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THE CIRCULAR TRANSITION OF PRODUCTION SYSTEMS: AN INTEGRATED APPROACH FOR ANALYZING, MODELING AND EVALUATING SCENARIOS

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"Remembering that people and their
technologies are a part of the natural
world may make it possible to imitate
the best workings of biological ecosystems
and construct artificial ones that
can be sustained over the long term."

Frosch and Gallopoulos, 1989

With sincere gratitude,
to Professor Simboli for his guidance,
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INTRODUCTION

For decades, production systems have been conceived based on the assumptions that resources and raw materials were almost unlimitedly available goods, and that the waste generated could be considered an "external issue" with respect to the production systems themselves. This linear approach has gradually revealed its limitations, highlighting increasing pressure on natural ecosystems, vulnerabilities in supply chains, and a significant loss of value throughout the product life cycle. The recognition of these critical issues by the scientific community, along with the growing public awareness of environmental challenges, has supported the emergence of a new paradigm known as Circular Economy (CE), that progressively become a key element of European policies and regulations. Within the framework of the European Green Deal, CE plays a central role in efforts to reduce dependence on virgin resources, limit environmental impacts, and promote new forms of industrial competitiveness. The so-called *circular transition* aims to move beyond the traditional "take–make–dispose" model by adopting regenerative approaches capable of preserving the value of products over time, thanks to the adoption of strategies for reduction, reuse, repair, remanufacturing, recycling, etc., generally referred to as the "10R" framework and also known as circular solutions. The implementation of circular solutions within production systems requires the activation of eco-innovation processes, understood as the set of technological and organizational changes needed to reduce environmental impacts and improve resource efficiency throughout the entire product life cycle. Eco-innovation thus becomes a central component of the transition, contributing to the reconfiguration of processes, relationships among actors, and value creation logics. However, it is important to acknowledge that adopting circular solutions within production systems originally designed around linear models, entails a high degree of complexity. These systems are embedded within contexts characterized by a wide range of interdependent technical, economic, environmental, social, and regulatory variables, all of which are subject to constant change. Representatives in this sense are the supply chains, identified as priority contexts by the 'Circular Economy European Action Plan', the European Commission's main program aimed at guiding the regulatory and industrial interventions necessary to make production systems more sustainable and circular. It has included in the last years electronics, batteries and vehicles, textiles, construction, and building supply chains, all of which are characterized by high production volumes, structural complexity, and significant environmental impacts. Among these, textile industry is a particularly significant case. Since the adoption of the 'Circular Economy Action Plan' in 2020, it has been subject to a series of regulatory measures that are redefining production approaches, stakeholder responsibilities, and information requirements throughout the entire production chain. Some of the most important measures include: the proposed regulation on eco-design; the obligation to separate textile waste; and the Strategy for

Sustainable and Circular Textiles, which includes: i) introducing mandatory eco-design requirements; ii) stopping the destruction of unsold or returned textiles; iii) action to reduce the accidental release of microplastics into the environment; iv) clearer information and a Digital Product Passport; v) Limits on greenwashing; vi) harmonized rules for textile Extended Producer Responsibility with eco-modulation of tariffs. These measures show how regulation is one of the most important drivers, capable of guiding and accelerating the circular transition of production systems. At the same time, it represents an external variable that increases the complexity of the supply chain decision-making context, as the assessment of applicable circular solutions also depends on an evolving regulatory framework. In addition to the regulatory dimension, production systems are influenced by several other factors, including raw material prices, the evolution of production and digital technologies, shifts in consumer behavior, global market trends, and the limited availability of reliable data across the various stages of the supply chain. These variables, often interdependent and subject to rapid change, make the definition and implementation of innovative pathways toward the CE particularly complex. This complexity makes traditional approaches, methods and tools - which are mostly static and one-dimensional - inadequate to support strategic decision-making. Instead, it is necessary to adopt integrated approaches, methods, and tools that are capable of interpreting the systems' complexity, considering the simultaneous effect of heterogeneous variables, evaluating different CE scenarios, introducing temporal dynamics and which are truly decision-informed support tools along the transition path towards increased circularity. Choices for change, then, necessarily require that decision-makers have at their disposal methodologies, tools, metrics, and indicators that consider these aspects and are capable of analyzing and modeling complex production systems and simulating circular scenarios, conceived as possible alternative configurations of the linear system that integrate one or more circular solutions at different levels of scale: products, processes, supply chains, and territorial systems.

In this context, one of the theoretical-methodological approaches that can support the transition to circular systems is that of Industrial Ecology (IE), an interdisciplinary research field that studies the functioning of anthropogenic systems in analogy with biological systems. The goal of IE is to reorganize production systems, so they evolve towards operating modes that are environmentally and economically sustainable in the long term. IE provides methods and tools to support the transition from linear to circular production and consumption models, which include: Industrial Metabolism; Design for the Environment; Extended Product Responsibility (EPR); Product-oriented environmental policy (IPP); Material/substance flow analysis (MFA/SFA); Life cycle assessment and Life cycle costing (LCA, LCC); Dynamic Input/Output models; Industrial Symbiosis, Product-Service Systems (PSS).

It should also be noted that in IE studies, a crucial role has historically been attributed to the technological and innovation variables. In more recent studies, often associated with CE issues, the use of Information and Communication Technology (ICT) for the detection, collection, and analysis of data (quantitative and qualitative) is becoming increasingly common. Within the industry 4.0 framework, in particular, the achievement of sustainability (environmental, economic, and social) through greater efficiency in the use of material and energy resources becomes increasingly relevant. Innovation, and digital technologies especially, are recognized as making a significant contribution in this regard. The progressive shift towards industrial computerization, which consists of applying innovative technologies to improve the productivity of processes, operators, and machines, with a view to integrating processes and organizations with each other and with external actors, provides an increasingly broad basis for improving the analysis and proposing increasingly viable circularity strategies. In the debate on the different paths to be taken to achieve environmental sustainability goals, the relationship between Industry 4.0 and CE clearly emerges. Sensors, monitoring systems, digital platforms, and interoperability tools make it possible to collect, integrate, and analyze large amounts of data throughout the entire product life cycle, improving traceability, transparency, and coordination between actors. Artificial Intelligence further expands these opportunities by offering advanced capabilities for analysis, prediction, and support in complex decision-making processes.

