources and encourage the development of a circular economy;
- Resource recovery: Business focused on the production of secondary raw materials, from waste or tailings. If organic waste was previously discarded, in the circular economy is used for agricultural inputs and electricity generation. Recyclable materials are reprocessed to be re-inserted into new production chains, respecting the cascade of value;
- Lifetime extension: Business models that prioritize the extension of the product life cycle, through repair, modernization, resale. Disposable products are replaced by durable materials, generating changes in habits, and avoiding the rapid generation of waste by single-use products;
- Sharing: Businesses that increase the use of existing products and assets, reducing their production demand, ending idleness, and allowing more than one user per product.
- Product as Service: Businesses that deliver services instead of products through dematerialization, where product ownership remains with the supplier, who sells the benefits of use. The consumer becomes a user, without the need to purchase the product, acquiring convenience, effectiveness, and greater durability of the assets.

There is still considerable scope for the future growth of circular business models, such as exposed by Ludeke-Freund *et al.* (2019), who identified possible 26 business models that may have high circularity. However, this growth will be subject to economic realities - and the more widespread adoption of these business models will not occur unless there is a solid underlying business case (OECD, 2019). Despite the existence of an ideal for business models operating in line with the principles of circular economy, it is important to consider the adequacy of the entire existing market, and in this perspective of transition, the temporal dimension is essential. An organization can adopt different circularity strategies (or related R-strategies, which will be explored in the further section) in its redirection process, but the isolated adoption of one or more circularity practices does not constitute a circular model, even though it is valid for reducing the environmental impacts of linear production models.

The analysis of the implemented strategies should be, therefore, beyond an essential step in the creation of a competitively sustainable business model (Teece, 2010). It is essential for monitoring and evaluating the transition of an organization towards a circular economy, given the importance of highlight the economic, social, and environmental potential impacts that justify the implementation of the CE approach.

2.3. Circularity and R-strategies

The application of the principles and characteristics of a circular economy can be observed in terms of circularity, especially regarding the maintenance and cascading of the value of products and components. There are several strategies to reduce the consumption of natural resources and minimize the production of waste, known by waste management schools as R-strategies (CE & MVO, 2015; EMF, 2015; Potting *et al.*, 2017; Vermeulen *et al.*, 2014; Reike *et al.*, 2018). The existing 1R-lists' differ mainly in the number of strategies presented and generally present a set of strategies ordered from 'low R' (such as a total change in the way services and products are delivered) to 'high R' (recycling and energy recovery).

Potting *et al.* (2017) proposed a correlation of R-strategies (Table 2.1) to the circularity strategies addressed to reduce the consumption of natural resources and materials and minimize the production of waste. According to their levels of circularity, they can be ordered for priority (Potting *et al.*, 2017) as their contribution to the broad establishment of a circular economy, given the reduction in consumption of natural resources, reuse, remanufacturing, and recycling of materials (Walker *et al.*, 2018).

As shown in Table 2.1, the first circularity strategy – 'Smarter product manufacturing and use' – is preferred overextending the lifetime of products once it is associated with the following R-strategies (R0, R1, and R2), considered as high circularity R-strategies.

Table 2.1 – Circularity strategies within the production chain in order of priority from a CE transition perspective

Circularity strategies	R-strategies	Description
Smarter product use and manufacture	Refuse (R0)	Make product redundant by abandoning its function or by offering the same function with a radically different product.
	Rethink (R1)	Make product use more intensive (e.g., through sharing products or putting multifunctional products on the market).
	Reduce (R2)	Increase efficiency in product manufacture or use by consuming fewer natural resources or materials.
Extended lifespan of product and its parts	Re-use (R3)	Re-use by another consumer of discarded product with is still in good condition and fulfils its original function.
	Repair (R4)	Repair and maintenance of defensive product so it can be used with its original function.
	Refurbish (R5)	Restore an old product and bring it up to date.
	Remanufacture (R6)	Use parts of discarded product in a new product with the same function.
	Repurpose (R7)	Use discarded product or its parts in a new product with a different function.
Useful application of materials	Recycle (R8)	Process materials to obtain the same (high grade) or lower (low grade) quality.
	Recovery (R9)	Incineration of materials with energy recovery.

Source: Potting *et al.* (2017).

The second circularity strategy – ‘Extended lifespan of the product and its parts’ is the next option and is followed by the strategy ‘Useful application of materials’, which is associated with recycling of materials through recovery. As argued by Potting et al. (2017, p. 23): “Incineration from which energy is recovered has the lowest priority in a circular economy, because it means the materials are no longer available to be applied in other products (low-circularity strategy)".

Transition strategies adoption should be guided by its levels of circularity, considering the best practices possible and the value cascade. Smarter product manufacturing and use, for example by product sharing, is generally preferable to extending product life, because this product is used for the same function as the product or more users being served by a product (a strategy with high circularity).

Product life extension is the next option, and recycling should only be considered when necessary to recover component value. Incineration, from which energy is recovered, has the lowest priority in a circular economy because it means that the materials are no longer available for application in other products (low circularity strategy). As a general rule, greater circularity represents the broad internalization of the principles and characteristics of a circular economy.

2.4. Circular archetypes

The concept of circular archetypes was introduced by a European initiative called Circulator, funded by EIT Funded by EIT Raw Materials (a body of European Union). Circulator aims to support organizations in making conscious strategic choices regarding the sustainability of their business model and value proposition. The central idea of Circulator is that circular business models typically consist of a mixture of different strategies, that can be organised in three main categories: (i) circular value creation strategies: strategies that directly act upon the material and product resources in the business model, as substitution, resource efficiency, optima product use, repair, reuse, remanufacturing, and recycling; (ii) value proposition strategies: that help deliver circular value to the customer, such as Product Service Systems, asset sharing, branding and cost reduction. The third category, (iii) value network strategies, set up strategies to engage with actors beyond the company borders to achieve circular value networks, as industrial symbiosis, tack back management, online platforms, and value chain collaboration.

Each archetype groups specific strategies that have been observed in existing business cases in the context of the circular economy, available at a web-based tool, representing a particular focus of the business as the main entry point for developing a circular business model. The synthesis of companies' main characteristics grouped to each one of the four archetypes and their combined strategies towards a circular economy are further detailed in Chapter 5 (Table 5.1).

2.5. Sociotechnical transition theory applied to circular economy

Sociotechnical transition theory was formulated by Rip and Kemp in 1998 on the basis of a multi-level framework. Accordingly, transitions emerge from connections between processes and actors at different levels, namely: (i) niche-innovations; (ii) sociotechnical regimes; and (iii) sociotechnical landscape (Rip and Kemp, 1998; Geels, 2002; Geels and Schot, 2007). Focusing on transitions to a circular economy, these three levels correspond to the CE micro, meso, and macro levels. This multi-level framework has contributed significantly to research on transformative changes towards sustainability (Berkhout *et al.*, 2004; Grin *et al.*, 2010; Van den Bergh *et al.*, 2011).

Emphasizing the need for a co-evolvement of sustainable innovation and social change, its concepts enlightens a systematic analysis of processes that promote a fundamental shift in sociotechnical systems (Truffer and Coenen, 2012; Markard *et al.*, 2012; Boschma *et al.*, 2017). In fact, the sociotechnical transition theory has been extensively employed in empirical studies investigating sustainability transitions in energy, mobility, and agriculture areas, rational use of natural resources, and waste management (Rip and Kemp, 1998; Kemp, Schot, and Hoogma, 1998; Geels, 2002; Brown *et al.*, 2003; Loorbach and Rotmans, 2006; Geels and Schot, 2007; Jackson *et al.,* 2014; Almeida and Melo, 2017). Large firms with 'complementary assets' (Teece, 1986; 2006) can better explore technological niches in these domains. They are called 'incumbent firms' because they might support sustainability-oriented innovations with their 'complementary assets' and resources from a sustainability transition vision.

Geels (2002) states that ‘incumbent firms’ should strategically reorient themselves since they usually tend to preserve existing systems and regimes. With regard to this issue, Kemp and Loorbach (2006:125) argue that sociotechnical transition approach “seeks to overcome the conflict between long-term imperatives and short-term concerns”. This multi-level approach can help organizations understand the continuous development and dissemination of innovations in alignment with the CE principles. It is at the interface between the micro and the meso levels that new circular markets and business models emerge. Especially during the development of niche-innovations, large incumbent firms should set up special research, development and innovation (RD&I) programs and budgets concerning high-circularity R-strategies (R0-R2).

3
Circularity measurement systems: a comparative analysis

CE transitions require the capability to measure and evaluate progress on circularity performance in different contexts and levels (Ruggieri *et al.*, 2016; Ghisellini *et al.*, 2016; Kirchherr *et al.*, 2017; Potting *et al.*, 2017; Saidani *et al.*, 2019). For this, three levels of indicators and metrics have been considered by researchers and practitioners: (i) micro; (ii) meso; and (iii) macro level. The micro level comprises products, companies, and consumers. The meso level refers to developing an eco-industrial network, which benefits regional production systems and the environment. Finally, the macro level means circular economy development in global, national, regional, or local contexts.

In particular, at the micro level, the CE paradigm introduces a new perspective to look at business ecosystems. In this regard, organizations must prepare themselves for CE transitions based on insights into their circularity performance. Accordingly, organizations need measurement frameworks addressed to assess their circularity from a transition perspective.

Nowadays, there is a consensus on the need for appropriate methodological approaches to monitor and evaluate the implementation of circularity strategies in business contexts. Studies carried out on indicators for measuring the adoption of multiple CE strategies by organizations are still in the embryonic stage (An *et al.*, 2018; Janik and Ryszko, 2019; Saidani *et al.*, 2019). Besides, existing guidelines and standards developed for businesses (e.g., the BS 8001:2017 standard on circular economy implementation in organizations) have been criticized for lacking monitoring C-indicators that associate circular economy with sustainability (Pauliuk, 2018; British Standards Institution, 2017).

The lack of standard indicators to track progress on circularity within organizations generates misunderstanding and contradiction, which can be translated into a challenge to CE transitions per se (An *et al.*, 2018; Saidani *et al.*, 2019; Iacovidou *et al.*, 2017; Corona *et al.*, 2019; Moraga *et al.*, 2019; Potting *et al.*, 2017; 2018).Very few indicators capture the effect of strategies concerning smarter product use and manufacture and also extension of the life span of products. Another concern is that in general C-indicators focus primarily on physical parameters. Social and environmental indicators are less well-defined and less frequently included in circularity performance measurement frameworks. Same phenomenon occurs for measuring the progress of implementing high-level circularity strategies (An *et al.*, 2018; Saidani *et al.*, 2019; Moraga *et al.*, 2019; Kristensen and Mosgaard, 2020; Rincón-Moreno *et al.*, 2021).

Linder *et al.* (2017) suggested that circularity indicators at the micro level should focus on product quality by measuring the fraction of a product originating from used products. They compared five existing product-level C-indicators in light of the following criteria: validity, reliability, transparency, generality, and aggregation principles. Saidani *et al.* (2017) tested three product circularity indicators and criticized them for their helpfulness in different business contexts and alignment with CE principles. In turn, Walker *et al.* (2018) tested and compared the same three C-indicators with a life-cycle assessment-based method to assess material circularity. From a broader perspective, Pauliuk (2018) proposed a dashboard of C-indicators for the quantitative assessment of CE concerning product systems, businesses, and organizations, based on the standard BS 8001:2017 framework (BSI, 2017). In the proposed dashboard, the set of C-indicators can measure physical circularity, monetary value, and potential environmental impacts.

In 2017, Elia *et al.* presented a revision of 16 circularity indicators, from the perspective of reducing inputs, reducing the use of natural resources, increasing the share of renewable and recyclable resources, reducing emissions, reducing losses of materials, and product value retention. The authors conclude that none of the revised indicators can monitor all the requirements established for a circular economy and that none of the revised systems successfully contemplated the aspect of product value retention.

Through multiple correspondence analysis, based on 24 elements of a circular economy, Parchomenko *et al.* (2018) analyzed a set of 63 circularity metrics and identified three main groups: (i) a resource efficiency cluster, (ii) a stock and material flow cluster, (iii) a product-centered cluster. They conclude that, although value retention is one of the central elements of EC, few metrics have been addressed to this issue.

Sassanelli *et al.* (2019) also reinforced the perspective and signal that all 45 circularity measurement systems reviewed in their work were focused on measuring only a few specific aspects related to CE. The authors also evaluated the methodological approach used by each evaluated system, and point out that, in general terms, the analyzed papers propose a new structure, method, index, or approach, but generally starting with a set of documents and metrics that already exist, in particular the methodology of Life Cycle Analysis (LCA).

The review conducted by Corona *et al.* (2019) on circularity measurement systems aimed to: (i) identify the fundamentals of circularity metrics used so far and their applications, (ii) assess the validity of current circularity metrics, and (iii) provide recommendations on how to measure circularity. However, the authors reinforced that none of the evaluated systems addresses the concept of CE in its entirety.

Saidani *et al.* (2019) analyzed 55 circularity measurement systems and proposed a taxonomy for circularity indicators, presenting a circularity indicator selection tool based on ten categories, including systemic level: of the systems for measuring circularity. circularity analyzed by Saidani *et al.* (2019), 20 were classified as applicable to organizations.

Kristensen and Mosgaard (2020) reviewed 30 circularity measurement systems specific to the micro-level, classifying them into nine categories, according to the focus of the analyzed indicators. The work shows the most used metrics for each category, showing that most indicators for circularity at the micro-level are expressed in rates or indices, ranging from zero to one, or with self-invented scales, calculated from economic information. They also point out that most indicators are focused on the external circles of the EC (low circularity strategies) and that the number of indicators decreases when moving towards internal circles (high circularity strategies). Although recycling is a low circularity strategy, recycling indicators are more developed than those for reuse and repair, which Kristensen and Mosgaard (2020) point to as a possible result of a long history of waste management compared to that of EC.

Focusing also on the CE microlevel, Rincón-Moreno *et al. (*2021) analyzed the C-indicators currently found in the literature, particularly at the macro level, and introduced improvements according to the context in which they could be applied at the micro level (i.e., companies from different sectors). Additionally, they tested the improved C-indicators in Spanish companies located in the Basque Country region to prove their CE assessment suitability.

The diversity of indicators used in the context of the circular economy denotes can generate divergences in the understanding of the principles of circular economy and the aspects of circularity that must be measured, as well as different measurement approaches (Kristensen and Mosgaard, 2020; WBCSD, 2018).

The development of appropriate metrics represents a key point in the transition to a circular economy, insofar as it encourages and supports the establishment of realistic goals, which can be monitored and able to track progress concerning global ambitions in this context. The importance of metrics is highly relevant, as they also shape thinking and language within the concept, as well as influencing its development, being able to highlight and promote particular and hidden aspects (Parchomenko *et al.*, 2018). But the lack of consistent measurement structures has already been recognized as a major challenge for the implementation of the circular economy in government policies and business strategies (CE, 2019). Companies must change their business models, adapt strategies and empower their workforce, and governments must adjust policies to make the circular economy viable. To understand where an organization is currently, on its way to the circular transition, it is necessary to set goals monitored by key performance indicators (KPIs), which also allow guiding decision making in adopting circularity strategies (WBCSD, 2018).

It is necessary to isolate and evaluate the real impact of adopting a strategy linked to the circular economy, and here it is necessary to make a distinction as to the applicability of circularity measurement systems, especially about the measurement object: we can measure both the transition process to a circular model as to the impact of the change itself. Potting *et al.* (2018) delimit the measurement scopes in: (i) monitoring the transition process, and (ii) monitoring its effects. The first scope that aims at measuring the adoption of circularity strategies is addressed to a better understand of the degree of internalization of circular practices and the dynamics of transition within the same systemic level. Ideally, circularity metrics should provide an indication of how well the EC principle has been applied (Saidani *et al.*, 2017; Parchomenko *et al.*, 2018).

The impact of these practices must be measured in the second scope, referring to the achievement of circularity objectives themselves, as follows: (i) reducing the consumption of natural resources and greenhouse gas emissions; and (ii) maintaining value and generating a positive socio-environmental impact. In the second scope, the contribution of circular strategies to sustainable development must be measured and be comprehensive enough to avoid transferring the load from reduced material consumption to increasing environmental, economic, or social impacts (Corona *et al.*, 2019). Both analyses are relevant to the transition process that precedes the establishment of a circular economy, insofar as monitoring progress in this direction contributes to the identification of success factors, allows the economic valuation of the change in strategic direction over time (Potting *et al.,* 2018; CE, 2019), measure the progress and effectiveness of these actions and assess the main trends within each context and systemic level.

3.1. Circularity measurement systems for organizations

Seeking to understand and differentiate systems for measuring circularity of organizations according to the scope proposed by Potting et al. (2018), "monitoring the transition process", and depending on the methodology adopted, this work visited the main circularity measurement systems already reviewed by the literature. Initially, review articles were consulted to select C-indicators dedicated to the circularity of organizations.

Measurement systems identified in gray literature were also considered, as recommended by Kristensen and Mosgaard (2020). The selection of measurement systems was carried out based on bibliographic and documentary analysis, considering the following selection criteria: (i) approach to the circular economy (sustainability indicators and metrics were not considered); (ii) analysis unit-organizations (systems dedicated to measure the circularity of products, materials, and components, as well as dedicated to countries, regions, and cities were not considered. They were only considered when expressly referring to the circularity of companies; and (iii) transversality (generic systems, i.e., systems composed mostly of indicators with specific sectoral applications were discarded).

Next sections give a brief descriptive analysis of each model.

3.1.1. Five Category Index Method (FCIM)

Reviewed by Elia *et al.* (2017) and Saindani *et al.* (2019), the FCIM was presented by Li and Su (2012), as a way to assess the level of circularity of companies in the Chinese chemical industry (Elia *et al.*, 2017). The model, which used the Weighted Sum Model method, was applied to secondary data from the Chinese chemical industry. It was classified as generic by Saidani *et al.* (2019). The FCMI uses standard values as a reference for calculating the circularity of companies, with five dimensions aggregated in the index: economic development, resource exploitation, pollution reduction, ecological efficiency, and development potential. It focuses on the environmental and economic analysis of the circularity of materials, not to mention circularity strategies. The company's level of development is based on the score in a ranking of four categories, translated into status: (i) traditional economic development model, (ii) transition from traditional to a circular model, (iii) Good economic development circular and (iv) mature development of a circular economy.

Li and Su (2012) indicate that the development of the circular economy, applied to the scope of the proposed system, is at a stage of transition from the traditional development model to the circular model. They point out that, in the future, more importance should be given to the efficiency of resource exploitation and its potential development, to raise the level of development of the circular economy. Despite being classified as applicable to organizations (Saidani *et al.*, 2019) and in fact proposing a value for the level of development of a circular economy, it analyzes the level of circularity from the chemicals themselves, not attending to all circularity strategies and considering only components of low circularity R-strategies.

3.1.2. The Circular Economy Toolkit (CET)

The system developed by Evans and Bocken (2013) is available as an online toolkit, consisting of guidelines and tools to help companies assess their potential for improvement towards a circular economy. Companies can use the tool to get an overview of the potential for improvement in seven categories, based on their answers to 33 questions, which qualitatively cover all R-Strategies. The analytical tool, as classified by Kristensen and Mosgaard (2020), provides an analysis of the potential areas for improvement or business generation, according to the product design and its current commercial operations. Despite this, the system does not indicate which improvements are necessary for greater circularity (Rossi *et al.*, 2020).

The results are evaluated based on the company position in a 3X3 matrix, guided by the opportunity and viability of each category. If there is a great business opportunity and the product design is appropriate, it is classified as a potential 'high opportunity'. If there are few business opportunities and the product design does not help the service, it will be classified as a minor opportunity. Although it does not internalize the concepts of circularity strategies and circular business models, not developed at the time, it makes strong mention of the Product as a Service (PSS) business model. The model was built from a literature review, interviews with companies, to understand their approaches to business modelling, and 13 practical workshops. The opportunity assessment tool should be complemented by reading the toolkit, case studies, and the tools provided, demanding continuity of the assessment by the company itself.

3.1.3.
Eco-cost/Value Ratio (EVR)

The Eco-cost/Value Ratio was proposed by Scheepens *et al.* (2016), and reviewed in different works (Kristensen and Mosgaard, 2020; Saidani *et al.*, 2019; Pauliuk, 2018; Rossi *et al.*,2020). This model presents a unique indicator, which expresses how clean or dirty a product is, and expresses resource efficiency in terms of the relationship between ecological impacts and the value of a product, in an approach of economic valuation of environmental impact. Again, despite being classified by Saidani *et al.* (2019) as an indicator of circularity applicable to companies, circularity is evaluated in terms of its material flows and financial resources, through the combination of the Eco-efficient Value Creation methodologies (benchmarking for the model) and the Circular Transition Framework (describing the stakeholder activities necessary for the transition to sustainable business models).

Scheepens *et al.* (2016) recognize that for a circular business model, still undefined at the time, the situation is a little more complex than for a linear product chain: at the 'end of waste', a new value chain starts, adding value by recycling the flow of materials and closing the cycle. They conclude, based on the evaluation of different projects, that EVR helps to avoid pitfalls in the design of circular business models, associating the material cycle with the environmental impact of products as a value perceived by the market (Scheepens *et al.*, 2016). Rossi *et al.* (2020) emphasize that the EVR has a high complexity of application since it requires prior knowledge of Life Cycle Analysis (LCA).

3.1.4.
Value-based Resource Efficiency Indicator (VRE)

Created by Di Maio *et al.* (2017), the Value-based Resource Efficiency Indicator (VRE) was revised in the works of Kristensen and Mosgaard (2020) and Saindani *et al.* (2019). It provides a unique indicator for the resource efficiency of products or processes, calculated according to the value of inputs, and a comparison to the traditional calculation of resource efficiency, based on volume (Saidani *et al.*, 2019). Measures resource efficiency and the circular economy in terms of the market value of "stressed" resources, assigning market prices as weight since it understands that this value incorporates the elements of scarcity versus the competition, as well as taxes that represent social externalities urgent and environmental issues. Circularity is defined as the percentage of the value of stressed resources incorporated into a service or product that is returned after the end of its useful life, allowing to distinguish the resource efficiency of a process (KPIs for industry and governance) from the resource efficiency of a process. product (consumer KPI's and governance).

VRE focuses on the economic dimension, and the authors themselves recognize the general lack of information on the environmental and social impact, which are considered only when pricing resources. Validated from secondary data, the model incorporates, at a certain level, strategies for reinsertion of materials, considering them in the components of mass balance and pricing.

3.1.5.
Circular Transition Indicators (CTI)

Designed by the expert group of the World Business Council for Sustainable Development, the CTI (WBCSD, 2018) was reviewed by Saidani *et al.* (2019), who classified it as an indicator focused on the economic impact of a circular performance. CTI's structure is based on an assessment of material flows within the company's boundaries, combined with additional indicators on resource efficiency and effectiveness, as well as the value-added by businesses towards a circular economy (WBCSD, 2018).

It considers aspects of all three circularity strategies, albeit under the exclusive perspective of the material flow, in three evaluation modules: (i) close the loop, which measures a company's ability to close the cycle of its materials; (ii) optimize the loop, with indicators that illustrate companies' performance in maximizing resource efficiency and reinsertion of materials in the production chain; and (iii) value the loop, which connects material flow indicators to conventional financial systems. The overall performance of a company's circularity can be calculated based on the balance between linear and circular material flows and consists of four main flows of the company: circular inlet, linear inlet, circular flow, and linear flow. The general circularity performance is the average between the percentages of circular input and circular output, composed of the weighted average of the individual percentage of circularity of each of the materials, being necessary to account for the circularity at the material flow level by the Material Flow Analysis (MFA) and index aggregation by the high-level methodology.

Circular business models are treated like any other business model, since there is no need to demonstrate the circular added value, which will be calculated by the methodology. The transition perspective is presented to the extent that the tool still assesses, in the prioritization phase, the risks and opportunities to be addressed, in addition to providing guidance for the projection of scenarios.

3.1.6.
Material Circularity Indicator (MCI)

The first version of the Material Circularity Indicator (MCI) methodology, published in 2015 by the Ellen MacArthur Foundation, notes the increased utility of products and materials, combining the mass of materials with their time duration (Corona *et al.*, 2019; Kristensen and Mosgaard, 2020). It considers the recycled content in a product, together with the waste of materials and its useful life - but only for materials considered within the technical cycle.

The updated version of the MCI (EMF, 2019) includes an extension of the methodology to include the treatment of biological materials - a significant advance compared to other measurement systems. The institution (EMF, 2019) informs that the indicators allow comparing different versions ‘scenarios’ of a product in relation to its circularity at the design level, and can be used as a tool for decision making and evaluation or classification of companies, providing an online tool to track progress towards a business model based on the circular economy, which is why MCI was considered in this analysis. However, it applies a linear index to calculate the flow of non-recycled or non-recyclable materials, does not take into account environmental and economic risks (Kristensen and Mosgaard, 2020; Rossi *et al.,* 2020), and mentions only once the opportunity to business model change, not to mention circularity strategies.

According to Saindani *et al.* (2019), the measurement system is applicable for measuring the circularity of companies, based on the aggregation of the MCI of several products. MCI uses the Circular LCA methodology, which extends the limits of the traditional Life Cycle Assessment and calculates the impacts for each successive product life cycle, taking into account the probable component failure, damage, and loss rates, the ability to reuse and remanufacture components, recycling or disposal, losses and contamination of the environment, and all transport and interventions, such as maintenance or disassembly.

3.1.7. Sustainable Circular Index (SCI)

The model presented by Azevedo *et al.* (2017) has been reviewed by several authors (Parkhomenko *et al.,* 2018; Corona *et al.*, 2019; Saidani *et al.,* 2019). A company's Sustainable Circular Index (SCI) is formed by a set of indicators related to the social, economic, environmental, and circularity dimensions of materials, aggregated in an index using the Simple Additive Weighting (SAW) method. Inputs from virgin and recycled materials, reused components, useful life, and intensity of use are considered, compared to a similar average product.

The model also considers the increase in the durability of products and the repair, maintenance, and sharing business models, starting from the MCI, previously presented. The proposed indicators were based on recognized and accepted methodologies/criteria, used by companies in their daily routines and sustainability reports, such as the sustainability tripod, the G4 version of the GRI, which represents the first global standards for sustainability reports, and ISO 14031, which guides the design and use of environmental performance assessment within an organization. For its construction, the Delphi interview methodology was also used, applied to stakeholders from different sectors, and its validation was done in primary data.

3.1.8. Circularity Measurement Toolkit for manufacturing SMEs (CMT)

The model presented by Garza-Reyes *et al.* (2019) starts from the principles of CE and contemplates the nine R-strategies in the qualitative assessment of circularity in small and medium-sized companies. With structure nominally based on the work of Elia *et al.* (2017) and Masi *et al.* (2018), the CMT considers circularity actions such as efficient use of resources, internal adoption of circularity, internal environmental programs, external adoption of circularity, circular purchases and partnerships, recovery actions, acceptance and incentives, research and development and development of legislation. The study also defines detailed practices that could contribute to the execution of these actions and proposes a standard categorization for small and medium-sized companies in nine levels of circularity, similar to the levels of maturity, with level nine being the lowest and level one being the highest.

These levels are described according to their characteristics, as follows : (i) circular developer; (ii) circular promoter; (iii) circular; (iv) waved; (v) curved; (vi) saw-tooth; (vii) V-shape up; (viii) Ʌ-shape down; and (ix) linear. After categorizing the levels of circularity, their characteristics were "converted" into formulas, with the establishment of limit values for each level. To conduct the circularity assessment, the participating organization answers a questionnaire in which statements are evaluated qualitatively, with options of 'Yes', 'Partially', or 'No'. The CMT used the Delphi technique for validating data from secondary sources.

3.1.9.
Leading Indicator Database (LID)

Kravchenko *et al.* (2020) propose a procedure for a systematic selection of suitable performance indicators to support a sustainability-oriented decision-making process, the Leading Indicator Database (LID). According to the authors, the LID allows a systematic selection of sustainability indicators relevant to circular economy initiatives, among more than 270 indicators classified according to circularity strategies, company characteristics, and its sustainability objective. It uses a hypothetical-deductive approach to develop and evaluate the model, which starts from iterations between existing theories and knowledge, with a mixture of methods (Kravchenko *et al.,* 2020), proceeding to formulate a hypothesis for testing in workshops with specialists and representatives of organizations.

The hypothesis tested in the article is that the correlation of sustainability performance indicators to the strategies and business models of a circular economy can support companies in the selection of sustainability indicators for the evaluation of circular initiatives (Kravchenko *et al.*, 2020).

To use the tool, the authors emphasize that it is essential to define the scope of the selection of indicators, describing an EC initiative and elaborating its details, explaining which corporate decisions it affects (for example, orientation to business processes), and focus on a strategy specific circular economy (Kravchenko *et al.,* 2020). It is also necessary to define a baseline scenario, in which an EC initiative scenario can be compared, and involve a multidisciplinary team to support the selection of suitable indicators. Companies that participated in the evaluation workshop expressed the need for a support step to assist in the formulation of the sustainability strategy and objectives, necessary for using the tool, emphasizing the importance of a facilitator for the indicator selection procedure. Besides, the participants suggested that some key performance indicators would be used easily without the need for the LID (Kravchenko *et al.,* 2020), which was not explored at work.

3.1.10.
Circular Economy Indicators for Organizations (CEIO)

Rossi *et al.* (2020) proposed a set of indicators that relate the principles of the circular economy, the circular business model, and the three pillars of sustainability. It was based on the premise that a requirement for EC indicators is the ability of these indicators to achieve EC principles while helping to meet the specificities and needs of each Circular Business Model. The authors propose a level of intensity of correlation between the proposed indicators, the principles of EC and CBM, relating them to the pillars of sustainability: environmental, economic, and social. The model was developed based on the hypothetical-deductive approach, following several iterations (cycles) and testing the theory in three companies with different circular business models. A mix of research methods (for example, expert advice, user feedback, and case studies) has been applied (Rossi *et al.,* 2020).

Subsequently, the final hybrid set of 18 indicators is associated with the fields of the Business Analysis Canvas model, in order to identify how the indicators can reflect the impact of circularity strategies in creating value for its customers. These indicators were applied in three Brazilian companies, characterized by three different circular business models. The results show that data from the economic and social dimensions were not available, representing a barrier in identifying the positive impacts of the circular economy, as they must be presented in the three dimensions of sustainability.

3.1.11. Circulytics

The new measurement system of Ellen MacArthur Foundation (EMF, 2020), Circulytics, aims to measure the aspects that allow the circular transformation of a company, considering aspects such as the strategic importance of the circular economy and the innovative capacity for the circular economy, to support companies in the transition process. Circulytics generates a single score (Scorecard), which comprises two categories: enablers and outcomes (EMF, 2020).

The Circulytics score is presented on a scorecard, which is shared confidentially with each company and was designed to, in the future, help to increase the understanding of the strengths and areas for further development, from industry benchmarks. The Score has seven themes, five for the category of enablers and two for outcomes. The Enabler category aims to indicate the likelihood that a company will capture circular economy business opportunities in the future. It includes indicators that allow a transformation across the company, on topics such as strategic prioritization of the circular economy and internal learning programs. The Outcomes category shows a snapshot of a company's circularity. For companies that deal with material flows in their main businesses, the value of the Outcomes category is given mainly from the inputs, outputs, and processing of materials, in terms of their circularity. For companies that provide services, the results are given in terms of the degree of alignment of their services with the principles of the circular economy. Thus, the indicators are different depending on the type of company.

Each of the seven themes is related to indicators, qualitative and quantitative, which are aggregated to generate a single score, in a methodology similar to Simple Additive Weighting (SAW). Each qualitative indicator response option is translated into a quantitative 'score' from 0 to 100, and each quantitative indicator requires a percentage input from 0 to 100. Each indicator receives a weight, which is used to calculate a weighted average score for each theme. Sequentially, each theme also receives a weight, and these weights are used to calculate a weighted average score, which is the score at the category level. Finally, each of the two categories is given a weight, which is used to calculate an overall score, with the conversion from the numerical score to the letter scale.

The Circulytics score is presented on a scorecard, which is shared confidentially with each company and was designed to, in the future, help to increase the understanding of the strengths and areas for further development, from industry benchmarks.

3.2.
Research guidance: monitoring the transition process

The approaches adopted for measuring aspects related to the circular economy are synthesized in Table 3.1, according to the following questions: (i) whether the model considers corporate strategies for the transition of the business model or circular business models; (ii) if the system considers the hierarchy and prioritization of R-strategies, according to their correlation with circularity strategies and (iii) if the system measures the impact effects of adopting circular practices, in an impact perspective, (iv) if the system evaluates the intensity of adoption of circular practices, in a perspective of transition; (v) what is the methodology used for proposing C-indicators; and (vi) who have reviewed each cited work.

Amongst the methodological approaches used for proposing and/or selecting indicators, the Life Cycle Assessment (LCA) is the most used method for estimating environmental impacts of products and components, as previously pointed out by other authors (Schepens *et al.*, 2016; Walker *et al.*, 2018; Sassanelli *et al.*, 2019), and is sometimes associated with resource and input valuation methodologies and approaches linked to Material Flow Analysis (i.e., MFA; MFCA). However, due to the circular economy's intrinsic focus on preserving value and material, most of the proposed methods focus on measuring material consumption, with recycling being the most dominant EC strategy considered (Kravchenko *et al.*, 2020).

As stated by Bocken *et al.* (2016), resource efficiency itself is not a circular strategy, as it deals only with the quantity and flow of materials and must be combined with other R-strategies to close the cycle of products and materials or decrease the speed of use of resources through material replacement, repair, reuse and remanufacturing, to support the transition to a circular economy (Kristensen and Mosgaard, 2020).

A fundamental characteristic of the Circular Economy is the prioritization of circularity strategies according to their hierarchy (EMF, 2013; Kristensen and Mosgaard, 2020; Potting *et al.*, 2018) as presented in the previous chapter. Kristensen and Mosgaard (2020) indicate that this prioritization of EC principles is not present in the revised indicators, although some indicators allow the user of the indicator to compare different EC principles, which was also verified in the measurement systems reviewed in this research.

As for the measurement object, some systems assess the impact of adopting circular economy practices (EVR; SCI; MCI; LID), others the stage of adopting these practices, in a transition perspective (CET; CMT). It is pertinent to comment that, among the systems that propose to a hybrid analysis (FCIM; CEIO; CTI; Circulytics), there is no homogeneity in the approach: some include the principles of circular economy in the model, others the hierarchy according to R-strategies or circularity strategies, combined use is not common.

.

Table 3.1 – Comparative analysis of the reviewed circularity measurement systems

System [authors]	**(i) Business strategy**	**(ii) R-strategy hierarchy**	**(iii) Impact perspective**	**(iv) Transition perspective**	**(v) Methodology**	**(vi) Review (authors)**
Five Category Index Method (FCIM) [Li and Su, 2012]			**x**	**x**	Weighted Sum Model	Elia *et al.* (2017); Saidani *et al.* (2019).
The Circular Economy Toolkit (CET) [Evans and Bocken, 2013]	**x**	**x**		**x**	Interviews, surveys, and workshops	Rossi *et al.* (2020); Kristensen and Mosgaard (2020).
Eco-efficient Value Ratio (EVR) [Scheepens *et al.*, 2016]	**x**		**x**		Eco-efficient Value Creation (LCA based) and Material Flow Analysis (MFA)	Kristensen and Mosgaard (2020); Saidani *et al*. (2019); Rossi *et al*. (2020); Pauliuk (2018).
Sustainable Circular Index (SCI) [Azevedo *et al*., 2017]	**x**		**x**		Simple Additive Weighting (SAW) + Delphi tudy + MCI (LCA based)	Parkhomenko *et al.* (2018); Corona *et al.* (2019); Saidani *et al*. (2019); Rossi *et al*. (2020).
Circularity Indicator (MCI) [EMF, 2015; 2019]			**x**		Circular LCA	Corona *et al.* (2019); Saidani *et al.* (2019); Kristensen and Mosgaard (2020); Rossi *et al.* (2020);
Circularity measurement for SMEs [Garza-Reyes *et al.,* 2019]	**x**	**x**		**x**	Delphi Study, interviews, and surveys	N/A
Circular economy indicators for organizations (CEIO) [Rossi *et al.,* 2020]	**x**		**x**	**x**	Hypothetic deductive approach, interviews, and surveys	N/A
Circular Transition Indicators (CTI) [WBCSD, 2020]		**x**	**x**	**x**	Material Flow Analysis (MFA) + High level methodology	N/A
Circulytics [EMF, 2020]	**x**			**x**	Delphi + Simple Additive Weighting (SAW) + Material Flow Analysis (MFA)	N/A
Leading indicator database [Kravchenko *et al.*, 2020]	**x**		**x**		Hypothetic deductive approach	N/A

Measuring and assessing the circularity of organizations (or their contribution to EC) is crucial in developing business policies and strategies, but circularity metrics often have contradictions in form and content, which contributes to confusion and misunderstanding of the concept (Corona *et al.*, 2019; WBCSD, 2018). Academia, industry, and public managers share the need to develop indicators related to the circular economy (CE), and many tools, indexes, metrics, indicators have been designed for this purpose. However, it is of utmost importance to know what these indicators measure to use them properly, within the diffuse and complex concept of EC (Saidani *et al.*, 2019).

From the analysis and comparison of circularity measurement systems and organizations, objects of a recent systematic review, the research gap addressed in this dissertation can be objectively identified. It refers to the methodological approach used to define indicators and metrics of circularity, which mostly focuses on the evaluation of the implementation stage and the impact of low circularity strategies, without a procedure for prioritizing the various R-strategies, according to their contribution for the broad implementation of a circular business model. Despite different methodological approaches identified in the literature, there are research gaps regarding the proposal of generic models for measuring and evaluating the circularity of organizations, due to the adoption of different circularity strategies associated with circular business models.

4
Research methodology

Based on the research design presented in Table 1.1, this chapter details the methods adopted in each phase of this research, as follows: (i) literature review and documentary analysis on the central research themes; (ii) conceptual modelling for complex sociotechnical systems, integrating general morphological analysis (GMA) and multicriteria decision-making (MCDM) methods; and (iii) definition and calculation of composite circularity indicators and overall circularity performance index at the micro level.

4.1.
Literature review and documentary analysis

A literature review and documentary analysis on ‘circular economy’, ‘sociotechnical transition theory applied to a circular economy’, and ‘circularity performance measurement’ were conducted by accessing the Scopus, Web of Science, and Science Direct databases from the period of 2000 to 2020. By way of illustration, Table 4.1 shows the search history in Scopus database. Furthermore, a backward search based on references cited in the selected documents complemented this analysis.

Table 4.1 – Search history in Scopus database

Ref.	Search query	Documents (n)
#1	TITLE-ABS-KEY ("Circular economy") AND (Definition* OR Concept*)	2006
#2	TITLE-ABS-KEY ("Circular economy") AND ("Measurement system*" OR "Measuring" OR "indicator*")	734
#3	TITLE-ABS-KEY (Circularity) AND ("Measurement systems" OR "Measuring" OR "indicator*")	568
#4	TITLE-ABS-KEY ("Circular economy")AND(MCDA OR MCDM OR Multicriteria)	59
#5	TITLE-ABS-KEY(Circularity AND (MCDA OR MCDM OR Multicriteria)	15
#6	TITLE-ABS-KEY ("Circular economy") AND (GMA OR Morphological analysis)	1
#7	#2 AND #3 AND #4 AND #5 AND #6	0

Reinforcing the perception of the circular economy as a megatrend, it is possible to observe a significant increase in scientific production on the subject. Given the great availability and multidisciplinary of articles around the concept of circular economy, articles of the type review will be prioritized for theoretical foundation, where the literature already produced is contemplated.