The PhD project of which the present thesis is part of the final stage, was founded by the National Recovery and Resilience Plan – NRRP (Ministerial Decree 351/2022), with the following theme: *"Innovative qualitative and quantitative approaches, methods, and tools for the ecological and digital transition of businesses, social inclusion, and territorial cohesion".* The research direction of the PhD project has thus been oriented from the beginning towards the study of the gaps that hinder the effective adoption of circular strategies in production systems at different levels of scale (processes, supply chains, territorial systems). These strategies are increasingly recognized as essential to the ecological transition and can be supported by digital solutions that help ensure their effective implementation. The main critical issues emerged concern the following aspects: i) representation of the technological and organizational characteristics of contexts; ii) identification of the most appropriate circular solutions; iii) simulation of transformation effects; iv) definition of reliable metrics and indicators; v) role of digital technologies in the management and interpretation of information flows.

Based on these premises, the research question formulated is the following:

RQ: Given the structural, organizational, and managerial characteristics of a specific production system, how can its transition toward a Circular Economy be supported in an efficient and effective way?

To address the main research question, it is necessary to develop additional sub-questions, which have been formulated as follows:

Q1: How can the structural and operational characteristics of the production system under analysis be identified?

Q2: What are their main critical issues from an environmental point of view (in order to determine the circularity gaps)?

Q3: How can internal and external variables affecting the system be identified and managed?

Q4: How can the potential circular solutions be evaluated?

Q5: Which IE/ICT-based methods and tools can be potentially used?

Q6: Which metrics and indicators can be used to measure the level of circularity and sustainability gained?

To answer the research questions mentioned above, from a methodological point of view, the project involved theoretical analysis, data collection and systematization, discussions with local stakeholders, and direct experimentation with quantitative and qualitative tools. In particular, different software tools for representation, modeling, impact assessment, and simulation were tested. The visiting period at CERDI - Center for Studies and Research on International Development (Clermont-Ferrand, France) was specifically dedicated to the in-depth study of dynamic modeling and simulation methods. At the same time, there was also participation in the PRIN (Projects of great national interest) project "MAX-SHEEP[1]: *Modeling and evaluation of circular scenarios in local contexts. Applications in the sheep supply chain"*. This involvement was particularly valuable, as it provided an opportunity to test methods and tools in a concrete application context, further consolidating the methodological basis of the research.

The thesis aims to offer both taxonomic (systematization of approaches, methods, tools) and exploratory (operational tests and analysis of the potential and limitations of integrated approaches)

[1] MAX-SHEEP research project: https://www.max-sheep.com/ (Accessed on: 27/11/2025)

contributions. It also proposes a conceptual basis for the potential future development of a 'Circular Simulation-based Decision Support System' capable of guiding decision-makers in the ecological and digital transition, in line with the strategic objectives of the NRRP. *Figure 1* summarizes the research model adopted and provides an overview of the thesis structure, of which the following sections present both the organization and the main contents.

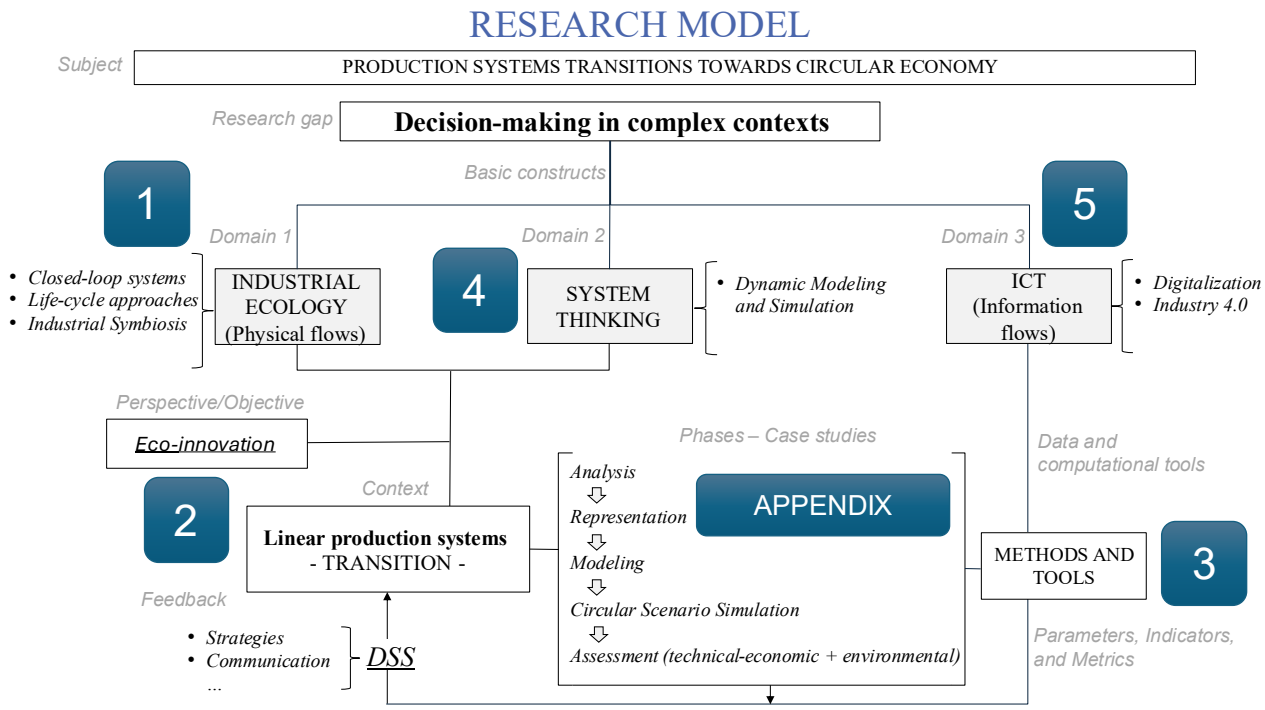


Figure 1. *PhD project research model*

Conceptual model representing the structure of the PhD project and its theoretical and methodological frameworks. The model integrates three main domains - Industrial Ecology (physical flows), System Thinking (system dynamics), and Information and Communications Technology (ICT)/Industry 4.0 (information flows) - to address the decision-making gap in complex production contexts and to support the transition from linear to circular systems. The integration of these approaches forms the basis for the development of methods and tools that inform decision-making processes, finally converging into a Decision Support System (DSS).

THESIS STRUCTURE

The thesis is organized into five chapters corresponding to the scientific articles developed during the PhD course - already published, in the process of being published, or currently being submitted.