The importance of developing a strategic measurement framework for monitoring and evaluating the circularity performance at the micro level was reinforced after this review.

4.2.
Conceptual modelling for complex sociotechnical systems

Conceptual modelling for complex sociotechnical systems (Ritchey, 2003; 2011; 2012) was used to develop a strategic measurement framework for monitoring and evaluating organizations' circularity performance from the CE transition perspective. The proposed framework integrates general morphological analysis (GMA) (Zwicky, 1969; Ritchey, 2003; 2011; 2012) and two multicriteria decision-making methods, namely Analytic Hierarchy Process (AHP) (Saaty, 1980; 1990) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981).

4.2.1.
General morphological analysis (GMA)

Created by Zwicky (1969), general morphological analysis (GMA) is a method for identifying and investigating the whole set of possible relationships in any given, multidimensional, and complex problem that can be parameterized. This method comprises five (iterative) steps, as follows (i) formulating very concisely the problem of circularity measurement to be solved; (ii) identifying all parameters that might be of importance for solving the problem; (iii) constructing the morphological matrix, which contains all parameters and their possible states; (iv) evaluating the consistency of possible morphological configurations in relation to the purpose to be achieved; and (v) defining and choosing consistent configurations of suitable solutions.

GMA is a method for identifying and investigating the whole set of possible relationships in any given, multidimensional, and complex problem that can be parameterized (Zwicky, 1969; Ritchey, 2003, 2011, 2012). This method has been employed in several management areas, such as engineering design, strategic planning, scenario-building, technological and business foresight, design thinking, and decision-making processes involving multidimensional issues (Martins *et al.*, 2020; Arciszewski, 2018; Álvarez and Ritchey, 2015). Notably, in CE transitions, the organization can explore distinct circular business scenarios using a visual representation called morphological matrix (Figures 2 and 3 in Chapter 5). For each scenario, the organization can define new value propositions, make consistent strategic choices (circularity strategies and associated R-strategies), and define targets based on composite C-indicators and respective overall Circularity Performance Index (CPI).

Combined with GMA, a hybrid multicriteria decision-making (MCDM) approach was used for: (i) defining criteria for selecting C-indicators under each R-strategy; (ii) ranking the R-strategies by importance for CE transitions, selecting and weighting the C-indicators associated with the ten R-strategies proposed by Potting *et al.* (2017).

Next items describe the two MCDM methods chosen for integrating the proposed framework – focus of this research: (i) the Analytic Hierarchy Process (AHP) method; and (ii) the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

4.2.2.
Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) method, developed by Saaty in 1980 (Saaty, 1980; 1990) was employed in two moments during the framework development, namely: (i) for weighting the criteria for selecting the C-indicators associated with each R-strategy; and (ii) for weighting the R-strategies, assuming the cascading hierarchy define by Potting *et al.* (2017).

This method was employed with support of the SuperDecisions® software (Creative Decision Foundation, 2019), encompassing four steps: (i) defining the criteria and the scale for pairwise comparison of these criteria; (ii) building the pairwise comparison matrix showing the preference of one criterion over the other; (iii) consistency check from the pairwise comparison matrix, calculating the Consistency Ratio (CR); and (iv) calculating the weights of each criterion, if the CR is accepted.

The first step consists of defining the criteria for ranking and selecting C-indicators by R-strategy and the scale to be adopted during the pairwise comparison of these criteria. The scale to be adopted is the nine-pointed scale proposed by Saaty (1980, 1990), as shown in Table 4.2.

Table 4.2 – The nine-pointed scale defined by Saaty

Level of importance	Definition
1	Same importance
2	Preference between the same and moderate
3	Moderate preference
4	Preference between moderate and strong
5	Strong preference
6	Preference between strong and very strong
7	Very strong preference
8	Preference between very strong and absolute
9	Absolute preference

Source: Saaty (1980, 1990).

The second step aims at building the pairwise comparison matrix showing the preference of one criterion over the other, based on judgmental values defined consensually by experts and using the Saaty's scale (Table 4.1).

In the third step, a consistency checking from the pairwise comparison matrix should be done, calculating the Consistency Ratio (CR). The consistency of the matrix is acceptable only if the CR≤0.10. If a matrix is inconsistent, then new pairwise comparison judgments are required. Once the inconsistency is accepted, it is possible to calculate the weights of criteria, following the procedure described in Saaty (1980, 1990) and in Costa (2002).

4.2.3. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), introduced by Hwang and Yoon (1981), was chosen for ranking and selecting C-indicators by R-strategy. The scale to be adopted ranges from level 9 (the C-indicator fully meets the criterion) to level 1 (the C-indicator does not meet the criterion). Levels 7, 5, and 3 are intermediate levels in this scale.

This method comprises five steps, as follows: (i) consensual judgments by experts concerning the performance of C-indicators in light of each criterion (ii) identify the positive ideal solutions A+ (benefits) and A- (costs; (iii) calculate the Euclidean distances from the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS) of each C-indicator by R-strategy; (iv) calculate the closeness coefficient of each alternative C-indicator concerning PIS; and (v) the ranking order of all C-indicators can be determined for each R-strategy. The best alternatives are those that have the higher value i and, therefore, should be chosen because they are closer to the PIS. This procedure should be done for each one of the ten R-strategies. All the formulas and parameters used in Chapter 5 can be found in Hwang and Yoon (1981).

4.2.4. C-Indicators selection sensitivity analysis

In the proposed model and in previous work (Franco *et al.*, 2021), the selection of C-Indicators in a transition management perspective is conducted with the support of a hybrid approach between Analytical Hierarchical Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), considering each R-strategy that could be adopted by one organization and their hierarchal contribution to a circular economy (Potting *et al.*, 2017). However, considering that detailed analysis of several works of literature review on circularity indicators to organizations confirmed that the combination of different MCDM was rarely applied in the C-Indicators selection field, a sensitivity analysis concerning the selection of C-indicators phase's for each R-strategy will be conducted with the support of this ELECTRE I method (Roy, 1968).

The method calculates the percentage of the relation between the two variables and aims to obtain a subset of alternatives, in which the alternatives that are part of that subset over-classify those that they do not do. The ability of ELECTRE I to compare an available set of alternatives separately concerning each attribute (or criteria) gives an edge over other outranking methods (Yadav *et al.*, 2020). For comparison purposes, the judgments from Franco *et al.* (2020) are replied to calculation and criterion weighting and are considered as input for this method, where two indices are generated: the concordance index, which will measure the relative advantage of each C-Indicator collected from the literature over the others, and the discordance index, which measures the relative disadvantage between them.

The procedure for executing ELECTRE I approach is simple and it should be applied when all the criteria have been coded in numerical scales with identical ranges (Almeida, 2011). In such a situation we can assert that an alternative “a outranks b” (that is, “a is at least as good as b”) is denoted by aSb when two conditions concerning the concordance index and the discordance index are attended. The strength of the concordant coalition (concordance index) must be powerful enough to support the assertion over aSb, and it is given by the sum of the weights associated with the criteria forming that coalition.

The main objective is to compare the results of the application of the hybrid method AHP-ELECTRE I to the hybrid method proposed in this dissertation (AHP-TOPSIS), and thus reinforce the robustness of the selection phase of circularity indicators for each R-strategy, among other insights to be discussed in Chapter 5.

4.3.
Definition and calculation of composite C-indicators

The definition and calculation of ten composite C-indicators associated with the R-strategies, as well as an overall Circularity Performance Index (CPI), were based on a methodological and user guide published by the Organisation for Economic Co-operation and Development (OECD) and also on reference works on constructing composite indicators (OECD, 2008; Saisana and Tarantola, 2002; Singh *et al.*, 2007; Permanyer, 2011; Rowley *et al.*, 2012; Greco *et al.*, 2019). Equations are presented in Chapter 5 – Section 5.4.

5
Strategic measurement framework to monitor and evaluate circularity performance at the micro level

The concept of a CE transition requires multi-level frameworks regarding the definition of circularity goals and targets for different time horizons, and desired change timeframes for companies or economic sectors with implications for national, regional or local public policies.

In line with the theoretical background and the research methodology presented in previous chapters, a strategic measurement framework for monitoring and evaluating the circularity performance of organizations from a CE transition perspective is here presented. From the CE transition perspective, the framework here proposed can be applied in organizations with two-fold objectives: (i) to measure composite C-indicators' values and overall CPI of an organization associated with R-strategies for evaluating progress before (*ex-ante*), during (*ex-durante*), and after (*ex-post*) the transition process; and (ii) to help the organization to rethink its value proposition and circularity strategic choices.

Figure 5.1 schematically represents the framework comprising six phases, as follows:

- Defining a morphological matrix for the problem of circularity measurement from a CE transition perspective;
- Defining and weighting criteria for ranking and selecting C-indicators associated with R-Strategies, using the AHP method;
- Ranking and selecting C-indicators for each R-strategy with support of the TOPSIS method;
- Calculating the composite C-indicators of a given organization, according to its value proposition and circularity strategic choices (until the level of R-strategies' choice);
- Calculating the overall Circularity Performance Index (CPI) of this organization from composite C-indicators; and
- Analysis of the organization's circularity performance in light of the sociotechnical transition theory.

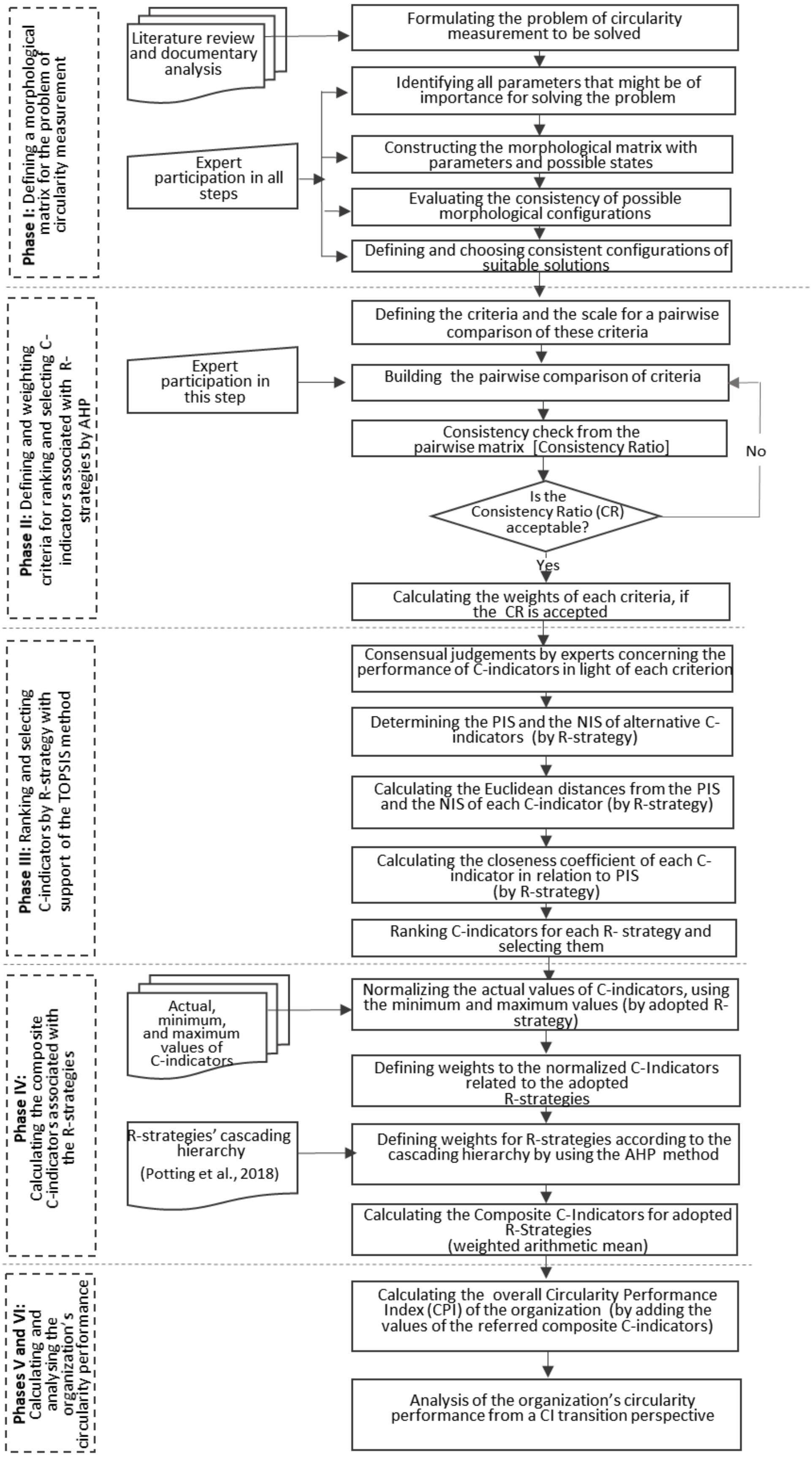

Figure 5.1 – General view of the strategic measurement framework to monitor and evaluate the circularity performance at the micro level.
Source: Franco *et al.* (2021).

5.1. Phase I: Defining a morphological matrix for the problem of circularity measurement from a transition perspective

For better understanding the interconnections of value proposition, circularity strategic choices, and C-indicators at the micro level, the general morphological analysis (GMA) method was considered a helpful methodological approach.

Following the steps previously described in section 4.2 – item 4.2.1, a morphological matrix interconnecting value proposition, circularity strategic choices, and C-indicators can be represented as shown in Figure 5.2.

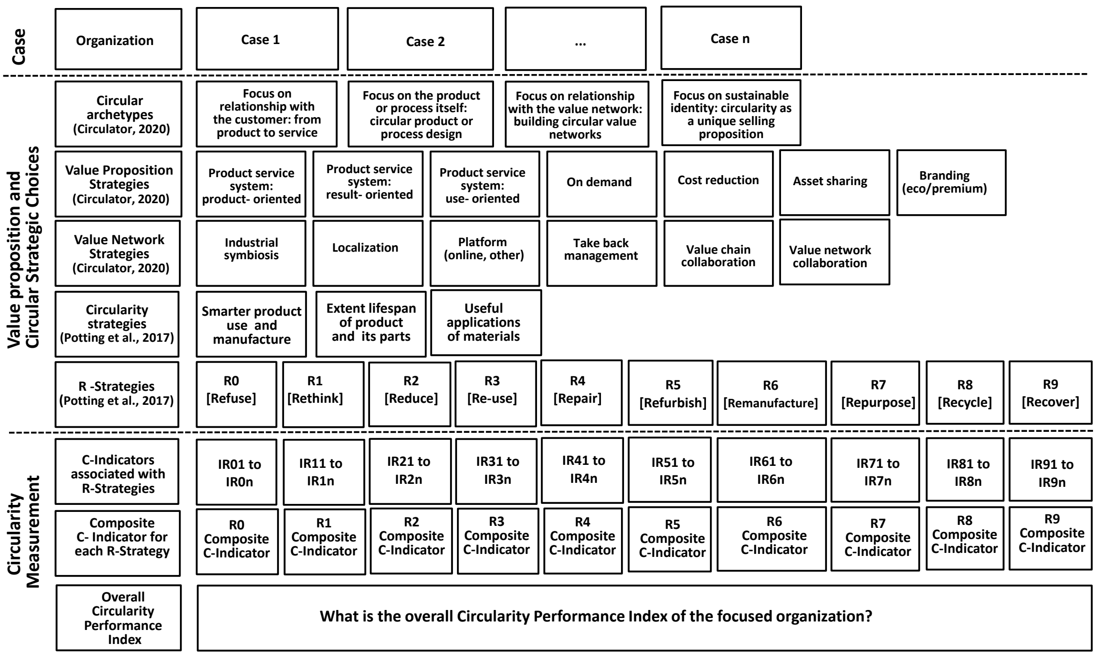

Figure 5.2 – Morphological matrix interconnecting value proposition, circularity strategic choices, and C-Indicators
Source: Franco *et al.* (2021).

Based on the literature review and experience of five senior experts selected to collaborate in the applied phase of the research, the parameters considered for integrating the morphological matrix are summarized in the following items.

5.1.1. Circular archetypes

Circulator (2020) identifies four circular archetypes, each one representing a specific business focus as the main entry point for developing a circular business model. Table 5.1 synthesizes the main characteristics of companies grouped to each archetype and their combined strategies towards a circular economy.

Table 5.1 – Circular archetypes according to Circulator (2020)

Circular archetype	Description
Focus on relationship with the customer: from product to service	Companies within this archetype focus on providing a service that directly addresses their customers' needs, rather than selling a product. They typically put a strategic focus on business strategies, like product-service systems or on-demand production, allowing them to apply sustainable materials management strategies within their own company, or allowing others to do so, e.g., by offering a sharing platform.
Focus on the product or process itself: a circular product or process design	Companies within this archetype put their main focus on improving the circularity of their products or production processes by directly addressing the sustainable materials management strategies. This archetype is mainly interesting for companies for which switching to a service model or collaborating with their value network is less feasible or attractive.
Focus on relationship with the value network: building circular value networks	To master the circularity of a product without having control over all stages of a product's lifecycle, collaboration with other companies downstream and upstream in the value chain, and/or with customers and other stakeholders is a key success factor. Companies within this archetype put their strategic focus on building circular value networks that are up to a challenging task and possibly the greatest business rewards in the long run.
Focus on sustainable identity: circularity as a unique selling proposition	This archetype groups companies that do not emphasize one of the three strategy categories but choose to put forward are a circular business as a central element in their company identity.

Source: Circulator, 2020.

5.1.2. Value proposition and value network strategies

The second and third dimensions are defined by Circulator (2020) as follows:

- Value proposition strategies: Strategies that help deliver circular value to the customer. These are ways of delivering value to the customer that typically enable the inclusion of circular value creation strategies in the business model. In the Business Model Generation (BMG) framework (Osterwalder *et al.*, 2010), these strategies are linked to the product offer, customer segments, and customer relationships elements;
- Value network strategies: Strategies to engage with actors beyond the company borders to achieve circular value networks. These are strategies that go beyond the company itself, acknowledging that a truly circular business entails the full value network to be involved in the creation of shared value. In the BMG framework, value network strategies can be linked to the delivery channel, customer relationships, key partners, or key resources and capabilities elements.

5.1.3. Circularity and R-strategies

Circularity strategies are addressed to reduce the consumption of natural resources and materials and minimize waste production. According to their levels of circularity, they can be ordered for priority as suggested by Potting *et al.* (2017).

As mentioned before, the R-strategic framework presented by Potting *et al.* (2017) was chosen for integrating the morphological matrix, since it contains a well-defined and comprehensive set of ten R-strategies, grouped around three main circularity strategies, namely: (i) smarter product use and manufacture; (ii) extended lifespan of the product and its parts; and (iii) extended lifespan of product and its parts. According to Potting *et al.* (2017), the ten R-strategies are:

- Refuse (R0): Make product redundant by abandoning its function or by offering the same function with a radically different product;
- Rethink (R1): Make product use more intensive (e.g., through sharing products or putting multifunctional products on the market);
- Reduce (R2): Increase efficiency in product manufacturing or use by consuming fewer natural resources or materials;
- Reuse (R3): Reuse by another consumer of discarded product which is still in good condition and fulfils its original function (and is not waste) for the same purpose for which it was conceived;
- Repair (R4): Repair and maintenance of defective product so it can be used with its original function;
- Refurbish (R5): Restore an old product and bring it up to date;
- Remanufacture (R6): Use parts of discarded product in a new product with the same function;
- Repurpose (R7): Use discarded product or its parts in a new product with a different function;
- Recycle (R8): Process materials to obtain the same (high grade) or lower (low grade) quality;
- Recovery (R9): Incineration of materials with energy recovery.

5.1.4.
C-indicators associated with R-strategies

According to Corona *et al.* (2019), the first step in evaluating circularity metrics is to define the set of requirements that must be met, depending on the correct measurement of progress towards the circular economy.

C-indicators associated with R-strategies are key elements for the strategic measurement framework designed to monitor and evaluate the circularity performance of organizations within a CE transition perspective.

Qualitative research based on content analysis (Neuendorf, 2017) was conducted to identify C-indicators' subsets associated with each R-strategy. This analysis was based on the assumption that since organizations are part of the micro level, they will significantly benefit from using existing C-indicators created with already available data and based on a CE concept agreed upon with stakeholders (European Commission, 2018; Kravchenko *et al.*, 2019; Rincón-Moreno *et al.*, 2021; WBCSD, 2020; GRI, 2020).

One of the main sources used in this study was the standard GRI 306: Waste 2020, updated on 19 May 2020. It highlights the relationship between materials and waste to help organizations identify and adopt waste-related practices and measure significant actual and potential waste-related impacts throughout value chains (GRI, 2020). The GRI waste disclosures can be help organizations collecting data for and responding to C-indicators associated with some of the ten R-strategies. Next, Table 5.2 shows the list of C-indicators associated with the ten R-strategies and the information sources.

As mentioned before in Section 4.2, from the CE transition perspective, the organization can explore distinct circular business scenarios using the morphological matrix (Figure 5.2). For each scenario, the organization can define new value propositions, make consistent strategic choices (circularity strategies and associated R-strategies), and define targets based on composite C-indicators and respective overall Circularity Performance Index (CPI).

Table 5.2 – C-indicators associated with the R-strategies

Refuse (R0)					
Ref.	**Measurement driver**	**Short label**	**Metrics**	**Suggested calculation**	**Sources**
IR01	Transitioning to and applying new circular business models	New circular business models adoption	% of revenue from new business models adoption	(total annual revenue from new business models / total annual revenue) x 100%	GRI 306 (2020).
IR02	Substitution of hazardous substances	Substitution of hazardous substances	% of hazardous substance substituted	[mass of hazardous substances substituted (annual consumption)/ total mass of hazardous substances (previous annual consumption)] x 100%	GRI 306(2020); European Commission (2018); Rossi *et al.* (2020); WBCSD (2020).
IR03	Substitution of non-renewable energy	Substitution of non-renewable energy	% of renewable energy consumption	[renewable energy (annual consumption)/ total energy (annual consumption)] x 100%	Rossi *et al.* (2020); WBCSD (2020).
IR04	Substitution of non-renewable raw materials	Substitution of non-renewable raw materials	% of renewable, biobased, or biodegradable materials consumption	[renewable material/biobased or biodegradable (annual consumption)/ total material (annual consumption)] x 100%	Rossi *et al.* (2020); WBCSD (2020).
IR05	Substitution of non-virgin content	Substitution of non-virgin materials	% of virgin material consumption	[non virgin material (annual consumption)/ total material (annual consumption)] x 100%	European Commission (2018); WBCSD (2020).
Rethink (R1)					
Ref.	**Measurement driver**	**Short label**	**Metrics**	**Suggested calculation**	**Sources**
IR11	Design for disassembly (modularity)	Modularity	Time (time unit) and number of products needed for disassembly (n)	[(% modularity of product Xi * total of product with modularity Xi)/ total of products] x 100	Sánchez-Ortiz *et al.* (2020); GRI306 (2020).
IR12	Product take-back	Product take-back	% of products taken back	[total products take-back(annual) / total products delivered (annual)] x 100%	GRI306 (2020); GRI301 (2016).
IR13	Improving materials selection	Critical materials	% of critical materials	(mass of product defined as critical/ total mass of product) x 100%	GRI306 (2020).
IR14	Shared use	Shared use	Number of users by product (n)	(total of products/ total of customers) x 100%	Consumer Choice Center (2020).
IR15	Durability of product	Durability	% of time added in lifespan of product or material Average of the real durability of selected products (time unit)	Complex index, concerning materials lifespan	Geyer and Van Wassenhove (2000). Sánchez-Ortiz *et al.* (2020).
IR16	Potential use during lifetime	Potential use during lifetime	Time of usability (years) Number of possible usages (n)	Complex index, concerning functionality time	Geyer and Van Wassenhove (2000).

Reduce (R2)					
Ref.	**Measurement driver**	**Short label**	**Metrics**	**Suggested calculation**	**Sources**
IR21	Reduction of materials consumption	Raw materials intensity reduction	% of reduction in materials consumption per production unit	100 - [(Raw materials consumption (current year)) /(Raw materials consumption (past year)) X 100]	Rossi *et al.* (2021); GRI 301 (2016); Sánchez-Ortiz *et al.* (2020).
IR22	Reduction of energy intensity	Energy intensity reduction	% of reduction in energy consumption per production unit	100 - [(Energy consumption in current year / production unit) /Energy consumption in past year/ production unit)]) X 100	GRI 302 (2018); Sánchez-Ortiz *et al.* (2020).
IR23	Reduction of energy consumption	Energy consumption reduction	% of reduction in energy consumption	100 - [(Energy consumption (current year) /Energy consumption (past year) X 100]	GRI302 (2018).
IR24	Reduction of waste generation	Waste generation reduction	% of reductions in waste generation	100 -[Waste generation (current year) /Waste generation (past year) X 100]	GRI 302 (2018); Sánchez-Ortiz *et al.* (2020).
IR25	Reduction of waste intensity – material losses	Material losses reduction	% of reduction in waste generation per production unit	100- [(Total waste generation (current year) / production unit) /waste generation (past year) / production unit)]) X 100	GRI 306 (2020); Sánchez-Ortiz *et al.* (2020); Rincón-Moreno *et al.*, (2021).
IR26	Water intensity reduction	Water intensity reduction	% of reduction in water consumption per production unit	100 - [(Water consumption (current year) / production unit) /Water consumption (past year) / production unit)]) X 100	Rincón-Moreno *et al.* (2021).
IR27	Water consumption reduction	Water consumption	% of reduction in water consumption	100 - [Water consumption (current year) / water consumption (past year) X 100]	GRI 303 (2018).
Reuse (R3)					
Ref.	**Measurement driver**	**Short label**	**Metrics**	**Suggested calculation**	**Sources**
IR31	Reuse rate	Reuse rate	% of reused products	[products called to reuse (annual) /total number of products used (annual)]x 100%	Rossi *et al.* (2020); WBCSD (2020).
IR32	Product take-back	Product take-back	% of recaptured products	[total products take-back(annual) / total products (annual)] x 100%	GRI 306 (2020); GRI 301 (2016).
IR33	Consumers awareness about reuse benefits	Consumer awareness	% of customers receiving second life products, by customer segment	Percentage of customers receiving second life products, by customer type	GRI 306 (2020).
IR34	Reuse business model	Reuse business model	% of revenue from reuse business models adoption	(total annual revenue re-use business / total annual revenue) x 100%	Authors' suggestion.
IR35	Potential use during lifetime	Potential use	Time of usability (time unit) Number of possible uses	Complex index, concerning functionality time.	Geyer and Van Wassenhove (2000).
IR36	Products directed to reuse	Ownership time	Average time of ownership	Average time of ownership of a product by one customer	GRI 306 (2020).

Repair (R4)					
Ref.	**Measurement driver**	**Short label**	**Metrics**	**Suggested calculation**	**Sources**
IR41	Product longevity extension	Longevity extension	Time added in the lifespan of the product or materials (time unit)	Complex index, concerning materials lifespan	Rossi *et al.* (2020); Sánchez-Ortiz *et al.* (2020); GRI 306 (2020).
IR42	Input materials or design characteristics of outputs that limit or prevent their recovery or limit the length of their life.	Critical material	% of critical content	(mass or parts of the product defined as critical/ total mass or parts of product) x 100%	GRI 301(2016).
IR43	Extension of producer responsibility or product stewardship	Extension of producer responsibility	% of customers with access to repair and maintenance services	(number of customers with access to repair and maintenance services/ total number of customers) x100	GRI 306 (2020).
IR44	Engaging with consumers to raise awareness about repair advantages	Consumer awareness	% of customers engaged in repair model	(number of customers receiving repair services or repaired products/ total number of customers) x100	GRI 306 (2020).
IR45	Repair business model	Repair business model	% of revenue from repair business models adoption	(total annual revenue re-use business / total annual revenue) x 100%	Authors' suggestion.
IR46	Products repair	Potential repair	% of products successful repaired	[products successfully repaired /total number of products received to repair]x 100%	Rossi *et al.* (2020).
Refurbish (R5)					
Ref.	**Measurement driver**	**Short label**	**Metrics**	**Suggested calculation**	**Sources**
IR51	Reclaimed products	Product take-back	% of reclaimed products to refurbishment	[total products take-back(annual) / total products delivered (annual)] x 100%	GRI 301 (2016); GRI 306 (2020).
IR52	Quantity of the total refurbished parts (or components)	Refurbished content	% of refurbished parts (or components)	Quantity of the total recovery or parts (components) of the product, without necessarily going through all stages of the remanufacturing.	Rossi *et al.* (2020).
IR53	Refurbish sales	Refurbishment business model	% of revenue from refurbish business models adoption	(total annual revenue from refurbish / total annual revenue)x 100%	Authors' suggestion.
IR54	Engaging with consumers to raise awareness about refurbishment advantages	Consumer awareness	% of percentage of customers in refurbishing model	(number of customers receiving refurbishing services or refurbished products/ total number of customers) x100	GRI 306 (2020).
IR55	Products successfully refurbished	Refurbishment potential	% of products successfully refurbished	[products or parts successfully refurbished /total number of products or parts received for refurbishment]x 100%	Authors' suggestion.

Remanufacture (R6)					
Ref.	**Measurement driver**	**Short label**	**Metrics**	**Suggested calculation**	**Sources**
IR61	Reclaimed products - (% product take-back)	Product take-back	% of product reclaimed for remanufacturing	[total products take-back(annual) / total products eligible (annual)] x 100%	GRI 301 (2016); GRI 306 (2020).
IR62	Remanufactured products	Remanufacturing effectiveness	% of remanufactured products	[total products successfully remanufactured (annual) / total products tacked back (annual)] x 100	Rossi *et al.* (2020).
IR63	Remanufacturing business sales (%)	Remanufacturing business model	% of revenue from remanufacturing business	[(total annual revenue from remanufacture / total annual revenue)] x 100%	Authors' suggestion.
IR64	Consumers awareness about remanufacturing benefits	Consumer awareness	% of customers of remanufacturing business model	(Number of customers receiving remanufacturing services or remanufactured products/ total number of customers) x100	GRI 306 (2020).
IR65	Remanufactured content	Remanufacturing potential	% of products or parts successfully remanufactured	(products or parts successfully remanufactured /total number of products or parts received for remanufacturing)x 100%	Authors' suggestion.
Repurpose (R7)					
Ref.	**Measurement driver**	**Short label**	**Metrics**	**Suggested calculation**	**Sources**
IR71	Non-virgin material consumption (%)	Secondary raw materials	% of total of non-virgin materials or components	[non virgin content/ total content] x 100%	An *et al.* (2018); WBCSD (2020); European Commission (2018); GRI 306 (2020); Rossi *et al.* (2020); Sánchez-Ortiz *et al.* (2020).
IR72	Hazardous waste diverted from disposal	Hazardous waste diverted from disposal	Total weight of hazardous waste diverted from disposal (metric tons) % of repurposing operations	[total weight of hazardous waste with energy recovery (annual)/ total weight of hazardous waste input (annual)] x 100%	GRI 306 (2020).
IR73	Non- hazardous waste diverted from disposal	Non- hazardous waste diverted from disposal	% of non-hazardous waste used repurpose	[total mass of non-hazardous waste with repurpose (annual)/ total non-hazardous waste input (annual)] x 100%	GRI 306 (2020).
IR74	Secondary raw materials	Total weight of waste diverted from disposal	% of secondary raw materials consumption	[secondary raw materials (annual consumption)/ total raw materials (annual consumption)] x 100%	GRI 306 (2020); WBCSD (2020).

Recycle (R8)					
Ref.	**Measurement driver**	**Short label**	**Metrics**	**Suggested calculation**	**Sources**
IR81	Overall recycling rates	Overall recycling rates	Overall recycling rate (%)	[total mass material recycled (annual)/ total materials input (annual)] x 100%	European Commission (2018); An *et al.* (2018); GRI 306 (2020).
IR82	Recycling rate for specific waste streams	Recycling rate for waste streams	Recycling rate for waste streams (%)	[total Xi mass material recycled (annual)/ total materials (Xi) input (annual)] x 100%	European Commission (2018); An *et al.*, (2018); GRI 306 (2020).
IR83	Waste generation	Waste generation	% of residual waste	[total mass of residual waste (annual)/ total materials input for recycling (annual)] x 100%	An *et al.* (2018); GRI 306 (2020); European Commission (2018).
IR84	New materials required	Material take-back	% of new materials required for recycling	[total mass of raw material input (annual)/ total mass of materials recycled (annual)] x 100%	GRI 306 (2020).
IR85	Reverse logistics processes to divert products and materials from disposal	Reverse logistics	% of customers with access to reverse logistics services	(Number of customers with access to reverse logistics services/ total number of customers) x100	GRI 306 (2020).
IR86	Total waste diverted from disposal	Trade in recyclable materials	% of diverted from disposal	[total mass of waste recycled or composed (annual)/ total materials input for recycling (annual)] x 100%	GRI 306 (2020); European Commission (2018).
IR87	Reverse logistics processes to divert products and materials from disposal	Recycling potential	% of customers receiving recycling and composting services (by customer segment)	(number of customers receiving recycling and composting services or remanufactured products/ total number of customers) x100	GRI 306 (2020); European Commission (2018).
Recovery (R9)					
Ref.	**Measurement driver**	**Short label**	**Metrics**	**Suggested calculation**	**Sources**
IR91	Waste diversion from landfills	Waste diversion from landfill	% of waste diverted from disposal to energy recovery	[total mass of material input for recovery (annual) - total material directed to landfills	Sánchez-Ortiz *et al.* (2020); GRI 306 (2020).
IR92	Residual products	Recovery rate	% of residual products	[total mass of residual products (annual)/ total materials input for recovery (annual)] x 100%	GRI 306 (2020); WBCSD (2020).
IR93	Energy recovery	Potential recovery	Recovered energy (mega joules or multiples)	total amount of recovered energy - energy consumption (annual) - (in MJ or multiples)	WBCSD (2020); An *et al.* (2018).
IR94	Total weight of hazardous waste directed to disposal	Hazardous waste directed to disposal	Total weight of hazardous waste diverted from disposal (metric tons) Breakdown of recovery operations (%)	[total weight of hazardous waste with energy recovery (annual)/ total weight of hazardous waste input (annual)] x 100%	GRI 306 (2020).
IR95	Total weight of non-hazardous waste directed to disposal	Non-hazardous waste directed to disposal	% of non-hazardous waste used for energy recovery	[total mass of non-hazardous waste with energy recovery (annual)/ total non-hazardous waste input (annual)] x 100%	GRI 306 (2020).
IR96	Energy recoverability benefit rate	Energy recoverability benefit	Benefit rate of recycling Benefit rate of energy recovery versus land filling	European Commission (JRC) is working on new indicators that assess the benefits of recycling or energy recovery versus landfilling	An *et al.* (2018).
IR97	Raw materials input	Raw materials input	% of new materials required for recovery (%)	[total mass of raw materials (annual)/ total materials input (annual)] x 100%	WBCSD (2020).

The proposed morphological matrix (Figure 5.2) has 5,040 theoretically possible configurations of design options, i.e., 4 × 7 × 6 × 3 ×10 configurations associated with ‘value proposition and circular strategic choices’. Figure 5.3 shows an illustrative example of a consistent morphological configuration (highlighted in grey) representing circular strategic choices of a hypothetical organization (Company A) associated with R2, R8, and R9 strategies.

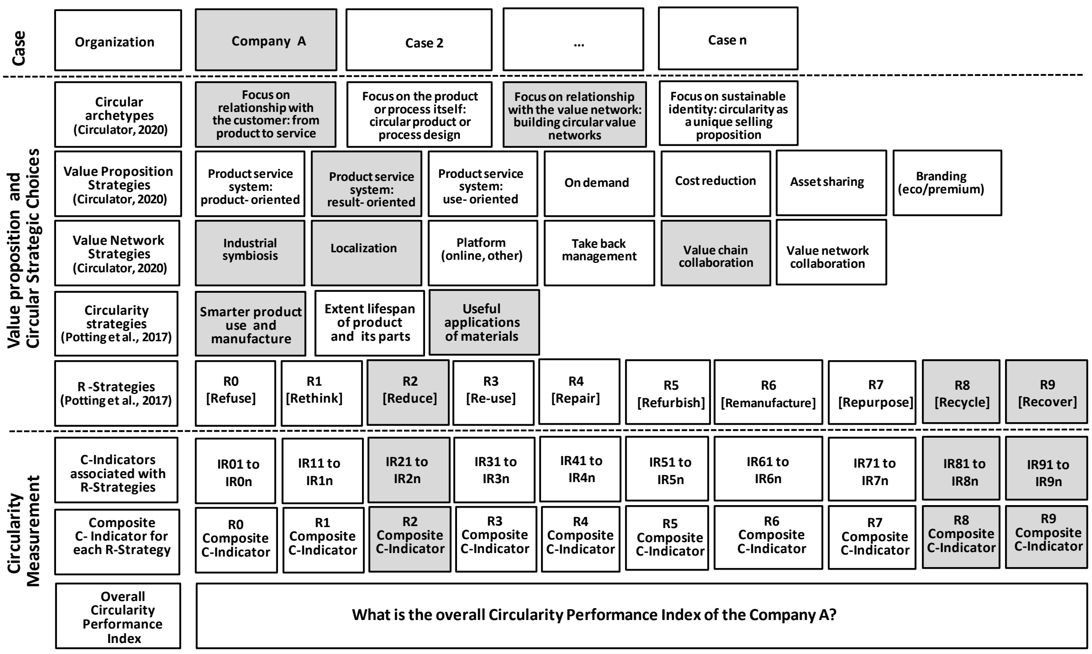

Figure 5.3 – Illustrative example of a consistent morphological configuration representing the circular strategic choices associated with R2, R8, and R9 strategies.
Note: The blocks highlighted in grey correspond to the combined design options that describe a chosen circular business scenario.
Source: Franco *et al.* (2021).

Pieroni *et al.* (2019) argue that a complex, interconnected and uncertain job of incorporating CE concepts and principles requires the organization’s capacity to propose distinguished value proposition strategies and rethink their business models. In this illustrative example, two ‘circular archetypes’, one ‘value proposition strategy’, three ‘value network strategies’, and two ‘circularity strategies’ comprise a consistent morphological configuration of circular strategic choices associated with R2, R8, and R9 strategies.

5.2. Phase II: Defining and weighting criteria for ranking and selecting C-indicators associated with R-strategies by the AHP method

The objective of this second phase of the framework is to define and assign weights to the criteria for ranking and selecting indicators among the 58 C-indicators listed in Table 5.2, those that will integrate the measurement framework at the micro level.

Many participatory approaches have been suggested in the literature to make this subjective weighting exercise as participative and transparent as possible (OECD, 2008; Greco *et al.,* 2019). These approaches can be a single or multi-stakeholder for deciding on the weighting scheme to be chosen. Stakeholders could be expert analysts, policymakers, or even citizens to whom decisions are addressed (OECD, 2018). In this research, the criteria weighting involved five senior experts with background in strategic planning, circular economy, and sustainability measurement research fields.

Amongst the multicriteria decision-making methods, the Analytic Hierarchy Process (AHP) method introduced by Saaty (1980; 1990) was chosen for several reasons already mentioned. For this research, the AHP method can determine the relative importance of criteria for ranking and selecting C-indicators by R-strategy, encompassing four steps, as described before (See Item 4.2.2).