Chapter 1 - Theoretical Background: Circular Economy (CE) and Industrial Ecology (IE) - defines the theoretical background of the research. A comparative bibliometric analysis is presented, integrated with a content analysis, aimed at investigating how the two research areas of reference for the PhD project, IE and CE, have established themselves, how they have evolved over time, and what methodological and conceptual connections link them. The results highlight how some of the founding concepts of CE have long been present in the scientific corpus of IE, suggesting the existence of a real "scientific heritage" transferred from IE to CE. The study highlights how CE has progressively incorporated contributions from IE following more specialized trajectories. In contrast, IE continues to maintain a broader, more exploratory approach. Chapter 1 constitutes the theoretical foundation of the thesis and guides the entire research process, providing the conceptual basis necessary to study and analyze production systems and to model and simulate applicable circular solutions. The bases of IE - such as life cycle thinking, interpreting systems through material, energy, and information flows, understanding industrial systems as interdependent networks, and the need to assess environmental, economic, and social trade-offs - are key elements in evaluating different circular scenarios. The evaluation of circular scenarios enables the redesign of linear systems into new organizational and managerial forms known as "eco-industrial systems" which, within the context of IE, represent groups of companies, production activities, and infrastructures that interact with each other and with the surrounding environment, forming an integrated system characterized by synergistic exchanges of materials, energy, and information. Inspired by the functioning of natural ecosystems, in which the waste from one process becomes a resource for another, the eco-industrial system involves the implementation of solutions that close the cycles of material and energy flows, reducing the consumption of virgin raw materials and minimizing waste and environmental impacts. These elements recur transversely in the following chapters and guide the overall methodological approach of the study.

Chapter 2 - The role of external variables: Extended Producer Responsibility in the circular transitions of the textile supply chain - addresses the circular transition processes in the textile sector, one of the supply chains most affected by recent European regulatory and policy interventions. Starting with an examination of the evolution of Extended Producer Responsibility (EPR) regulations in the sector, the chapter reconstructs how current regulatory guidelines, in particular the EU Strategy for Sustainable and Circular Textiles, are requiring a profound revision of production models, life

cycle management, and traceability throughout the entire value chain. The analysis highlights two regulatory issues that are particularly relevant to the supply chain's transition to a CE: defining the scope of EPR (including extending responsibility to entities such as merchants and e-commerce) and identifying the ownership of secondary raw materials. Alongside regulatory challenges, there are also structural issues in the sector, such as the fragmentation of global supply chains, low consumer awareness of sustainability issues, the heterogeneity and proliferation of environmental and social certifications, and the need to enhance the selection, reuse, and recycling phases. The chapter also highlights technological and organizational innovations that can promote the evolution of collection, sorting, and recycling systems - from mechanical, thermo-mechanical, chemical, and biological recycling technologies to advanced sorting systems based on spectrometry and artificial intelligence. The role of Life Cycle Assessments (LCA) in supporting the choice of textile waste management pathways is also discussed, highlighting how variables such as the efficiency of recycling processes, the quality of the fractions collected, the modeling of the use phase, and replacement coefficients have a decisive influence on the estimated environmental impacts. Chapter 2, taking the textile supply chain as an example, highlights how the circular transition can be strongly driven by regulatory drivers and, at the same time, influenced by a set of technological and behavioral variables. This configuration requires a structural rethinking of material management systems and a clear definition of roles, responsibilities, and enabling infrastructures. The complexity that emerges from this case demonstrates how the circular transition, in order to be efficient and effective, requires the evaluation of different circular scenarios, adopting integrated approaches, methods, and tools capable of assessing the simultaneous effect of different variables involved.

Chapter 3 - Methods and tools for evaluating circular scenarios - represents the first operational step of the thesis and focuses on mapping the methods and tools useful for analyzing and evaluating circular scenarios. Developed in collaboration with the "MAX-SHEEP" research project, the chapter proposes a systematization of the main methods and tools from different disciplinary fields, with the aim of identifying those most useful for supporting the various stages involved in developing a model for evaluating circular scenarios in industrial systems (towards eco-industrial systems). The analysis reveals the existence of a wide range of tools capable of analyzing the technical, economic, environmental, and organizational aspects of products, processes, supply chains, and territorial systems. Some of these tools, although created for different purposes, show areas of functional overlap, suggesting the possibility of extending or integrating their respective applications. At the same time, this overlap can lead to duplication of analyses, underscoring the importance of a conscious and consistent selection of tools aligned with the objectives of the study. The chapter also

emphasizes the need for tools capable of processing dynamic scenarios in space and time, an essential feature for describing the evolution of circular scenarios in different contexts. Given the complexity of the systems and the multiplicity of variables involved, it is essential that the models also incorporate exogenous variables in order to provide more realistic analyses and support informed decisions. The analysis conducted identifies four main operability dimensions:

- analysis and representation of economic-productive systems, using flow-charts, sankey diagrams, Material Flow Analysis (MFA), and industrial symbiosis approaches;
- analysis and spatial representation of networks, using Geographical Information Systems (GIS) and Social Network Analysis (SNA);
- scenario development, through scenario analysis, Agent-Based Modeling (ABM), and System Dynamics (SD);
- impact assessment, through carbon footprint, water footprint, Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA).

These four dimensions correspond to the fundamental activities for modeling and simulating circular scenarios towards greater sustainability (environmental, economic, and social). In this regard, the fourth dimension, dedicated to impact assessment, plays a particularly important role since circular solutions do not automatically guarantee economic, environmental, or social benefits compared to the linear scenario and therefore require rigorous integrated methods and tools to assess their overall effects. Chapter 3 provides a systematic foundation for selecting and integrating methods and tools to support studies aimed at informing decisions toward circular transition. This constitutes a key step for the subsequent development of work oriented toward integrated Decision Support Systems (DSS).