Based on the methodological approaches adopted by the International Bank for Reconstruction and Development and the World Bank (Görgens and Kusek, 2009; Kusek and Rist, 2004), the following criteria are suggested to be used in this phase:

- **C1 - Relevance:** The C-indicator should be a valid measure of the result/outcome of a circularity strategy;
- **C2 – Measurability**: The C-indicator has the capacity to be counted, observed, analyzed, tested, or challenged. If one cannot measure a C-indicator, then progress towards a circular economy cannot be determined;
- **C3 - Accuracy**: Accurate C-indicators are considered correct. The data measure what they are intended to measure each circularity strategy;
- **C4 - Credibility**: The indicator has been recommended and used by leading experts and organizations in the context of circular economy and Sustainability (Global Reporting Initiative, for example);

- **C5 - Precision:** Precision means that the data collected have sufficient detail concerning the C-indicator;
- **C6 – Timeliness**: The C-indicator must be timely in several aspects. Particularly, the time-lag between output delivery and the expected change in outcome and impact C-indicators must also be reflected in the indicators that are chosen. The system (monitoring and evaluation system and related C-indicators) allows progress to be tracked in a cost-effective manner at the desired frequency for a set period.

The scale to be adopted in this first step is the nine-pointed scale shown in Table 4.1, as defined by Saaty (1980, 1990).

Following the steps described in Item 4.2.2, the results of criteria weighting by pairwise comparison using the AHP method are shown in Tables 5.3 and 5.4. The SuperDecisions® software (Creative Decision Foundation, 2019) was used in this step.

Table 5.3 – Criteria weighting by AHP pairwise comparison

Criterion	C1	C2	C3	C4	C5	C6
C1 – Relevance	1	1	2	3	3	2
C2 – Measurability	1	1	2	3	3	2
C3 – Accuracy	1/2	1/2	1	2	2	1
C4 – Credibility	1/3	1/3	1/2	1	1	1/2
C5 – Precision	1/3	1/3	1/2	1	1	1/2
C6 – Timeliness	1/2	1/2	1	2	2	1

Note: Consistency Ratio (CR) = 0.03 [CR<0.1 indicates consistency in judgments].

Table 5.4 – Final criteria weighting by the AHP method

Criterion	Weight
C1 – Relevance	0.27
C2 – Measurability	0.27
C3 – Accuracy	0.15
C4 – Credibility	0.08
C5 – Precision	0.08
C6 – Timeliness	0.15

5.3. Phase III: Ranking and selecting C-indicators by R-strategy by TOPSIS method

Tables 5.5 to 5.14 present the results of the third phase concerning the ten R-strategies, highlighting in a grey pattern the selected C-indicators that will integrate the measurement system for monitoring and evaluating the organization's circularity performance (composite C-indicator for adopted R-strategy and overall Circularity Performance Index).

Table 5.5 – Euclidian distances, closeness coefficients, and ranking of C-indicators under 'Refuse' strategy (R0)

Ref.	C-indicator	Euclidian Distances D+	Euclidian Distances D-	Closeness Coefficient (CCi)	Final ranking	
IR01	New business models adoption	0.21	0.17	0.45	IR02	1.00
IR02	Substitution of hazardous substances	0.00	0.28	1.00	IR03	1.00
IR03	Substitution of non-renewable energy	0.00	0.28	1.00	IR05	0.70
IR04	Substitution of non-renewable raw materials	0.22	0.14	0.39	IR01	0.45
IR05	Substitution of virgin materials	0.11	0.26	0.70	IR04	0.39

Table 5.6 – Euclidian distances, closeness coefficients and ranking of C-indicators under 'Rethink' strategy (R1)

Ref.	C-Indicator	Euclidian distances D+	Euclidian distances D-	Closeness Coefficient (CCi)	Final ranking	
IR11	Modularity	0.22	0.22	0.50	IR14	0.79
IR12	Product take-back	0.11	0.33	0.74	IR12	0.74
IR13	Critical materials	0.22	0.25	0.53	IR13	0.53
IR14	Shared use	0.08	0.32	0.79	IR11	0.50
IR15	Durability	0.31	0.16	0.35	IR15	0.35
IR16	Potential use	0.32	0.08	0.21	IR16	0.21

Table 5.7 – Euclidian distances, closeness coefficients and ranking of C-indicators under 'Reduce' strategy (R2)

Ref.	C-Indicator	Euclidian distances D+	Euclidian distances D-	Closeness coefficient (CCi)	Final ranking	
IR21	Raw materials intensity reduction	0.00	0.30	1.00	IR21	1.00
IR22	Energy intensity reduction	0.25	0.15	0.37	IR23	1.00
IR23	Energy consumption reduction	0.00	0.30	1.00	IR27	1.00
IR24	Waste generation reduction	0.13	0.27	0.68	IR24	0.68
IR25	Material losses reduction	0.29	0.06	0.17	IR22	0.37
IR26	Water intensity reduction	0.27	0.11	0.29	IR26	0.29
IR27	Water consumption	0.00	0.30	1.00	IR25	0.17

According to the final ranking of C-indicators under each R-strategy, the indicators ranked in the first three positions were selected for R0 to R7. In turn, for R8 and R9, the indicators selected are ranked in the first five positions. This choice is justified by the number of indicators identified in the literature (much more C-indicators for those R8 and R9 than for the other R-strategies).

Table 5.8 – Euclidian distances, closeness coefficients, and ranking of C-Indicators under ‘Re-use’ strategy (R3)

Ref.	C-indicator	Euclidian distances		Closeness coefficient (CCi)	Final ranking	
		D+	D-			
IR31	Re-use rate	0.10	0.44	0.81	IR36	0.85
IR32	Product take-back	0.11	0.48	0.81	IR31	0.81
IR33	Consumer awareness	0.36	0.22	0.39	IR32	0.81
IR34	Re-use business model	0.17	0.42	0.70	IR34	0.70
IR35	Potential use	0.50	0.00	0.00	IR33	0.39
IR36	Ownership time	0.08	0.46	0.85	IR35	0.00

Table 5.9 – Euclidian distances, closeness coefficients and ranking of C-indicators under ‘Repair’ strategy (R4)

Ref.	C-indicator	Euclidian distances		Closeness coefficient (CCi)	Final ranking	
		D+	D-			
IR41	Longevity extension	0.20	0.32	0.61	IR46	1.00
IR42	Critical material	0.16	0.35	0.68	IR45	0.70
IR43	Extension of producer responsibility	0.35	0.16	0.32	IR42	0.68
IR44	Consumer awareness	0.36	0.24	0.40	IR41	0.61
IR45	Repair business model	0.17	0.40	0.70	IR44	0.40
IR46	Potential repair	0.00	0.44	1.00	IR43	0.32

Table 5.10 – Euclidian distances, closeness coefficients, and ranking of C-indicators under ‘Refurbish’ strategy (R5)

Ref.	C-indicator	Euclidian distances		Closeness coefficient (CCi)	Final ranking	
		D+	D-			
IR51	Product take-back	0.12	0.35	0.75	IR55	1.00
IR52	Refurbished content	0.33	0.13	0.28	IR51	0.75
IR53	Refurbishment business model	0.17	0.35	0.67	IR53	0.67
IR54	Consumer awareness	0.36	0.14	0.28	IR52	0.28
IR55	Refurbishment potential	0.00	0.40	1.00	IR54	0.28

Table 5.11 – Euclidian distances, closeness coefficients, and ranking of C-indicators under ‘Remanufacture’ strategy (R6)

Ref.	C-indicator	Euclidian distances		Closeness coefficient (CCi)	Final ranking	
		D+	D-			
IR61	Product take-back	0.25	0.26	0.51	IR62	1.00
IR62	Remanufacture effectiveness	0.00	0.40	1.00	IR63	0.67
IR63	Remanufacture business model	0.17	0.35	0.67	IR61	0.51
IR64	Consumer awareness	0.36	0.14	0.28	IR65	0.28
IR65	Remanufacture potential	0.33	0.13	0.28	IR64	0.28

Table 5.12 –. Euclidian distances, closeness coefficients and ranking of C-indicators under ‘Repurpose’ Strategy (R7)

Ref.	C-indicator	Euclidian distances		Closeness coefficient (CCi)	Final ranking	
		D+	D-			
IR71	Secondary raw materials	0.10	0.29	0.74	IR74	1.00
IR72	Hazardous waste diverted from disposal	0.31	0.00	0.00	IR71	0.74
IR73	Non- hazardous waste diverted from disposal	0.24	0.11	0.32	IR73	0.32
IR74	Total weight of waste diverted from disposal	0.00	0.31	1.00	IR72	0.00

Table 5.13 –. Euclidian distances, closeness coefficients and ranking of C-indicators under ‘Recycle’ strategy (R8)

Ref.	**C-indicator**	**Euclidian distances**		**Closeness coefficient (CCi)**	**Final ranking**	
		D+	**D-**			
IR81	Overall recycling rates	0.21	0.32	0.60	IR82	1.00
IR82	Recycling rate for waste streams	0.00	0.42	1.00	IR83	0.77
IR83	Waste generation	0.11	0.37	0.77	IR81	0.60
IR84	Material take-back	0.25	0.30	0.54	IR86	0.59
IR85	Reverse logistics	0.37	0.11	0.23	IR84	0.54
IR86	Trade in recyclable materials	0.20	0.29	0.59	IR85	0.23
IR87	Recycling potential	0.42	0.00	0.00	IR87	0.00

Table 5.14 –. Euclidian distances, closeness coefficients and ranking of C-indicators under ‘Recover’ strategy (R9)

Ref.	**C-indicator**	**Euclidian distances**		**Closeness coefficient (CCi)**	**Final ranking**	
		D+	**D-**			
IR91	Waste diversion from landfill	0.10	0.67	0.87	IR93	1.00
IR92	Recovery rate	0.18	0.61	0.77	IR91	0.87
IR93	Potential recovery	0.00	0.71	1.00	IR97	0.83
IR94	Hazardous waste directed to disposal	0.16	0.64	0.80	IR94	0.80
IR95	Non-hazardous waste directed to disposal	0.16	0.64	0.80	IR95	0.80
IR96	Energy recoverability benefit	0.70	0.11	0.14	IR92	0.77
IR97	Energy generation	0.14	0.68	0.83	IR96	0.14

Table 5.15 presents the final list of C-indicators selected for integrating the measurement system.

Table 5.15 –. C-Indicators selected for integrating the circularity measurement system

R-strategy	**Ref.**	**C-indicator**	**Adjusted closeness coefficient (CCi) after selection**
Refuse (R0)	IR02	Substitution of hazardous substances	0.32
	IR03	Substitution of non-renewable energy	0.32
	IR05	Substitution of virgin materials	0.22
	IR01	New business models adoption	0.14
Rethink (R1)	IR14	Shared use	0.38
	IR12	Product take-back	0.36
	IR13	Critical materials	0.26
Reduce (R2)	IR21	Raw materials intensity reduction	0.25
	IR23	Energy consumption reduction	0.25
	IR27	Water consumption	0.25
	IR24	Waste generation reduction	0.16
	IR22	Energy intensity reduction	0.09
Re-use (R3)	IR36	Ownership time	0.27
	IR31	Re-use rate	0.26
	IR32	Product take-back	0.26
	IR34	Re-use business model	0.22
Repair(R4)	IR46	Potential repair	0.42
	IR45	Repair business model	0.29
	IR42	Critical material	0.29
Refurbish (R5)	IR55	Refurbishment potential	0.41
	IR51	Product take-back	0.31
	IR53	Refurbishment business model	0.28
Remanufacture (R6)	IR62	Remanufacture effectiveness	0.46
	IR63	Remanufacture business model	0.31
	IR61	Product take-back	0.23

Table 5.15 –. C-Indicators selected for integrating the circularity measurement system (cont.)

R-strategy	Ref.	C-indicator	Adjusted closeness coefficient (CCi) after selection
Repurpose (R7)	IR74	Total weight of waste diverted from disposal	0.48
	IR71	Secondary raw materials	0.36
	IR73	Non- hazardous waste diverted from disposal	0.16
Recycle (R8)	IR82	Recycling rate for waste streams	0.29
	IR83	Waste generation	0.22
	IR81	Overall recycling rates	0.17
	IR86	Trade in recyclable materials	0.17
Recovery (R9)	IR93	Potential recovery	0.23
	IR91	Waste diversion from landfill	0.20
	IR97	Energy generation	0.19
	IR94	Hazardous waste directed to disposal	0.19
	IR95	Non-hazardous waste directed to disposal	0.19

5.3.1. Ranking and selecting C-indicators by R-strategy by ELECTRE I method - comparison with TOPSIS

According to Almeida (2011), the methods of the ELECTRE family are applied in two main steps. Initially, the over-classification relationship is built, where a comparison is made pair by pair of alternatives. This step includes the initial input of weights of criteria obtained through the application of AHP methodology in the previous stage, presented in Table 5.4 The decision matrix for each R-Strategy is structured considering the previous evaluation of the performance of the indicators against each criterion, according to Franco *et al.* (2020) and the previous step presented. From these data, concordance indexes [C (a, b)] were calculated for each pair of alternatives, in a concordance matrix for different R-Strategies. Then, for each pair of indicators, the discordance indexes [D (a, b)] were also calculated, as determined by Roy (1968). So, the agreement threshold (p = 0.7) and the veto threshold (q = 0.4) were defined. That is, when comparing two alternatives there will be a veto if a difference of 0.4 or more points is obtained in their performance related to the criterion.

From the defined over classing relations, the kernel was defined. The kernel consists of a subset of alternatives that do over class other alternatives. The subsets of indicators for each of the circularity strategies, considering the related R-Strategy and the possible kernels are obtained for the agreement threshold and the veto threshold defined. To enable a more accurate analysis of the selection from the application of the ELECTRE I method, a sensitivity analysis was performed regarding the agreement (p) and veto (q) thresholds, resulting in three kernel's configurations: Kernel A, Kernel B and Kernel C. In addition to the sensitivity analysis for the results obtained for the selection of indicators by the AHP-ELECTRE I method, Table 5.16 compares the results from the application of both methods for ranking and selecting C-indicators for each R-strategy.

Table 5.16. Selected C-indicators by R-strategy by AHP-ELECTRE I and AHP-TOPSIS

	AHP- ELECTRE I				AHP -TOPSIS
R-Strategy	Kernel	p	q	Selected C-indicators	Selected C-indicators
Refuse (R0)	A	0.3	1	IR01, IR02, IR03, IR05	IR01, IR02, IR03, IR05
	B	0.3	0.3	IR02, IR03, IR05	
	C	*	0,2	IR02, IR03	
Rethink (R1)	A	0.2	1	IR11, IR12, IR13, IR14	R12, IR13, IR14
	B	0.2	0.4	IR12, IR14	
	C	0.2	0.4	IR12, IR14	
Reduce (R2)	A	0.3	0.4	IR21, IR23, IR24, IR27	IR21, IR22, IR23, IR24, IR27
	B	0.7	0.4	IR21, IR23, IR27	
	C	1	0	IR21, IR23, IR27	
Re-use (R3)	A	0.3	0.6	IR31, IR32, IR34, IR36	IR31, IR32, IR34, IR36
	B	0.75	0.6	IR31, IR34, IR36	
	C	0.75	0.4	IR31, IR36	
Repair (R4)	A	0.3	1	IR41, IR42, IR45, IR46	IR42, IR45, IR46
	B	0.3	0.4	IR42, IR46	
	C	0.5	0.4	IR46	
Refurbish (R5)	A	0.1	1	IR51, IR53, IR54, IR55	IR51, IR53, IR55
	B	0.1	0.4	IR51, IR55	
	C	0.8	0.4	IR55	
Remanufacture (R6)	A	0.1	0.5	IR61, IR62, IR63, IR64	IR61, IR62, IR63
	B	0.3	0.5	IR61, IR62, IR63	
	C	0.3	0.4	IR62	
Repurpose (R7)	A	0.3	0.5	IR71, IR74	IR71, IR73, IR74
	B	0.8	0.4	IR74	
	C	1	0	IR74	
Recycle (R8)	A	0.3	0.5	IR81, IR82, IR84, IR86	IR81, IR82, IR83, IR84, IR86
	B	0.3	0.4	IR82, IR84	
	C	0.8	0.4	IR82	
Recovery (R9)	A	0.5	0.3	IR91, IR93, IR94, IR95, IR97	IR91, IR93, IR94, IR95, IR97
	B	0.6	0.3	IR91, IR93, IR97	
	C	0.6	0.2	IR93	

From the results obtained in the previous phase, it was possible to demonstrate the applicability of the proposed hybrid methodology for selecting C-indicators.. From the initial set of 58 indicators (Table 5.2), 38 were selected in Kernel A (Table 5.16), 24 in Kernel B and, 14 in Kernel C. The results obtained in the sensitivity analysis concerning the use of the AHP-ELECTRE I model confirm, therefore, that the higher the agreement threshold (p) and lower the veto threshold (q), smallest the number of indicators in the kernel and the better the attendance of indicators to the selection criteria. This is denoted by the C kernel, which has more restrictive values of p and q.

The maintenance of the same indicators used in previous work (Franco et al 2020) in the first phase of this research, as well the values used to evaluate the performance of the indicators against the selection criteria and the weights of the criteria itself in the second phase, allows the comparison of the results for the two different applications of AHP hybrid methods for C-Indicators selection.

It is possible to note that, when comparing the results of the application of the AHP-ELECTRE I model with the results of the AHP-TOPSIS approach, similarity and coherence in the selected C-indicators are observed, although a variation in the number of indicators is observed from kernel to kernel.

A differential of AHP-ELECTRE I, when compared with the AHP-TOPSIS approach, refers to its applicability to problems that require the selection of the smallest possible number of indicators. On the other hand, an observed disadvantage lies in the fact that the approach can exclude essential indicators from the kernel, especially if high agreement thresholds are established. This finding confirms that the hybrid AHP-TOPSIS approach is the best for the strategic measurement model, as proposed in this dissertation.

5.4. Phase IV: Calculation of the composite C-indicators associated with R-strategies

The objective of this phase is to calculate the composite C-indicators associated with the R-strategies adopted by a given organization. This is done by normalizing the C-indicators, using the minimum and maximum values obtained from benchmarking studies or other reference sources.

Table 5.17 shows an illustrative example with the actual, minimum, and maximum values for each C-Indicator associated with one of the R-Strategies chosen by the organization.

Table 5.17 – Actual, minimum, and maximum values for C-indicators associated with 'Reduce' strategy (R2).

Ref.	C-Indicator	Actual value	Minimum value	Maximum value
IR21	Materials consumption reduction	$IR21_{AV}$	$IR21_{Min}$	$IR21_{Max}$
IR23	Energy consumption reduction	$IR23_{AV}$	$IR23_{Min}$	$IR23_{Max}$
IR27	Water consumption reduction	$IR27_{AV}$	$IR27_{Min}$	$IR27_{Max}$
IR24	Waste generation reduction	$IR24_{AV}$	$IR24_{Min}$	$IR24_{Max}$
IR22	Energy intensity reduction	$IR22_{AV}$	$IR22_{Min}$	$IR22_{Max}$

From the minimum and maximum values, the C-Indicators are then calculated by the following equation:

$$\text{Normalized C-Indicator} = \frac{\text{Actual value} - \text{Minimum value}}{\text{Maximum value} - \text{Minimum value}} \quad (1)$$

Considering, for example, the normalized C-Indicator $IR21_N$, it must be estimated as follows:

$$IR21_N = \frac{IR21_{AV} - IR21_{Min}}{IR21_{Max} - IR21_{Min}} \quad (2)$$

The next step aims to define weights to the normalized C-Indicators related to the R-Strategies adopted by the organization. The weights to be assigned to these C-Indicators can be easily obtained by adjusting the values of CCi (resulting from Phase III). Before going to the next step, the R-Strategies should also be weighted by the AHP method with the support of SuperDecisions® software (Creative Decision Foundation, 2019). Tables 5.18 and 5.19 show the pairwise comparison of R-Strategies and the final weights resulting from the experts' judgments.