Chapter 4 - Comparing static and dynamic modeling approaches for circular scenario evaluation - explores the differences between static and dynamic approaches applied to circular scenario modeling, highlighting their limitations, potential, and possible synergies. Considering the results obtained previously, the contribution starts with the recognition that CE requires an understanding of complex system dynamics, characterized by nonlinear interactions, multiple feedbacks, and continuously evolving external variables. In this context, chapter 3 highlighted how IE offers a solid methodological basis for mapping systems, quantifying material and energy flows, identifying circular solutions, and assessing their impacts. However, conventional IE-based models have limitations in representing the temporal dimension and dynamism of transition processes. The chapter therefore presents a qualitative reflection on the potential contribution of dynamic approaches, focusing on two of the most widely used methodologies in complexity modeling

nowadays: Agent-Based Modeling (ABM) and System Dynamics (SD). Both approaches make it possible to simulate the evolution of systems over time and analyze the interactions between actors, components, and external variables in terms of how they influence the system's overall behavior. Thus, they offer a particularly appropriate interpretative basis for evaluating circular scenarios. The analysis conducted reveals both the potential and the limitations of static and dynamic approaches: i) traditional IE approaches are particularly effective in mapping systems and measuring impacts (through MFA, LCA), but struggle to capture feedback, emerging dynamics, and evolutionary processes; ii) Dynamic approaches, on the other hand, enable the exploration of complex scenarios, the assessment of delayed effects, the simulation of adaptive behaviors, and the analysis of how alternative choices can influence trajectories and long-term performance. Unlike the previous chapters, chapter 4 introduces a set of criteria useful for defining when a method or tool can be considered truly integrated into the analysis and modeling of circular scenarios. The chapter also highlights a growing interest in recent literature in the integration of static and dynamic methods and the adoption of innovative digital transition tools. In particular, it discusses the potential of integrating Artificial Intelligence, Machine Learning, and new inference techniques (such as Amortized Bayesian Inference or Neural Posterior Estimation) into the processes of constructing, calibrating, and interpreting dynamic models. These innovations make it possible to manage large volumes of data, improve the quality of forecasts, identify hidden critical issues, and support more adaptive modeling of circular systems. Overall, chapter 4 highlights how the evaluation of circular scenarios requires a systemic and integrated approach, capable of combining the strengths of different modeling and simulation techniques; and the integration of static and dynamic approaches is a particularly relevant area of research for the purpose of this thesis.

Chapter 5 - An integrated decision-support framework for circular transition - proposes an integrated conceptual framework that illustrates how to manage the information flow of an industrial system (process, supply chain, territorial system) to support decision-making towards the transition to CE. The framework is based on the interoperability between physical and information flows and on the integration between digital technologies and modeling and simulation approaches discussed in detail in the previous chapters. To develop the conceptual model, the chapter addresses the role of ICT technologies, particularly those enabled by Industry 4.0, as key elements in enabling data-driven, adaptive, and sustainability-oriented decision-making processes, and shows how these technologies can be combined with static and dynamic approaches (LCA, MFA, System Dynamics, Agent-Based Modeling) to build a CE-oriented decision support system. Through a literature review, the contribution analyzes how information flow is an essential element in eco-industrial systems: the

ability to collect, integrate, and transform heterogeneous data improves transparency, traceability, coordination between actors, and the evaluation of circular alternatives. In this perspective, Industry 4.0 provides the digital infrastructure necessary to generate continuous and granular data throughout the entire product life cycle, while Artificial Intelligence (AI) contributes with advanced data analysis, interpretation, and modeling capabilities. The proposed conceptual framework integrates data acquisition flows, information transformation processes, static and dynamic models, and collaborative decision-making technologies. This architecture interprets digitization as a true multi-level cognitive structure, in which digital technologies constitute the connective layer between the operational and strategic dimensions of decisions. The goal is to transform the heterogeneity of data generated by production systems into structured knowledge and decision-making value, enabling the comparison of alternative circular solutions and the integrated improvement of their environmental, economic, and social performance. The last section of the chapter explores the role of AI in dynamic modeling, presenting a case study that demonstrates how advanced tools can support and accelerate the construction of stock-and-flow models (i.e., models representing the accumulation of quantities and their rates of change), the identification of feedback loops (i.e., causal structures in which system variables influence one another in cycles), the calibration of parameters, and the adaptation of the model to real data. The comparison between hand-built models and AI-supported models highlights the potential of the latter to speed up scenario generation, improve forecast accuracy, and expand analytical capabilities, while still requiring careful human supervision to ensure conceptual consistency and reliability of results. The chapter also discusses the main challenges related to the still fragmented nature of data infrastructures, the limited interoperability of information systems, the complexity of dynamic transition processes, and the critical issues of transparency, traceability, and reliability associated with AI-based models. It also highlights the limitations associated with the high energy and water consumption of the most advanced digital technologies, which require a careful balance between the benefits and environmental costs of digitization. Overall, chapter 5 outlines the fundamentals for the development of an "CE Simulation-based Decision Support Systems", showing how the integration of digital technologies, modeling, evaluation, and static and dynamic simulation can generate more adaptive, transparent, and sustainability-oriented decision-making systems. This framework can be a step towards the operational translation of conceptual innovation into industrial practices, providing a basis for future applications in real contexts and for the development of decision-making environments capable of supporting the complex transition to a real CE.

Appendix. The thesis includes an Appendix section, that provides operational documentation of the activities carried out with the various software tools tested during the research and organizes these

materials according to the phases outlined in the methodological design: analysis, representation, modeling, circular scenario simulation, and assessment. For each phase, screenshots, operational diagrams, examples of outputs, and configurations of the developed models are provided to concretely illustrate how the tools were applied in the case studies. Along with the visual elements, the Appendix also includes a summary of the potential and critical issues encountered during the use of the tools, such as technical limitations, data integration capabilities, simulation flexibility, and aspects related to sharing of outputs. These activities were conducted to understand how to design a model capable of supporting the decision-making process aimed at improving the circularity of the specific production system under analysis.

CHAPTER 1

Theoretical Background: Circular Economy and Industrial Ecology

The content of this chapter refers to an article developed during the first year of PhD program and initially presented at the XXXII National Congress of Commodity Sciences (AISME, September 19–20, 2024, Lecce, Italy). The work was subsequently expanded and discussed at the Green Deal, Circular Economy and Industrial Ecology Symposium (December 5–6, 2024, Clermont-Ferrand, France). The final version was then published as a book chapter in: Diemer, A., Rabanal, N., Nedelciu, E., Wierling, A. (2025), 'Green Deal, Circular Economy and Industrial Ecology', Editions Oeconomia, ISBN 979-10-92495-18-8.

TITLE:

INDUSTRIAL ECOLOGY AND CIRCULAR ECONOMY: PAST, PRESENT AND FUTURE DEVELOPMENTS. INSIGHTS FROM A BIBLIOMETRIC AND CONTENT ANALYSIS

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Abstract

The concept of Circular Economy (CE) has reached such a level of diffusion and relevance to be considered an autonomous scientific field and also a new economic paradigm. As recognized, many of the principles and tools underlying CE are shared with the research field of Industrial Ecology (IE). To investigate the interrelationships between the two, a cross-bibliometric analysis and a subsequent content analysis of the scientific literature was conducted, considering several parameters concerning authors, countries, keywords and typical research methods and tools. Results provide insights on the origin, current state and future development of the two fields.