Table 5.18 – R-strategies weighting by AHP pairwise comparison

R-Strategies	R0	R1	R2	R3	R4	R5	R6	R7	R8	R9
R0 – Refuse	1	1	2	3	4	5	6	7	8	8
R1 – Rethink	1	1	1	2	3	4	5	6	7	8
R2 – Reduce	1/2	1	1	2	3	4	5	6	7	8
R3 – Re-use	1/3	1/2	1/2	1	1	2	3	4	5	6
R4 – Repair	1/4	1/3	1/3	1	1	1	2	3	4	5
R5 – Refurbish	1/5	1/4	1/4	1/2	1	1	1	2	3	4
R6 – Remanufacture	1/6	1/5	1/5	1/3	1/2	1	1	1	2	3
R7 – Repurpose	1/7	1/6	1/6	1/4	1/3	1/2	1	1	1	2
R8 – Recycle	1/8	1/7	1/7	1/5	1/4	1/3	1	1	1	2
R9 – Recovery	1/8	1/8	1/8	1/6	1/5	1/4	1/2	1/2	1/2	1

Note: Consistency Ratio in judgments (CR) =0.01906 [CR<0.1 indicates consistency in judgments].

Table 5.19 – Final R-Strategies weighting by the AHP method

R-strategy	Weight
R0 - Refuse	0.25
R1 - Rethink	0.20
R2 - Reduce	0.19
R3 - Re-use	0.11
R4 - Repair	0.08
R5 - Refurbish	0.06
R6 - Remanufacture	0.05
R7 - Repurpose	0.03
R8 - Recycle	0.02
R9 - Recovery	0.02

Note: CR =0.01906 [CR<0.1 indicates consistency in judgments].

At that point, for calculating the composite C-Indicator the weight of each C-indicator should be multiplied by the weight of the focused R-strategy. Continuing with the illustrative example, Table 5.20 shows the final weights assigned to the five C-indicators under the 'Reduce' strategy (R2).

Table 5.20 – Weights assigned to the 'Reduce' strategy (R2) and associated C-indicators

			Weights (w)	
	R-strategy 'Reduce' (R2)	**0.19**		
Ref.	**C-indicator**		**Adjusted CCi values**	**Final weights**
IR21	Materials consumption reduction		0.25	0.047
IR23	Energy consumption reduction		0.25	0.047
IR27	Water consumption reduction		0.25	0.047
IR24	Waste generation reduction		0.17	0.032
IR22	Energy intensity reduction		0.09	0.018

The composite C-indicator regarding one of the R-strategies adopted by the organization can be calculated by the weighted arithmetic mean of its C-indicators, as follows:

X is the set of C-indicators associated with one R-strategy.

$$X = \{x_1, x_2 \ldots., x_n\}$$

W is the set of final weights assigned to them.

$$W = \{w_1, w_2 \ldots., w_n\}$$

The weighted arithmetic mean is calculated by equation (3).

$$\bar{x} = \sum_{i=1}^{n} w_i . x_i \qquad (3)$$

Continuing with the illustrative example, the composite C-indicator associated with the 'Reduce'(R2) strategy can be calculated as follows:

$$R2 = 0.047\ IR21_N + 0.047\ IR23_N + 0.047\ IR27_N + 0.032\ IR24_N + 0.018\ IR22_N \quad (4)$$

5.5. Phase V: Calculation of the overall Circularity Performance Index (CPI) of the organization

The overall Circularity Performance Index (CPI) represents the aggregation of the Composite C-Indicators for all R-Strategies adopted by the organization. This overall Index can be calculated by the sum of the referred Composite C-Indicators obtained in Phase IV, as follows:

R is the set of Composite C-Indicators associated with all R-Strategies adopted by the organization.

$$R = \{R0, R1, \ldots, R9\}$$

If a *Ri* Strategy is not adopted by an organization, the Composite C-Indicators associated with *Ri* equals zero.

The overall Circularity Performance Index (CPI) of the organization is calculated as follows:

$$\text{CPI} = \sum_{i=0}^{9} Ri \qquad (5)$$

5.6. Phase VI: Analysis of the organization's circularity performance from the CE transition perspective

In this phase, after having the respective composite C-indicators associated with the adopted R-strategies by the organization and its overall CPI, the organization should evaluate its circularity performance in comparison to other organizations of the same economic sector (sectoral benchmarking) or to those that have been classified in the same circular archetype (see Table 5.1).

If the organization strategically plans to maintain its value proposition and circularity strategies, it could redefine targets to improve its composite C-indicators for increasing its overall CPI in this chosen CE transition pathway. From the CE transition perspective, the organization can also explore distinct circular business scenarios using the morphological matrix (Figures 5.2 and 5.3). For each scenario, the organization can define new value propositions, make consistent strategic choices (circularity strategies and related R-strategies), and define targets concerning composite C-indicators and respective overall CPI.

5.7. Discussion of results

Nowadays, there is a consensus among academicians and practitioners on the need for appropriate methodological approaches to monitor and evaluate the implementation of circularity strategies in business contexts. In this research, the literature review and documentary analysis on existing C-indicators defined for the micro level provided an updated and comprehensive view concerning ongoing efforts to improve circularity performance measurement at this level, as discussed in Chapter 3. Besides, this review identified significant gaps in the literature that this research aims to fill.

From the CE transition perspective, the integration of a scenario-building method (GMA) and a hybrid multicriteria approach (AHP-TOPSIS) brings novelty to the current literature on the existing circularity performance measurement systems addressed to the micro level. Notably, GMA enabled identifying and visually representing the interconnections between value proposition, circularity strategic choices, and C-indicators associated with ten R-strategies. In turn, the use of two MCDM methods (AHP and TOPSIS) in phases II and III make it possible to reduce the number of C-indicators from 58 to 38 (Table 5.15). From the set of 38 indicators, ten composite C-indicators associated with the R-strategies, as well as an overall CPI, could be calculated following equations presented in Chapter 5 (Section 5.4).

To the best of our knowledge, previous studies on circularity performance measurement at the micro level have not explored a GMA-MCDM approach yet.

Within a morphological space, organizations can create consistent alternative configurations and CE transition scenarios (associated with different circular archetypes and circularity strategies) to explore and understand the interconnections between those parameters within their vision towards a circular economy. The results based on a GMA application attempted to fill the research gap on methodological approaches to identify and analyze the interconnections between value proposition, circularity strategic choices, and C-indicators. So far as we know, only one application GMA was addressed to CE frameworks (Lüdeke-Freund *et al.*, 2018). The authors employed GMA for mapping consistent patterns of circular business models (CBMs) from 26 existing models identified in the literature, focusing exclusively on CBMs. The morphological space proposed here goes beyond the chosen circular business model by the organization. In fact, this is the start point (upper layers in Figure 5.2).

One of the main contributions of this research refers to the identification and analysis of existing C-indicators and their classification by R-strategy, according to the framework proposed by Potting *et al.* (2007). As mentioned before, this framework was chosen since it contains a well-defined and comprehensive set of ten R-strategies, grouped around three main circularity strategies, namely: (i) smarter product use and manufacture; (ii) extended product and its parts' lifespan; and (iii) useful application of materials.

Qualitative research based on content analysis (Neuendorf, 2017) was carried out to define a set of C-indicators and subsets regarding each R-strategy (Table 5.2). From a CE transition perspective at the micro level, C-indicators associated with R-strategies are the key elements of the proposed framework designed to monitor and support CE transitions in organizations with impacts for meso and macro levels.

Another significant contribution is that the potential use of a hybrid methodological approach (that combined GMA with two MCDM methods) for selecting the most relevant C-indicators for each R-strategy could be highlighted. This hybrid approach fit the purpose of addressing the multiple dimensions of circularity performance measurement and special attention was paid to define which criteria and scale should be used during the expert pairwise comparison of these criteria. Based on reference guides from the International Bank for Reconstruction and Development (IBRD) and the World Bank (Görgens and Kusek, 2009; Kusek and Rist, 2004), the following criteria for selecting good quality C-indicators were suggested to be used in this phase: (i) relevance; (ii) measurability; (iii) accuracy; (iv) credibility; (v) precision; (vi) timeliness. Despite the results achieved in phases II and III, one of the limitations of the study refers to the fact that the weighting of criteria for ranking and selecting C-indicators and the selection process itself were carried out in consensus-building meetings by a limited number of experts (five senior academicians with background in strategic planning, circular economy, and sustainability measurement research fields). In this respect, Deniz (2020) argues that expert evaluation is the backbone of the MCDM methods.

The consensus degree is partly associated with the experts' failure to recognize that their choices not only depend on the objective response to alternatives but also is a function of their subjective structure (Squillante and Ventre, 2010). The mainstream research in MCDM methods highlights the ambiguity and uncertainty inherent to decision-making processes, and fuzzy logic has been the approach commonly used to overwhelm these problems (Deniz, 2020).

Since the criteria weighting and C-indicators selection were based on consensus-building meetings and not on a fuzzy logic approach, it is suggested that fuzzy logic and simulations should be employed in future research to compute the collective weightings and deal with uncertainty and ambiguity in judgments (Zadeh, 1969; Buckley, 1984). Besides, if the consensus-building approach is the methodological option for conducting the pairwise comparisons and C-indicators selection (instead of using fuzzy logic), one of the recommendations for reducing the probability of introducing bias during future applications of the proposed framework in organizations is to invite experts who have different backgrounds and come from various contexts.

These measures would provide greater robustness, reliability, and validity in terms of the proposed framework's sensitivity. The definition of ten composite C-indicators associated with the R-strategies, as well as an overall CPI, was based on a methodological and user guide published by the OECD and also on reference works on constructing composite indicators (OECD, 2008; Saisana and Tarantola, 2002; Singh *et al.*,2007; Permanyer, 2011; Rowley *et al.*,2012; Greco *et al.*, 2019). In Section 5.4, the calculation of the composite C-indicators associated with the R-strategies adopted by a given organization could be objectively explained through an illustrative example.

In line with sociotechnical transition theory (Rip and Kemp, 1998; Geels, 2002; Geels and Schot, 2007) and previous works by Potting *et al.* (2017; 2018), the results here presented suggest that it is essential to provide a temporal focus in a strategic measurement framework for organizations that are in CE transitions. In the words of Potting *et al.* (2017, p. 20):

> "It is useful to evaluate CE transitions by measuring progress before (*ex-ante*), during (*ex-durante*), and after (*ex-post*) the transition process. An ex-ante evaluation is relevant to explore whether proposed CE transitions actually have potential to bring about the intended CE effects. *Ex-durante* evaluation is important to monitor whether a CE transition process follows the planned route and leads to the desired effects. Ex-post evaluations should determine whether the effects of the CE transition process are in accordance with the set goals".

Finally, the main findings presented in this dissertation are aligned with the guidelines from the publication "Circular Transition Indicators V1.0: Metrics for Business, by Business" (WBCSD, 2020). Highlighting one of them:

> "Although the use of common indicators for circularity performance is essential to accelerating the transition to the circular economy, the value of the circular transition indicators for a company goes beyond the calculation in the guidance, analysis, and explanation for how circularity drives company performance. These indicators help companies to scope and prepare the assessment and interpret its results, understand its risks and opportunities, prioritize actions, and establish targets to monitor progress" (WBCSD, 2020, p.8).

6
Conclusions

In this dissertation, an attempt was made to propose a strategic measurement framework to monitor and evaluate the circularity performance of organizations from a CE transition perspective, aligned with the call made by several authors for further research about more effective monitoring and evaluation of circularity strategies with relevant C-indicators.

At the CE micro level, multiple transitions and scenarios might occur in the coming years, but only some of these will lead to higher levels of circularity of individual businesses and value chains. In this context, organizations from different sectors and sizes can benefit from the proposed framework for monitoring and assessing their CE transition progress. First, they can build CE transition scenarios, and then for each scenario, they can better choose which R-strategies would be implemented in the short, medium, and long-term.

In summary, the main findings of this research are:

- A generic morphological matrix comprising eight parameters and their possible states to define and visually represent possible CE transition scenarios for a given organization that aims to evolve through CE transitions;
- The potential use of a hybrid methodological approach (that combines GMA with two MCDM methods) for selecting the most relevant C-indicators for each R-strategy could be highlighted;
- An initial list of 58 C-indicators and metrics associated to ten R-strategies and a set of 38 selected C-indicators by adopting the hybrid AHP-TOPSIS method;
- Definition of ten composite C-indicators associated with the R-strategies, as well as an overall Circularity Performance Index (CPI), and a step-by-step procedure to calculate them in different CE transition scenarios.

Since the research's nature is essentially methodological, developing further a multiple case study focusing on organizations representing different 'circular archetypes' and various economic sectors could demonstrate the proposed framework's applicability and validity in real business contexts. Besides, the use a fuzzy logic approach instead of consensus-building meetings in the second and third phases of the framework could be a methodological improvement in relation to the model here proposed.

Future research could include a more in-depth analysis of circularity scores addressed to the lack of benchmarking models for comparing circularity performance of products and companies, based on the R-strategy framework. Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA) could be used in benchmarking modeling. Additionally, the potential complementarities between the 38 selected C-indicators would require further discussion and analysis. In this respect, two multicriteria methods could be employed – Analytic Network Process (ANP) and Decision Making Trial and Evaluation Laboratory (DEMATEL).

Finally, it would also be relevant to investigate and learn about the successful implementation of R-strategies by pioneering organizations and analyze their impact on the meso and macro levels.

As the origins of the Theory of Change lie in the field of monitoring and evaluation, this methodological approach could be useful to conduct evaluations of CE transitions in organizations from different sectors and levels of circularity performance. From this perspective, GMA could be applied on the development of new frameworks for measuring organizations' circularity performance and impacts of circular business transitions on the meso and macro levels by exploring alternative parameters or dimensions.

7
References

Accenture. **Circular Advantage:** Innovative Business Models and Technologies to Create Value in a World without Limits to Growth. Accenture Report. 2014.

Agyemang, M.; Kusi-Sarpong, S.; Khan, S.A.; Mani, V.; Rehman, S.T.; Kusi-Sarpong, H. Drivers and barriers to circular economy implementation: An explorative study in Pakistan's automobile industry. **Management Decision**, v.57, n.4, p. 971-994. 2019.

Allwood, J.M.; Ashby, M.F.; Gutowski, T.G.; Worrel, E. Material efficiency: A white paper. **Resour.Conserv. Recycl.** v.55, n.3, p. 362-381. 2011.

Almeida, M.F.L.; Melo, M.A.C. Sociotechnical regimes, technological innovation and corporate sustainability: from principles to action, **Technology Analysis & Strategic Management,** v.29, n.4, p.395-413. 2017.

Alvarez, A; Ritchey, T. Applications of general morphologyical analysis—From Engineering design to policy analysis. **Acta Morphologica Generalis** v.4, n.1, p.1-40, 2015.

An, V.; Maarten, C.; Veronique, V. H. **Indicators for a circular economy.** VITO CE Center Publication n.1. 2018. https://vlaanderen-circulair.be/en/summa-ce-centre/publications/indicators-for-a-circular-economy.

Antikainen, M.; Valkokari, K. A framework for sustainable circular business model innovation. **Technol. Innov. Manag. Rev**., v.6, n.7, p.5–12. 2016.

Arciszewski, T. Morphological analysis in inventive engineering. **Technological Forecasting and Social Chang**e, v. 126, p. 92-101, 2018.

Azevedo, S.G.; Godina, R.; Matias, J. C.O. Proposal of a sustainable circular index for manufacturing companies. **Resources,** v. 6, n 63. 2017.

Bakker, C.; Den Hollander, M.; Van Hinte, E.; Zijlstra, Y. **Products that last: Product design for circular business models**. TU Delft Library, Delft, the Netherlands. 2014b.

Bakker, C.; Wang, F.; Huisman, J.; Den Hollander, M. Products that go round: exploring product life extension through design, **Journal of Cleaner Production**, v.69, p. 10–16. 2014a.

Berkhout, F.; Smith, A.; Stirling, A. **Sociotechnical regimes and transition contexts**. In: Elzen, B., Geels, F.W., Green, K. (Eds.), System Innovation and the Transition to Sustainability. Edward Elgar, Cheltenham. 2004.

Bertoni, M. Multi-Criteria Decision Making for Sustainability and Value Assessment in Early PSS Design. **Sustainability**. v.11, 2019.

Blomsma, F.; Pieroni, M.; Kravchenko, M.; Pigosso, D.C.A.; Hildenbrand, J.; Kristinsdottir, A.R.; Kristoffersen, E.; Shabazi, S.; Nielsen, K.D.; Jönbrink, A.-K.; Li, J.; Wiik, C.; Mcaloone, T.C. Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation. **Journal of Cleaner Production**, v.241, n.118271, 2019.

Bocken, N. M. P.; Bakker, C.; Pauw, I. D. Product design and business model strategies for a circular economy. **Journal of Industrial and Production Engineering** v.33, n.5, p.301-320, 2016.

Bocken, N.M.P.; Strupeit, L.; Whalen, K.; Nußholz, J.L.K. A review and evaluation of circular business model innovation tools. **Sustainability,** v.11, n.8, 2019. http://doi.org 2210. 10.3390/su11082210.

Boschma, R.; Coenen, L.; Frenken, K.; Truffer, B. Towards a theory of regional diversification: combining insights from Evolutionary Economic Geography and Transition Studies, **Reg. Stud**., v.51, n.1, p.31-45, 2017.

British Standards Institution. BSI. **BS 8001:2017**. Framework for implementing the principles of the circular economy in organizations – Guide. London, UK: The British Standards Institution, 2017.

Brown, H.S.; Vergragt, P.; Green, K.; Berchicci, L. Learning for sustainability transition through bounded sociotechnical experiments in personal mobility. T**echnology Analysis and Strategic Management**, v.15, n.3, p.291-315, 2003.

Buckley, J.J. The multiple judge, multiple criteria ranking problem: a fuzzy set approach**. Fuzzy Set Syst**., n.13, p.25-37, 1984.

Chen, L. H.; Hung, P.; Ma, H. W. Integrating circular business models and development tools in the circular economy transition process: A firm-level framework. **Bus. Strat. Env.,** n.29, p.1887–1898, 2020.

Circle Economy. CE. **Master circular business with the value hill**. Amsterdam, NL: Circle Economy, 2016.

Circle Economy. CE. **The Circularity Gap Report** - Closing the Circularity Gap in a 9% World. Version 1.0 (January 2019). Circle Economy. 2019.

Circle Economy. MVO Nederland. **The potential for high value reuse in a circular economy**. Online publications. Circle Economy and MVO, 2015.

Circularity Gap Reporting Initiative (CGRi), 2020.**The Circularity Gap Report** 2020. https://www.circularity-gap.world/2020.

Circulator. The Circular Business Model Mixer. 2020. https://www.circulator.eu/mix-your-strategies.

Consumer Choice Center. CCC. **Sharing Economy Index**. 2020. https://consumerchoicecenter.org/sharing-economy-index-2020/

Corona, B.; Shen, L.; Reike, D.; Rosales Carreón, J.; Worrell, E. Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. **Resources, Conservation and Recycling.** v.151, n.104498, 2019.

Costa, H. G. **Introdução ao método de análise hierárquica**: análise multicritério no auxílio à decisão. Niterói, RJ: H. G. Costa, 2002.

Creative Decision Foundation. Super Decisions V.3.2 Manual (online). 2019. https://www.superdecisions.com/manuals.

De Jesus, A.; Mendonça, S. Lost in transition? drivers and barriers in the eco-innovation road to the circular economy. **Ecological Economics**, n.145, p.75-89. 2018.

Deniz N. Cognitive biases in MCDM methods: an embedded filter proposal through sustainable supplier selection problem. **J. Enterp. Inf. Manag**., v.33, n.5, p. 947-963.

Di Maio, F.; Rem, P.C. A robust indicator for promoting circular economy through recycling. **J. Environ. Prot**. n.06, p.1095-1104, 2015.

Di Maio, F.; Rem, P.C.; Baldé, K.; Polder, M. Measuring resource efficiency and circular economy: A market value approach. **Resources, Conservation and Recycling**, v.122, p. 163-171. 2017.

Dupas, G. (org.). **Meio ambiente e crescimento econômico:** tensões estruturais. – São Paulo: Editora UNESP, 2008.