1.1 Introduction

The Circular Economy (CE) over the years has become an increasingly popular term used to describe an alternative way of consuming and producing, in contrast to the so-called take-make-dispose model, typical of the linear economy. Today, great attention is being paid to this concept, especially by some regulations. In fact, some countries have demonstrated interest in taking the path toward circularity by redefining and formulating legislative measures that push businesses and citizens to change their production and consumption decisions with the goal of establishing a more sustainable economic model. For example, the China Circular Economy Promotion Laws (CCICED, 2008), recognized CE as a generic term for reduction, reuse and recycling measures in production and consumption (Ghisellini et al., 2016) and in the European Union, the Circular Economy Action Plan adopted in 2015 (European Commission, 2015) has led to the dissemination of relevant proposals in many sectors, e.g., through: i) a revision of the building materials regulation; ii) a strategy for sustainable textiles; iii) new rules on packaging; iv) a new regulation on eco-design of sustainable products, etc. Despite various legislative measures and the great popularity of the topic of CE from its emergence to the present, in 2023 the global economy is still only 7.2% 'circular', falling from 9.1% in 2018 and 8.6% in 2020 (Circle Economy, 2023). The concept of CE has assumed increasing importance worldwide in the literature as well. Over time, there has been an exponential growth in the number of scientific articles on the topic, of different nature (literature reviews, case studies, scientific reports, etc.) and published in different research areas (Ghisellini et al., 2016). This has led to many ambiguities in the scope of CE studies concerning definition, origin, and implementation (Mahanty et al., 2021). Also concerning the approaches, methods and tools used by CE the issue is quite controversial. In this regard, one of the scientific fields which certainly deserves wide consideration within CE is that of Industrial Ecology (IE) (Ghisellini et al., 2016; Saavedra et al., 2018). IE can be considered as an interdisciplinary research field that, since the 1960s, has promoted the development of solutions for designing economic systems so that they evolve in a more environmentally

sustainable way (Indigo Development, 1993). IE studies human systems by analogy with biological systems, in which the concept of material and energy 'waste' does not exist. Precisely, the transition of anthropogenic systems from linear to circular is one of the most distinctive elements of IE (Ayres, 1989; Jelinski et al., 1992; Graedel and Allenby, 1995; Erkman, 1997) and this is probably what makes it one of the major candidates to be considered the scientific basis of the CE. However, the debate is still open, there are those who argue that IE represents the scientific base of CE, those who argue that there is a strong link, and those who argue that a link was originally present but now CE is destined to have its own autonomy anyway (Saavedra et al., 2018; Mahanty et al., 2021; Kirchherr et al., 2023a). It should also be considered that CE is beginning to be discussed in the literature as a new research field, leading to an important reflection on what we know about CE today. The objective of this article is to analyze and understand, through a bibliometric and content analysis of the literature, the main characteristics of CE and IE by identifying possible relationships. The article is structured as follows: initially, a brief overview is given of the most relevant features of the two study areas, CE and IE. Subsequently, the results of the bibliometric analysis, with a summary of the main outcomes that emerged and the results of the content analysis, aimed at investigating specific aspects of the relationships between CE and IE are presented. Finally, the results of the two analyses are discussed and the main conclusions of the study are derived.

1.2 Conceptual framework

The first problem faced, in approaching an analysis referring to two such broad and complex concepts, was to define their scope, trying to give a synthetic explanation of the phenomena that they imply or at least the meaning we intended to associate with them.

1.2.1 Circular Economy

If attempting to define CE, it should be noted that there are more than 200 definitions in the literature (Kirchherr et al., 2023b; Kirchherr et al., 2017). There is wide agreement in considering it a promising alternative to the current production and consumption model, which is based on unlimited growth and increasing resource use. It represents a paradigm shift opposite to the so-called 'take-make-dispose' linear economic model, which has been made possible through the implementation of closed-loop solutions within economic systems (Ghisellini et al., 2016; D'Amato et al., 2017; Fisher et al., 2018; Suárez-Eiroa et al., 2019; Julianelli et al., 2020). There are many concepts covered within CE studies, which add to the definition of the CE as an umbrella term (Al-Thani and Al-Ansari, 2021; Homrich et al., 2018), covering a wide range of approaches, methods, tools and strategies oriented toward e.g.,

promoting environmental sustainability, resource use efficiency, and waste reduction. Also, the debate about the implementation of CE is becoming increasingly important, given the impact it is having at economic, technological and environmental level. The main actions of the CE are aligned with what the literature defines as the 3Rs (Reduce, Reuse, and Recycle) and, subsequently, the 10Rs (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover) (Ghisellini et al., 2016; Potting et al., 2017). However, the effective implementation of these actions is still a point of discussion, particularly in terms of the approaches, methods and tools that are needed. This is especially relevant given that the CE is increasingly recognized as a transformative business model aimed at promoting sustainable development and a harmonious society. Achieving such development requires a holistic and integrated approach that successfully balances the economic, environmental, technological, and social dimensions, while also taking into account the interactions among these factors (Ghisellini et al., 2016) as well as the development of methods and tools that can assess if a CE solution is really sustainable. Such tools are essential to support informed decision-making toward circularity, adapted for the specific sector and spatial scale under analysis (macro, meso and micro scale). In this context, IE emerges as a scientific field that certainly deserves significant attention (Ghisellini et al., 2016; Saavedra et al., 2018) as it provides essential tools and methods for the analysis and improvement of the sustainability of economic systems.

1.2.2 Industrial Ecology

In 1989, the journal Scientific American published an article fundamental to the establishment of IE. Written by Frosch and Gallopoulos and titled "Strategies for Manufacturing", the manuscript proposed the concept of an "industrial ecosystem" in which the use of energy and materials is optimized, waste and pollution are minimized, and every product of an industrial process finds an economically viable function. Frosch and Gallopoulos outlined a more integrated and environmentally sustainable model of industrial activity. At the same time, Graedel and Allenby introduced a structured definition of the field, which remains an essential reference: *"Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain sustainability, given continued economic, cultural, and technological evolution. The concept requires that an industrial ecosystem be viewed not in isolation from its surrounding system, but in concert with them. It is a systems view in which one seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized are resources, energy and capital"* (Graedel and Allenby, 1995). A distinct element of IE is the analysis of industrial systems in relation to the environment, with a focus on the interaction between the material, energy and information flows within a systemic context. The interrelationships among actors are a central element,

as they enable the identification of opportunities to create synergies, optimize resource use, reduce environmental impacts and promote sustainable solutions that integrate economic, environmental and social aspects. In CE studies, systemic interrelationships tend to be less explored, as the focus is mainly on closing material cycles and optimizing production chains independently. In contrast, IE is distinguished by its systems approach, which explores the complex and multidimensional connections among actors, sectors and resource flows in an integrated way. This approach provides not only the ability to identify opportunities for synergies between apparently disconnected systems, but also offers a broader vision that can address the challenges of sustainability.

1.3 Methodology

In the first phase, a bibliometric analysis was conducted. A bibliometric analysis is a quantitative review method that helps scholars to summarize and analyze prior studies (Zhang et al., 2022; Yu et al., 2013) in order to investigate research tendencies in a field, identify knowledge gaps, generate new research ideas, and position contributions to a field (Donthu et al., 2021). Considering the scope of the analyzed fields, in order to select contributions with a high focus on the topics under investigation, the keywords used were limited to 'industrial ecology' and 'circular economy' and the research domain to the title of the scientific contributions.

In a second phase, a more in-depth study was conducted through a content analysis. All literature reviews identified through the following search criteria were selected: 'industrial ecology' AND 'circular economy' in the title, abstract and keywords. Those documents with a typical structure of this type of contribution were all included as reviews, independent of the software's automatic classification. The study is structured on two levels: a general overview on the overall scientific production and an in-depth analysis.

1.3.1 Research design

For both bibliometric and content analysis, the data for the study were obtained from the Scopus database (Elsevier, 2023). Scopus is the world's most important multidisciplinary bibliographic database, released by Elsevier and accessible online by subscription; it covers 26,591 active peer-reviewed journals from more than 7000 international publishers.

For bibliometric analysis, the search performed consists of two data extraction steps (*Figure 1.1*):

- all documents published up to 2023 with the keyword 'circular economy' in the title: CE hereafter;

- all documents published up to 2023 with the keyword 'industrial ecology' in the title: IE hereafter.

The reason for restricting the search fields to the title only was to select those scientific publications that were effectively focused on the research topics, which being so wide-ranging, as tested, are often mentioned among the keywords or in the abstract even in articles that marginally treat the problem. In addition, only the title was selected because journals often do not allow repeating words in the title, even in keywords. This encourages authors to include a significant concept in the title. In this regard, an initial attempt was made to include publications that had both "industrial ecology" and "circular economy" in the title, but the limited nature of the results obtained (14) did not allow it to be used for bibliometric purposes.

The data concern citation information (author(s), document title, year, EID, source title, volume, issues, pages, number of citations, source and document type, publication stage, DOI, open access), bibliographic information (affiliations, serial identifiers (e.g. ISSN), PubMed ID, Publisher, Editor(s), Language of original document, Correspondence address, Abbreviated source title) and Abstract and Keywords (Abstract, Author keywords, Indexed keywords) were extracted from Scopus in .csv format and uploaded separately for IE and CE to Biblioshiny. Biblioshiny is an interface obtained using the R bibliometrics package (Aria and Cuccurullo, 2017), which helps scholars to easily use the main basic functions of bibliometrics and supports bibliometric analysis with analytics and plots for different levels of metrics and analysis of the conceptual structure, intellectual structure, and social structure of the data (Bibliometrix, 2024, Büyükkıdık, 2022). The aspects that were investigated for CE and IE are the following:

- *trend*: historical evolution of the concept (number of publications covered and published over the years). The data were extracted from Biblioshiny and organized so that they could be presented on a line graph. This graph shows the scientific evolution of CE and IE in comparison;

- *authors*: productivity of authors by Lotka's law. Lotka's Law (Nicholls, 1989) describes the distribution of author productivity in a given scientific field, asserting that the number of authors who publish N articles is inversely proportional to the square of N. In such a way, a few authors are highly prolific, while most contribute a small number of articles. This law is represented by a theoretical function that allows authors' productivity to be modeled and compared with observed data (Siccardi S. and Villa V., 2022). The graphs show the application of Lotka's Law to two separate datasets: one related to CE and the other to IE. The axes of the graph are interpreted as follows:

  - X-axis: number of papers written (productivity of authors);

  - Y-axis: percentage of authors who wrote that number of papers.

The curves represent:

- continuous line: observed distribution of data;

- dotted line: theoretical distribution predicted by Lotka's Law.

- *countries*: a world map showing the scientific output of countries is presented. The intensity of the gray color is given by the number of publications according to the search criteria. Darker gray indicates a larger number of publications in the indicated period;

- *author's keywords* (most relevant keywords): author's keywords are the keywords given by the authors. Data are extracted from Biblioshiny based on the keywords used by the authors and their frequencies. This data is processed to create a summary table that highlights the top 20 IE and CE keywords by highest frequency and highlights the common word. A pie chart showing the top 10 keywords in order of frequency for the last two periods of IE and CE is also shown. The keywords "circular economy" for CE and "industrial ecology" for IE were excluded. In addition, the general themes of "sustainable development" and "sustainability" are widely shared between the two domains (in the analysis they have the highest absolute frequency in both), it was decided to exclude these as well in order to give more relevance to other specific themes.

Additional representations tools (deriving from the Biblioshiny software (Büyükkıdık, 2022) are:

- *Three-field plot*: is a sankey diagram that summarizes the relationship between authors, keywords used and countries. The middle column represents the keywords most frequently used by the authors, the left column represents the authors' names, and the right column represents the authors' countries. The keywords "circular economy" for CE and "industrial ecology" for IE were excluded from the analysis, as were "sustainability," "sustainable development," and other major synonyms. The height of "nodes" and the strength of link correspond to the number of connections;

- *Thematic map*: the thematic map examines groups of author's keywords and their relationships to obtain 'themes'. These themes are characterized by properties (density and centrality). Density is shown on the vertical axis and centrality on the horizontal axis. These properties measure the relevance of the themes, differentiating them and considering them as important or less important. As the number of relationships a node has with other nodes in the network increases, so does its centrality and thus its importance. The density of a node shows its ability to develop and sustain itself. Each thematic map is linked to its respective network plot. The analysis is based on the author's keywords. The keywords "circular economy" for CE and "industrial ecology" for IE were excluded from the analysis, as were

also “sustainability,” “sustainable development,” and other main synonyms. The graph is obtained by applying the s.c. algorithm “walktrap” from the parameter settings.