Elia, V.; Gnoni, M-G.; Tornese, F. Measuring circular economy strategies through index methods: a critical analysis. **Journal of Cleaner Production,** v 142, p. 2741- 2751, 2017.

Ellen Macarthur Foundation. EMF. **Circularity indicators -** an approach to measure circularity. methodology. Ellen MacArthur Foundation. in collaboration with ANYSYS Granta. Cowes, UK, 2019.

Ellen Macarthur Foundation. EMF. **Circulytics.** method introduction. Ellen MacArthur Foundation, 2020. https://www.ellenmacarthurfoundation.org/assets/downloads/circulytics-methodintroduction.pdf

Ellen Macarthur Foundation. EMF. **Delivering the circular economy: A toolkit for policymakers**. Cowes, UK: EMF, 2015a.

Ellen Macarthur Foundation. EMF. T**owards a circular economy:** Business rationale for an accelerated transition. Cowes, UK: Ellen MacArthur Foundation, 2015b.

Ellen Macarthur Foundation. EMF. **Towards the circular economy: economic and business rationale for an accelerated transition**, v.1. Isle of Wight: EMF, 2013a.

Ellen Macarthur Foundation. EMF. **Towards the circular economy: economic and business rationale for an accelerated transition**, v.2. Isle of Wight: EMF, 2013b.

Ellen Macarthur Foundation. EMF. **Towards the circular economy:economic and business rationale for an accelerated transition**, v.3. Isle of Wight: EMF, 2014.

Ellen Macarthur Foundation. Granta Design. **Circularity Indicators**: An approach to measuring circularity, 2015. https://www.ellenmacarthurfoundation.org/assets/downloads/insight/Circularity-Indicators_Methodology_May2015.pdf.

European Academies Science Advisory Council. EASAC. **Indicators for a circular economy.** EASAC Policy Report 30. Halle (Saale), Germany: European Academies Science Advisory Council, 2016.

European Comission. EC. **Scoping study to identify potential circular economy actions, priority sectors, material flows and value chains.** European Commission. Brussels: European Commission, 2014.

European Commission. EC. **Measuring progress towards circular economy in the European Union:** Key Indicators for a Monitoring Framework. SWD(2018) 17 final. European Commission, Strasbourg, 2018.

Evans, J. L., Bocken, N.M.P. Circular economy toolkit. **Sustainable Design and Manufacturing**, 2014, p. 303-320. 2014.

Evans, J.; Bocken, N. **Circular economy toolkit.** Cambridge Institute for Manufacturing. 2013. http://circulareconomytoolkit. Org.

Forum For The Future. **The circular economy business model toolkit**. 2016. https://www.forumforthefuture.org/the-circular-economy-business-model-toolkit.

Franco, N. G.; Almeida, M. F. L.; Calili, R. A strategic measurement framework to monitor and evaluate circularity performance in organizations from a transition perspective. **Sustainable Production and Consumption,** v. 27, p. 1165-1182, 2021.

Garza-Reyes, J.A.; Salomé Valls, A.; Peter Nadeem, S.; Anosike, A.; Kumar, V. A circularity measurement toolkit for manufacturing SMEs. **International Journal of Production Research.** v. 57, p.7319-7343, 2019.

Geels, F.W. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. **Research Policy,** v.31 n.8/9, p. 1257-1274, 2002.

Geels, F.W.; Schot, J.W. Typology of sociotechnical transition pathways. R**esearch Policy** v.36, n.3, p.399–417, 2007.

Geissdoerfer, M.; Pieroni, M.P.P.; Pigosso, D.C.A.; Soufani, K. Circular business models: A review. **Journal of Cleaner Production,** v.277, n.123741. 2020.

Geissendoerfer, M.; Savaget, P.; Bocken, N. M. P.; Hultink, E. J. The circular economy – a new sustainability paradigm? **Journal of Cleaner Production.** v.143, p. 757- 768, 2017.

Genovese, A.; Acquaye, A.A.; Figueroa, A.; Koh, S.C.L. Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. **Omega,** v.66, p.344–35, 2017.

Georgescu-Roegen, N. **The entropy law and the economic process.** Cambridge, Mass., EUA: Harvard University Press, 1971.

Geyer, R.; Van Wassenhove, L. **Product take-back and component reuse**. Insead Working Paper Series. Insead, Fontainebleau, France. 2000.

Ghisellini, P.; Cialani, C.; Ulgiati, S. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. **Journal of Cleaner Production**, v.114, p.11-32. 2016.

Global Reporting Initiative. GRI. **GRI301: Materials**. GRI, The Netherlands. 2016. https://www.globalreporting.org/standards/media/1008/gri-301-materials-2016.pdf.

Global Reporting Initiative. GRI. **GRI302: Energy**. GRI, The Netherlands, 2018. https://www.globalreporting.org/standards/media/1009/gri-302-energy-2016.pdf.

Global Reporting Initiative. GRI. **GRI303: Water and Effluents**. GRI, The Netherlands, 2018. https://www.globalreporting.org/standards/media/1909/gri-303-water-and-effluents-2018.pdf.

Global Reporting Initiative. GRI. **GRI306: Waste**. GRI, The Netherlands, 2020. https://www.globalreporting.org/standards/media/2573/gri-306-waste-2020.pdf.

Görgens, M.; Kusek, J.Z. **Making monitoring and evaluation systems work**: A capacity development toolkit. Washington, DC: International Bank for Reconstruction and Development/ The World Bank. 2009.

Greco, S.; Ishizaka, A.; Tasiou, M.; Torrisi, G. On the methodological framework of composite indices: a review of the issues of weighting, aggregation, and robustness. **Soc. Indic. Res**. n.141, p. 61–94, 2019.

Grin, J.; Rotmans, J.; Schot, J. **Transitions to sustainable development; new directions in the study of longterm transformative change**. New York: Routledge, 2010.

Haydo, P.A. From morphological analysis to optimizing complex industrial operation scenarios. **Technological Forecasting and Social Change,** v.126, p. 147-160, 2018.

Hofmann, F. Circular business models: Business approach as driver or obstructer ofsustainability transitions? **Journal of Cleaner Production**, v.224, p. 361-374, 2019.

Homrich, A.S., Galvão, G., Abadia, L.G., Carvalho, M.M. The circular economy umbrella: Trends and gaps on integrating pathways. **Journal of Cleaner Production**, v.175, p.525-543, 2018.

Hwang, C. L., Yoon, K. **Multiple attribute decision making:** Methods and applications. Springer-Verlag, New York. 1981.

Hwang, C.-L.; Yoon, K. **Multiple Attribute Decision Making.** Methods and applications New York: 1981.

Iacovidou, E.; Velis, C.A.; Purnell, P.; Zwirner, O.; Brown, A.; Hahladakis, J.; Millward-Hopkins, J.; Williams, P.T. Metrics for optimising the multidimensional value of resources recovered from waste in a circular economy: a critical review. **Journal of Cleaner Production**, v.166, 910e938, 2017.

Jackson, M.; Lederwasch, A.; Giurco, D. Transitions in theory and practice: managing metals in the circular economy. **Resources,** v.3, n.3, p.516-543, 2014.

Janik, A.; Ryszko, A. Circular economy in companies: An analysis of selected indicators from a managerial perspective. **Multidiscip. Asp. Prod. Eng.** v.2, p. 523-535. 2019.

Jawahir, I.S.; Dillon Jr.; O.W. Sustainable manufacturing processes: New challenges for developing predictive models and optimization techniques, (Keynote Paper), **Proc. 1st International Conference on Sustainable Manufacturing** (SM1), Montreal, Canada. p. 1-19. 2007.

Jing, L., Peng, X., Li, J., Wang, J., Jiang, S. A decision approach with multiple interactive qualitative objectives for product conceptual schemes based on noncooperative-cooperative game theory. **Advanced Engineering Informatics,** v.38, p. 581-592, 2018.

Johansen, I. Scenario modelling with morphological analysis. **Technological Forecasting and Social Change**, v.126, p. 116-125, 2018.

Kalmykova, Y., Sadagopan, M., Rosado, L. Circular economy – From review of theories and practices to development of implementation tools. **Resour. Conserv. Recycl.**, n.135, p.190-201, 2018.

Kemp, R., Loorbach, D. **Transition management: a reflexive governance approach**. In: Voss, J., D. Bauknecht and R. Kemp (Eds). Reflexive Governance for Sustainable Development. Edward Elgar, Cheltenham. 2006.

Kemp, R., Schot, J., Hoogma, R. Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. **Technology Analysis & Strategic Management,** v.10, n.2, p.175-198, 1998.

King, A.M.; Burgess, S.C.; Ijomah, W.; Mcmahon, C.A. Reducing waste: repair, recondition, remanufacture or recycle? **Sustain. Dev.,** v.14, n.4, p. 257–267, 2006.

Kirchherr J.; Reike D.; Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. **Resources, Conservation & Recycling**, v.127, p. 221-232, 2017.

Korhonen, J.; Nuur, C.; Feldmann, A.; Birkie, S.E. Circular economy as an essentially contested concept. **J. Clean. Prod**., v.175, p.544-552, 2018.

Kravchenko, M.; Pigosso, D.C.A.; Mcaloone, T.C. A procedure to support systematic selection of leading indicators for sustainability performance measurement of circular economy initiatives. **Sustainability** .v.12, i. 3, 2020.

Kravchenko, M.; Pigosso, D.C.A.; Mcaloone, T.C. Towards the ex-ante sustainability screening of circular economy initiatives in manufacturing companies: Consolidation of leading sustainability-related performance indicators. **Journal of Cleaner Production,** v.241, 2019.

Kristensen, H.S.; Mosgaard, M.A. A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? **Journal of Cleaner Production,** v. 243, art. no. 118531, 2020.

Krohling, R. A.; Souza, D. T. T. M. Dois exemplos da aplicação da técnica TOPSIS para tomada de decisão. **Revista Sistemas de Informação da FSMA,** v. 8, p. 31-35, 2011.

Kusek, J.Z.; Rist, R.C. **Ten Steps to a Results-based Monitoring and Evaluation System**: A handbook for development practitioners. The World Bank, Washington, DC. 2004.

Kwon, M., Lee, J., Hong, Y.S. Product-service system business modelling methodology using morphological analysis. **Sustainability**, v.11 (5),n. 1376, 2019.

Laurenti, R.; Singh, J.; Frostel, B.; Sinha, R.; Binder, C.R. The socio-economic embeddedness of the circular economy: an integrative framework. **Sustainability**, v.10, n.7, 2018.

Leahy, K.; Daly, S.R.; Mckilligan, S.; Seifert, C.M. Supporting idea generation with design tools: Nesting design heuristics within morphological analysis. **Global Journal of Engineering Education**, v.20, n.3, p. 159-170, 2018.

Lewandowski, M. Designing the business models for circular economy—towards the conceptual framework. **Sustainability**, v. 8, n.1, p.43, 2016.

Li, R.H.; Su, C.H. Evaluation of the circular economy development level of Chinese chemical enterprises. **Procedia Environ. Sci.**, v.13, p.1595–1601, 2012.

Lieder, M.; Rashid, A. Towards circular economy implementation: A comprehensive review in context of manufacturing industry. **Journal of Cleaner Production**, v.115, p.36–51, 2016.

Linder, M.; Sarasini, S.; Van Loon, P. A metric for quantifying product-level circularity. **J. Ind. Ecol**., v.21, p.545- 558, 2017.

Lonca, G.; Muggéo, R.; Imbeault-Tétreault, H.; Bernard, S.; Margni, M. Does material circularity rhyme with environmental efficiency? Case studies onused tires. **Journal of Cleaner Production**, v.183, 424 – 435, 2018.

Loorbach D.; Rotmans J. **Managing transitions for sustainable development**. In: Olsthoorn X., Wieczorek A. (eds) Understanding Industrial Transformation. Environment & policy, vol 44. Springer, Dordrecht. 2006. https://doi.org/10.1007/1-4020-4418-6_10.

Lüdeke-Freund, F.; Gold, S.; Bocken, N.M.P. A review and typology of circular economy business model pattern. **Journal of Industrial Ecology,** v.23, n.1, p. 36-61, 2019.

Lyle, J. T. **Regenerative design for sustainable development.** New York: JohnLiley, 1994.

Manninen, K.; Koskela, S.; Antikainen, R.; Bocken, N.; Dahlbo, H.; Aminoff, A. Do circular economy business models capture intended environmental value propositions? **Journal of Cleaner Production,** v.171, p.413-422, 2018.

Markard, J.; Raven, R.; Truffer, B. Sustainability transitions: An emerging field of research and its prospects. **Research Policy,** v.41, p, 955–967, 2012.

Martins, F.; Almeida, M.F.; Calili, R.; Oliveira, A. Design thinking applied to smart home projects: A user-centric and sustainable perspective. **Sustainability,** v.12, n.3, 10031, 1-27, 2020.

Masi, D.; Day, S.; Godsell, J. Supply chain configurations in the circular economy: a systematic literature review. **Sustainability**, v.9, 1602. 2017.

Meadows, D. **Leverage points:** places to intervene in a system- IMSA, Unleashing the power of the Circular Economy, p.16, 45, 1999.

Mentink, B. **Circular business model innovation**: A process framework and a tool for business model innovation in a circular economy. 2014. http://resolver.tudelft.nl/uuid:c2554c91-8aaf-4fdd-91b7-4ca08e8ea621.

Moraga, G; Huysveld, S.; Mathieux, F; Blengini, G.A.; Alaerts, L; Van Acker, K; De Meester, S; Dewulf, J. Circular economy indicators: What do they measure? **Resources, Conservation and Recycling**, v.146, p. 452-461, 2019.

Natural Capital Coalition. Ncc. **Natural Capital Protocol**, 2016. www.naturalcapitalcoalition.org/protocol.

Netherlands Enterprise Agency.Circular Economy & SDGs: How circular economy practices help to achieve the Sustainable Development Goals, 2020. https://circulareconomy.europa.eu/platform/sites/default/files/3228_brochure_sdg_-_hch_cmyk_a4_portrait_-_0520-012.pdf.

Neuendorf, K. A. **The content analysis guidebook.** SAGE Publications, Inc., Thousand Oaks, California. 2017.

Ngan, S.L.; How, B.S.; Teng, S.Y.; Promentilla, M.A.B.; Yatim, P.; Er, A.C.; Lam, H. L. Prioritization of sustainability indicators for promoting the circular economy: the case of developing countries. **Renewable and Sustainable Energy Reviews**, v.111, p. 314-331, 2019.

Niero, M.; Kalbar, P.P. Coupling material circularity indicators and life cycle based indicators: A proposal to advance the assessment of circular economy strategies at the product level. **Resources, Conservation and Recycling,** v.140, p. 305-312, 2019.

Nußholz, J.L.K. Circular business models: defining a concept and framing an emerging research field. **Sustainability**, v.9, n.10, 1810, 2017. https://doi.org/10.3390/su9101810.

Oliveira, A., Calili, R.F, Almeida, M.F., Sousa, M. A systemic and contextual framework to define a country's 2030 agenda from a foresight perspective. **Sustainability**, v. 11, 6360, 2019.

Organisation for Economic Co-Operation and Development. OECD. **Business models for the circular economy:** Opportunities and Challenges from a Policy Perspective. Paris: OECD Publishing, 2019.

Organisation for Economic Co-Operation and Development. OECD. **Handbook on constructing composite indicators:** Methodology and user guide. Paris: OECD Publishing, 2008.

Osterwalder, A., Pigneur, Y. **Business model generation:** A handbook for visionaries, game changers, and challengers. Hoboken, NJ: John Wiley & Sons. 2010.

Parchomenko, A.; Nelen, D.; Gillabel, J.; Rechberger, H. Measuring the circular economy - a multiple correspondence analysis of 63 metrics. **Journal of Cleaner Production,** v. 210, p. 200-216, 2018.

Park, J.Y., Chertow, M.R. Establishing and testing the “reuse potential” indicator for managing wastes as resources. **Journal of Environmental Management**. v.137, p.45-53. 2014.

Pauli, G. **The blue economy:** 10 years, 100 innovations, 100 million jobs. Taos: Paradigm, 2010.

Pauliuk, S. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. **Resources, Conservation and Recycling,** v.129, p. 81-92, 2018.

Permanyer, I. Assessing the robustness of composite indices rankings. **Rev Income Wealth**, v.57, p. 306–326, 2011.

Pierroni, M. P. P.; Mcaloone, T.C.; Pigosso, D.C.A. Business model innovation for circular economy and sustainability: a review of approaches. **Journal of Cleaner Production,** v.215, p. 198- 216, 2019.

Pintér, L.; Hardi, P.; Martinuzzi, A.; Hall, J. Bellagio STAMP: Principles for sustainability assessment and measurement. **Ecological Indicators,** v.17, p. 20-28, 2012.

Potting J; Hekkert, M.P.; Worrell E; Hanemaaijer, A. **Circular economy:** Measuring innovation in product chains. The Hague: PBL Netherlands. Environmental Assessment Agency, 2017.

Potting, J.; Hanemaaijer, A.; Delahaye, R; Ganzevles, J.; Hoekstra, R.; Lijzen, J. **Circular economy. What we want to know and can measure.** System and baseline assessment for monitoring the progress of the circular economy in the Netherlands. The Hague: PBL Netherlands. Environmental Assessment Agency, 2018.

Prieto-Sandoval, V.; Jaca, C.; Ormazabal, M. Towards a consensus on the circular economy. **Journal of Cleaner Production**, v.179, p.605-615, 2018.

Reike, D.; Vermeulen, W.J.V.; Witjes, S. The circular economy: New or Refurbished as CE 3.0? — Exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. **Resources, Conservation and Recycling**, v.135, p. 246-264. 2018.

Rincón-Moreno, J.; Ormazabal, M.; Alvarez, M.J.; Jaca, C. Advancing circular economy performance indicators and their application in Spanish companies. **Journal of Cleaner Production**, 279, 123605, 2021.

Rip, A., Kemp, R. Technological change. In: S. Rayner, E.J. Malone (Eds.), Human Choice and Climate Change, vol. 2. Resources and Technology. Columbus, Ohio: Battelle Press, 1998.

Ritchey, T. General morphological analysis as a basic scientific modelling method. **Technological Forecasting and Social Change**, v.126, p.81-91, 2018.

Ritchey, T. **Modelling complex socio-technical systems using morphological analysis** (online). 2003. http://www.swemorph.com/pdf/it-webart.pdf.

Ritchey, T. Outline for a morphology of modeling methods: contribution to a general theory of modelling. **Acta Morph Gen**, 2012. http://www.amg.swemorph.com/pdf/amg-1-1-2012.pdf.

Ritchey, T. **Wicked problems–social messes: Decision support modelling with morphological analysis.** 2011.

Rodriguez-Anton, J.M.; Rubio-Andrada, L.; Celemín-Pedroche, M.S.; Alonso-Almeida, M.D.M. Analysis of the relations between circular economy and sustainable development goals. **Int. J. Sustainable Dev. World Ecol.**, v.26, n.8, p.708-720. 2019.

Rosa, P.; Sassanelli, C.; Terzi, S. Towards circular business models: a systematic literature review on classification frameworks and archetypes. **Journal of Cleaner Production**, v. 236, 117696, 2019.

Rossi, E., Bertassini, A.C., Ferreira, C.D.S., Neves Do Amaral, W.A., Ometto, A.R. Circular economy indicators for organizations considering sustainability and business models: Plastic, textile and electro-electronic cases. **Journal of Cleaner Production,** v.247, 2020.

Rowley, H. V.; Peters, G. M.; Lundie, S.; Moore, S. J. Aggregating sustainability indicators: Beyond the weighted sum. **J. Environ. Manage**. v.111, p. 24–33, 2012.

Roy, B. **Classement et choix en prèsence de points de vue multiples (**la méthode ELECTRE). RIRO, 8:57–75, 1968.

Roy, B.; Bouyssou, D. **Aide Multicritère `a la Décision** : Méthodes et Cas. Economica, Paris, 1993.

Ruggieri, A.; Braccini, A.M.; Poponi, S.; Mosconi, E.M. A meta-model of inter-organisational cooperation for the transition to a circular economy. **Sustainability**, v.8, n.11, 1153, 2016.