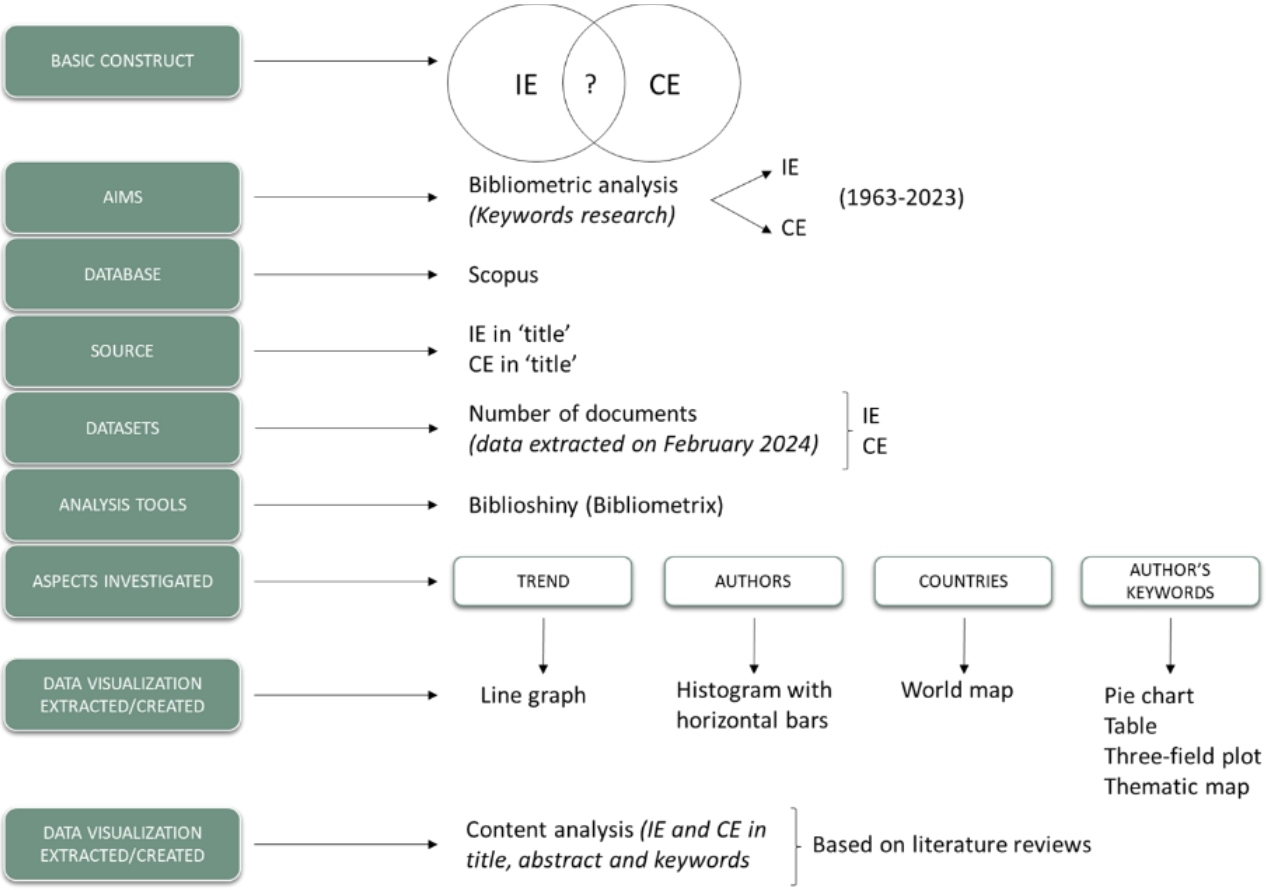


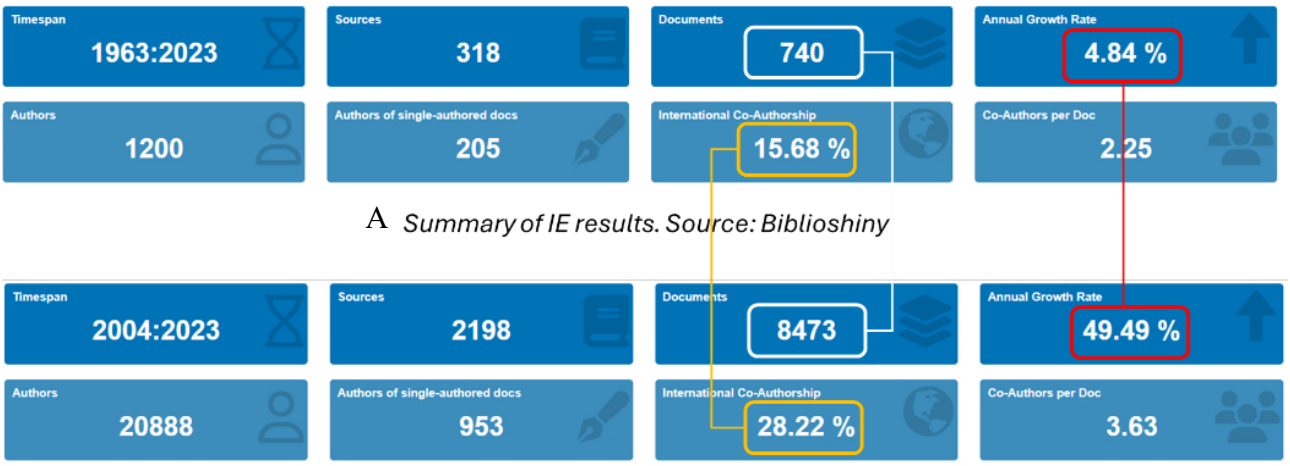
Figure 1.1 *Research design. Source: authors’ elaboration*

For the content analysis, the literature reviews identified through the following search criteria on Scopus were selected: “industrial ecology” AND “circular economy” in the title, abstract and keyword domains. The search was limited to the period 2004-2023, with 2004 representing the year of the first available result on Scopus. It was decided to consider only literature reviews for content analysis because the search results amount to 488 articles, a quantity that makes it impossible to conduct a thorough and systematic analysis on all identified documents. The choice to focus on reviews allows researchers to summarize the state of the art, identify the main research trends, and analyze the most significant contributions. Here, this approach is used to explore in depth the methods and tools used in the different studies, as well as to examine how literature addresses and structures these topics, highlighting connections between the two research fields, existing gaps, and opportunities for further developments. In total, 51 literature reviews published through 2023 were identified. Just 14 literature reviews were included in the analysis as relevant to the research objective.