Saaty, T. L. How to make a decision: the analytic hierarchy process. **Eur. J. Oper. Res.,** 48, 9–26, 1990.

Saaty, T. L. **The analytic hierarchy process**. New York: McGraw-Hill, 1980.

Saidani, M.; Yannou, B.; Leroy, Y.; Cluzel, F. How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework. **Recycling**., v.2, n.6. 2017.

Saidani, M.; Yannou, B.; Leroy, Y.; Cluzel, F.; Kendall, A. A taxonomy of circular economy indicators. **Journal of Cleaner Production**, v.207, p. 542-559, 2019.

Saisana, M.; Tarantola, S. **State-of-the-art report on current methodologies and practices for composite indicator development.** European Commission, Joint Research Centre, Institute for the Protection and the Security of the Citizen, Technological and Economic Risk Management Unit, Ispra, Italy. 2002.

Sanchez-Ortiz, J.; Rodríguez-Cornejo, V.; Río-Sánchez, R.; García-Valderrama, T. Indicators to measure efficiency in circular economies. **Sustainability,** v. 12, 4483, 2020.

Sassanelli, C.; Rosa, P.; Rocca, R.; Terzi, S. Circular economy performance assessment methods: a systematic literature review. **Journal of Cleaner Production,** v 229, p. 440-453, 2019.

Scheepens, A. E.; Vogtlander, J. G.; Brezet, J. C. Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: Making water tourism more sustainable. **Journal of Cleaner Production**, v.114, p.257–268. 2016.

Schroeder, P.; Anggraeni, K.; Weber, U. The relevance of circular economy practices to the Sustainable Development Goals. J**ournal of Industrial Ecology**, v. 23, n.1, p. 77-95, 2019.

Shamiyeh, M. (ed.). **Creating desired futures**: how design thinking innovates business. Birkhäuser Architecture, 2010.

Sihvonen, S.; Ritola, T. Conceptualizing ReX for aggregating end-of-life strategies in product development. **Procedia CIRP** v.29, p.639–644. 2015.

Singh, R. K., Murty, H. R., Gupta, S. K., Dikshit, A. K. Development of composite sustainability performance index for steel industry. **Ecol. Indic.** v.7, n.3, p.565–588, 2007.

Sousa-Zomer, T.T., Magalhães, L., Zancul, E., Cauchick-Miguel, P.A. Exploring the challenges for circular business implementation in manufacturing companies: An empirical investigation of a pay-per-use service provider. **Resource, Conservation and Recycling**, v.135, p.3-13, 2018.

Squillante, M., Ventre, V. Assessing false consensus effect in a consensus enhancing procedure. **Int. J. Intell. Syst.,** v.25, n.3, p. 274-285, 2010.

Stahel, W. R., Reday- Mulvey, G. **The potential for substituting manpower for energy.** Report to the Commission of the European Communities. Brussels, 1976.

Suárez-Eiroa, B.; Fernández, E.; Méndez-Martínez, G.; Soto-Oñate, D. Operational principles of circular economy for sustainable development: Linking theory and practice. **Journal of Cleaner Production**, v.214, p. 952-961, 2019.

Teece, D. J. Business Models, Business Strategy and Innovation. **Long Range Planning**, v.43, p. 172-194, 2010.

Teece, D. J. Profiting from technological innovation: implications for integration, collaboration, licensing, and public policy. **Research Policy,** v.15, n.6, p.285-305, 1986.

Teece, D.J. Reflections on profiting from technological innovation. **Research Policy,** v.35, n.8, p.1131-1146, 2006.

Truffer, B.; Coenen, L. Environmental innovation and sustainability transitions in regional studies. **Regional Studies**, v.46, p.1–22, 2012.

Unep Finance Initiative. UNEPFI. **Financing circularity**: Demystifying finance for circular economies. Paris: United Nations Environment Programme, 2020.

United Nations Environment Programme. UNEP. **Circular economy.** an alternative model for economic development. Paris: United Nations Environment Programme, 2006.

United Nations Environment Programme. UNEP. **Towards a green economy:** pathways to sustainable development and poverty eradication. United Nations Environmental Programme, 2011.

United Nations for Industrial Development Organization. UNIDO. **Global promotion and implementation of chemical leasing business models:** 10 years outlook. United Nations for Industrial Development Organization. 1 ed. Vienna, 2016.

United Nations. UN. **Our common future.** World Commission On Environment And a Development. United Nations. Oxford University Press. Brundtland. 1987.

Van den Bergh, J.C.J.M.; Truffer, B.; Kallis, G. Environmental innovation and societal transitions: Introduction and overview. **Environmental Innovation and Societal Transitions**, v.1, n.1, p.1-23, 2011.

Vergara, S.C. **Metodologia do trabalho científico.** 22ª ed. São Paulo: Cortez. 2002.

Vermeulen W.J.V.; Witjes, S.; Reike, D. **Advice about a framework for measuring the impact of circular procurement**. Faculty of Earth Sciences, Utrecht University, Utrecht. 2014.

Walker, S.; Coleman, N.; Hodgson, P.; Collins, N.; Brimacombe, L. Evaluating the environmental dimension of material efficiency strategies relating to the circular economy. **Sustainability,** v.10, p.666, 2018.

Willskytt, S.; Böckin, D.; Andre, H.; Tillman, A.-M.; Ljunggren Söderman, M. **Framework for analysing resource-efficient solutions**. Paper presented at the 12th Biennial International Conference on EcoBalance, 3–6 October, 2016.

Wisse, E. **Assessment of circular economy indicators in a region**: The case of the Metropole Region Amsterdam. Master Thesis – 45 ECTS Master Sustainable Business and Innovation Supervision Faculty of Geosciences, Utrecht University. Utrecht, 2016.

World Business Council For Sustainable Development. WBCSD. **Circular metrics landscape analysis.** World Business Council for Sustainable Development, 2018.

World Business Council For Sustainable Development. WBCSD. **Circular transition indicators** V1.0 Metrics for business, by business. World Business Council for Sustainable Development, in collaboration with KPMG. Switzerland. 2020.

World Economic Forum. WEF. **Towards the circular economy:** Accelerating the scale-up across global supply chains. World Economic Forum, 2014.

Zadeh, L.A. Fuzzy sets. **Inf.Control**, v. 8, p.338-353. 1965.

Zwicky, F. **Discovery, invention, research through the morphological approach.** New York: Macmillan Publishier, 1969.

Appendix I – The Analytic Hierarchy Process (AHP) method

The AHP method comprises four stages, according to the description of Saaty (1991) and Costa (2006):

- Organization of the hierarchical structure, by identifying the focus main criteria, criteria and sub-criteria (if any) and alternatives, reflecting the existing relationships between them;
- Data acquisition and collection of value judgments, through the comparison of the elements two by two and establishment of the matrices of comparisons;
- Analysis of the matrix of comparisons generated in the previous phase, which indicate the priority of each alternative in relation to the main focus;
- Analysis of derived performance indicators, such as performance indexes consistency for example.

According to Saaty (1991), the elements of a hierarchy for solving problems of decision are the main focus (or goal), the set of viable alternatives and the set of criteria, as shown in Figure 1.

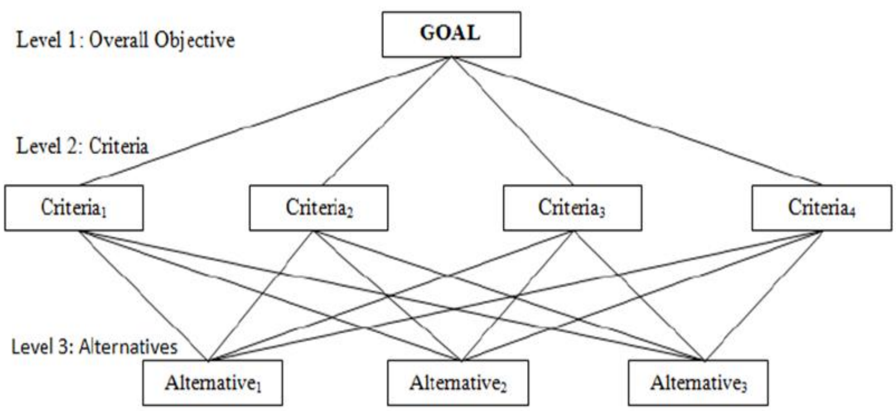

Figure 1 – Generic Hierarchical Structure (Saaty, 1991)

The main focus is the overall objective, which the problem solving will bring. At viable alternatives are the possibilities of choice within the problem so that the decision is made. Finally, the criteria are the characteristics or properties to be from which alternatives should be assessed.

The method points to value judgments, where the appraiser must compare the elements two by two in the light of a given criterion. The judgment is then the numerical representation of that relationship and the group of all judgments, considering the comparison of all elements in relation to a specific criterion, it can be represented through a square matrix (Saaty, 1991).

For establishing the judgment process, Saaty (1990) defined a specific scale to standardize value judgments, a scale that captures the existing natural subjectivity in qualitative variables. Table 1 below presents this scale.

Table 1– The nine-pointed scale defined by Saaty (1980, 1990).

Level of importance	Definition
1	Same importance
2	Preference between the same and moderate
3	Moderate preference
4	Preference between moderate and strong
5	Strong preference
6	Preference between strong and very strong
7	Very strong preference
8	Preference between very strong and absolute
9	Absolute preference

The judgment consists of the reflection of two questions: which of the two elements is the most important, in light of the intended objective, and with what intensity it is most important, using the scale from 1 to 9 presented in Table 1.

For the most important element, an integer value is used, while the least important receives the inverse of this unit, as illustrated in the example didactic in Figure 2.

Matrix

	A	B	C	D
A	1	5	6	7
B	1/5	1	4	6
C	1/6	1/4	1	4
D	1/7	1/6	1/4	1

Figure 2 – Judgment matrix. Source: Saaty, 1991

The letters A, B, C and D represent the elements to be compared two to two. The diagonal of the matrix always receives 1 because it is the comparison of the element with himself. In order to fill in the other fields, judgments are made for determine the intensity of importance, using the scale determined by Saaty.

For the inverse comparisons, that is, what is at the bottom left of the matrix, reciprocal values referring to each judgment are added, located at the top right of it.

With the duly structured reciprocal matrices, the vector of priorities, or weights, from the calculation of the normalized eigenvector of the maximum eigenvalue. There are specific methods for the approximate calculation of these values (Saaty, 1991). Such approaches were developed due to limitations computational data from the time the method was developed, and the cost of calculation of eigenvectors and eigenvalues for high-order matrices. For the purposes of this work, the precise value of both quantities will be used, which are denoted matricially by:

$$Aw = \lambda_{max} w$$

Where:
A represents the judgments matrix;
w represents the main eigenvectors, concerning the weights;
λ_{max} is the eigenvalue of A

With the characteristics of the judgment matrices in hand, through the Perron-Frobenius theorem, Saaty (1991) states that the solution has a single largest eigenvalue that corresponds to an eigenvector of components strictly positive. Theorems and proofs about the characteristics involving the matrices generated from the evaluation of specialists, are presented in their work.

Having computed the eigenvalues of the respective matrices, it is necessary to perform an analysis consistency of judgments to assess how far removed from consistency the judgments are.

A measure is used to assess the likelihood of judgments have been made purely at random and this measure is called Consistency Ratio (RC). For example, a RC = 0.3 says that there is a 30% chance the expert to answer the questions at random.

Saaty (1991) presents a simple and intuitive development for understand consistency analysis. Let's assume a consistent matrix, where the comparisons are based on exact measurements, that is, the weights are already known, then:

$$a_{ij} = \frac{w_i}{w_j}$$

As the judgment is perfect for all comparisons, $a_{ik} = a_{ij}.\ a_{jk}$ for any i, j, k, ranging from 1 to n, where n is the order of the matrix. It is also worth the statement:

$$a_{ij} = \frac{w_i}{w_j} = \frac{1}{w_i/w_j} = \frac{1}{a_{ij}}$$

Thus, a consistent matrix of pairwise comparisons is characterized.
Considering $x = (x_1, \ldots, x_n)$ and $y = (y_1, \ldots, y_n)$ can be written in notation matrix $A.\ x = y$, where A is the judgment matrix:

$$A = \begin{pmatrix} \frac{w_1}{w_1} & \cdots & \frac{w_1}{w_n} \\ \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \cdots & \frac{w_n}{w_n} \end{pmatrix}$$

Algebraically, this operation can be represented by:

$$\sum_{j=0}^{n} a_{ij} . x_i = y_i$$

For each i = 1, …, n
In that way:

$$\sum_{j=0}^{n} a_{ij} . w_j \frac{1}{w_i} = n$$

For i = 1, …, n
Or

$$\sum_{j=0}^{n} a_{ij} . w_j = n w_i$$

Which is equivalent to the equation:

$$Aw = nw$$

Thus, if $Aw = nw$ is valid, only one of the eigenvalues is different from zero and will be n, the largest eigenvalue being A.

If the elements of a positive reciprocal matrix suffer small variations, their respective eigenvalues will also vary in small amounts.

Using the results presented together with the axiom above, it can be said that if the main diagonal of a matrix has the elements equal to 1 and is consistent, small variations in the a_{ij} elements will cause the maximum eigenvalue λ_{max} remains close to n and the other eigenvalues close zero. Being $\lambda_{max} \geq n$.

Therefore, to calculate the priority eigenvector of a matrix of parity comparisons A, one must find the vector that satisfies the equation $Aw = \lambda_{max}w$.

The value of interest for the development of the methodology is the eigenvector normalized, so that the sum of w is equal to 1. For this, each element w_i is divided by its sum.

A measure of consistency, called the Consistency Index (CI), is used to calculate the deviation of λ_{max} with respect to n, since the use of the scale for the judgments generate variations in a_{ij}, changing λ_{max}.

$$CI = \frac{\lambda_{max}}{n-1}$$

It is common for evaluations carried out by specialists to generate inconsistencies, as it is part of human judgment, but we want them to be the smallest possible. To check for consistency, as mentioned above, the Consistency Ratio, having as definition:

$$CR = \frac{\text{CI}}{RI}$$

Where IR (Randomized Index) is the consistency index of a reciprocal matrix randomly generated, based on the scale of 1 to 9, with forced reciprocal (Saaty, 1991). This value is tabulated and varies according to the matrix order. In Table 2 the IR value is displayed for matrices of order 1 to 10.

Table 2 – IR value

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0,52	0,89	1,11	1,25	1,35	1,40	1,45	1,49

Source: Adapted from Saaty and Vargas, 2012.

The final assessment of the coherence of the judgment is made by comparing the CR. For the present development, the following considerations are made:

a) $CR \leq 0.1$ consists of a coherent judgment, basic premise of the method in relation to the coherence analysis, initially proposed to judge an evaluation as satisfactory;

b) $0.1 < CR < 0.2$ = Questionable judgment, considered for which expert review your judgments of the respective stage, analyzing the matrix constructed and seeks to improve any comparison (s) that have been inconsistent (s). However, it is not mandatory to change any judgment;

c) $CR \geq 0.2$ = Incoherent judgment, indicates that the paired comparisons that stage generated a high rate of inconsistency and the specialist is obliged to redo their judgments.

Once consistency in the judgment is reached, the vectors are calculated of priorities, that is, the relative weights of each element of the problem. This one calculation is performed by multiplying the priority matrices. In other words, for each alternative, the calculation consists of the weighted sum of the relative importance of each attribute by the level of preference of a given alternative in relation to the respective criterion (Souza, 2013). In the AHP method, each alternative receives a score using an additive value function. The alternatives with greater value will be preferable (Passos, 2010). Formalizing, the value function for each alternative will be:

$$F(a) = \sum_{j=1}^{n} w_j \, v_j(a)$$

Where:
$F\ (a)$ is the final alternative value a;
w_j is the weight of the j-th criterion;
v_j is the performance of the alternative in relation to the j-th criterion.

References

Saaty, T. L. A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology, v. 15, n. 3, p. 234-281, 1977.

Saaty, T. L. Decision making with the analytic hierarchy process. **International Journal of Services Sciences**, v.1, n.1, p. 83-98, 2008.

Saaty, T. L. **Método de análise hierarquica**. São Paulo: Mc - Graw Hill, 1991.

Saaty, T. L.; Vargas, L. G. **Models, methods, concepts & applications of the analytic hieratchy process.** 2 nd. ed. New York: International Series in Operations Research & Management Science, 2012.

Costa, H. G. **Auxílio multicritério à decisão: método AHP**. Rio de Janeiro: Abepro. 2006.

Appendix II - Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The TOPSIS method is described in this Appendix as presented by Hwang and Yoon,(1981). Basically, the technique comprises the following steps:

- Construction of the problem matrix or decision matrix, which brings the alternatives and criteria selected together with grades and evaluations;
- Calculation of the normalized matrix, using linear normalization or by vector;
- Calculation of the matrix with the respective weights for each criterion, defined previously by one or more decision makers;
- Identification of PIS (Positive Ideal Solution) and NIS (Negative ideal Solution);
- Calculation of distances between PIS and each alternative and between NIS and each alternative;
- Calculation of similarity for the positive ideal position, which will define the hierarchy of the alternatives studied.

Decision matrix A composed of alternatives and criteria is presented below:

$$A = \begin{matrix} & C_1 & \dots & C_n \\ A_1 & \\ \dots & \\ A_m & \end{matrix} \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{pmatrix}$$

Where A_1, A_2, ... A_m are viable alternatives and C_1, C_2, ..., C_n are criteria; x_{ij} indicates the performance of the A_i alternative according to the C_j.

The weight vector W = (w_1, w_2, ... , w_n) composed of the individual weights for each C_j criterion satisfies

$$\sum_{i=1}^{n} w_j = 1$$

The data in matrix A have different origins, and should be normalized with the objective of transforming it into a dimensionless matrix and thereby proceeding to a comparison between the various criteria. For application purposes in this research, the matrix A should be normalized for each criterion C_j, according to the following formula:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}, with\ i = 1, \ldots, m\ ; j = 1, \ldots, n$$

Thus, a normalized decision matrix A*n* represents performance relative to the alternatives and can be described by:

$$A_n = (p_{ij})_{mxn}\ , with\ i = 1, \ldots, m\ ; j = 1, \ldots, n$$

The algorithm to calculate the best alternative according to the TOPSIS technique comprises the following steps (Krohling and Souza, 2011):

Step 1: Calculation of the ideal positive solutions A^+ (benefits) and solutions negative ideals A^- (costs) as follows:

$$A^+ = (p_1^+, p_2^+, \ldots, p_m^+)$$

$$A^- = (p_1^-, p_2^-, \ldots, p_m^-)$$

Where:

$$p_j^+ = (max_{p_{ij}}, j \in J_{1;}\ min_{p_{ij}}, j \in J_2)$$

$$p_j^- = (min_{p_{ij}}, j \in J_{1;}\ max_{p_{ij}}, j \in J_2)$$

Where j_1 and j_2 represent the benefit and cost criteria, respectively.

Step 2: Calculation of Euclidean distances between A_i and A^+ (benefits) and between A_i and A^- (costs) as follows:

$$d^+ = \sqrt{\sum_{j=1}^{n} w_j\ (p_j^+ - p_{ij})^2}, with\ i = 1, \ldots, m.$$

$$d^- = \sqrt{\sum_{j=1}^{n} w_j\ (p_j^- - p_{ij})^2}, with\ i = 1, \ldots, m.$$

Step 3: Calculation of the relative proximity ξ_i for each alternative A_i with respect to ideal positive solution A^+ as:

$$\xi_i = \frac{d_i^-}{d_i^+ + d_i^-}$$

References

Hwang, C.-L.; Yoon, K. **Multiple attribute decision making. methods and applications**. New York: Springer-Verlag, 1981.

Krohling, R. A.; Souza, D. T. T. M. Dois exemplos da aplicação da técnica TOPSIS para tomada de decisão. **Revista Sistemas de Informação da FSMA**, v. 8, p. 31-35, 2011