In the selected papers, the methods and tools used in the contexts of IE and CE were reported and summarized in *Table 1.1*.

1.4 Results

Figures 1.2A and *1.2B* show a summary of the data extracted for the datasets referring to IE and CE over the period in which they were detected, according to the search parameters set.



A *Summary of IE results. Source: Biblioshiny*

B *Summary of CE results. Source: Biblioshiny*

Figure 1.2 *Summary of IE and CE results.*
Source: Biblioshiny

Looking at the overall data of the bibliometric study, two initial elements of reflection emerge clearly: i) some results date back to historical periods much earlier than those recognized as relevant for the research fields considered (in particular for IE); ii) there is a huge disparity in the volume of activity of one research field compared to the other, both as a total overall number of authors involved, sources and documents detected and as a growth trends. These aspects have been considered in the subsequent development of the analysis and in the interpretation of results.

Publication trends

Figure 1.3 indicates that, over the 60 years considered, there are three significant periods, the first 40 years in which only the term "industrial ecology" has been detected (Period 0 and Period 1 in figure), and then two blocks of 10 years in which IE and CE coexist (Period 2 and Period 3 in figure). It should be noted that in the period 1963-1990 there were only a few publications per year related to the IE field. Conventionally, IE is considered to have begun to develop as an autonomous discipline in the 1990s, moving from the publication of key articles (Frosch and Gallopoulos, 1989; Ayres, 1989; Jelinski et al., 1992; Graedel and Allenby, 1995; Erkman, 1997) and the formalization of the concept

of IE. Since the 1990s, the field has evolved significantly, with a gradual increase in publications and a broadening of the topics covered. This is confirmed by the fact that the higher number of publications started in 1992, instead prior to this date, from specific checks carried out, on the few articles published before this date, the presence of the term "industrial ecology" is to be considered not attributable to the research field. Subsequently, the 2004-2013 period shows a similar publication trend between the two fields, but from 2014 onwards, articles published on CE topics increase exponentially, while those on IE remain constant or decrease slightly.

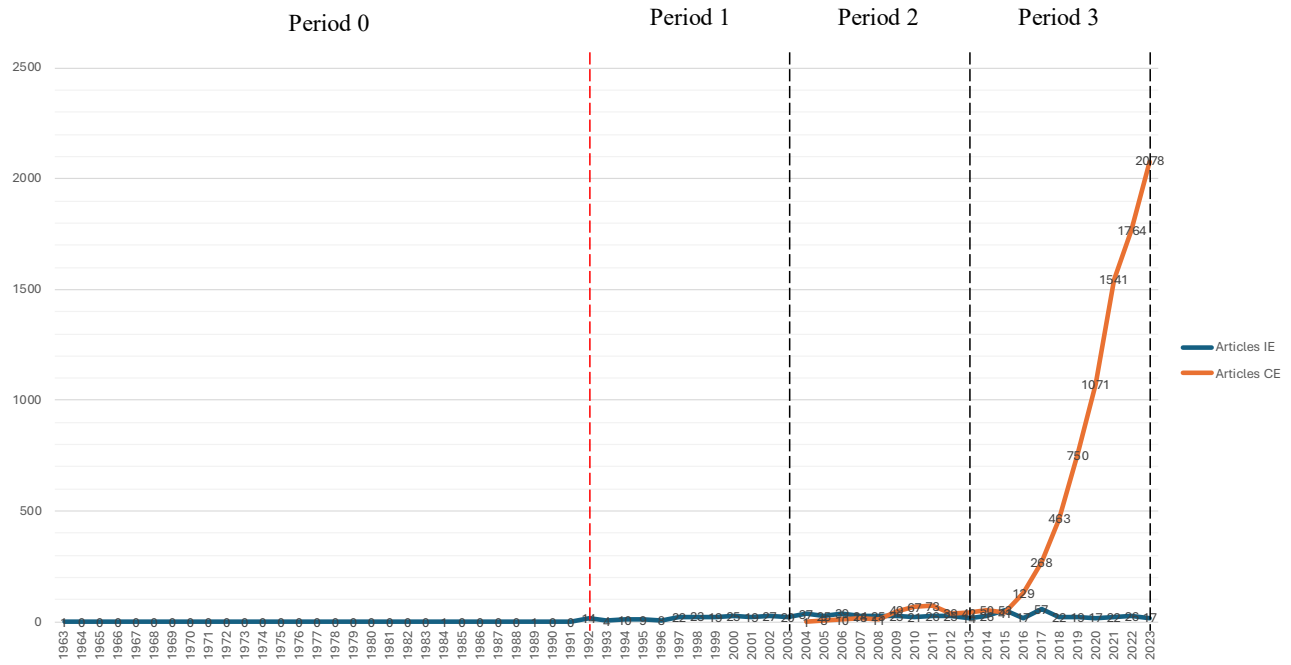


Figure 1.3. *Line graph - historical evolution of IE and CE.*

Source: authors' elaboration

Authors

In the case of CE (*Figure 1.4*), the continuous line (observed distribution of data) shows a higher percentage of occasional authors (1-2 documents), with a rapid decrease in productivity for authors with more than 5 articles. This suggests that CE is a relatively new or interdisciplinary field, characterized by sporadic contributions from many researchers. In addition, the number of prolific authors (10 or more articles) is lower than in Lotka's Law, showing fragmentation in productivity. In contrast, in the case of IE (*Figure 1.5*), the continuous line (observed distribution of data) better follows Lotka's theoretical curve. This reflects a more stable and established scientific community, with a nucleus of authors contributing continuously to the field. The more balanced distribution of prolific authors suggests that IE has a more mature structure than CE. For the CE, the very high number of authors with a single document (16480) suggests that the field is relatively young and

expanding rapidly. Many researchers are beginning to contribute to the topic, perhaps as occasional or interdisciplinary authors addressing the topic from other fields. This phenomenon may indicate that the CE is a trending topic with great academic attraction but a lack of an established core of prolific experts. In the case of IE, a smaller number of authors with only one document (977) suggests that the field is more mature and probably has a more stable community of experts. IE may have a higher barrier to entry, with researchers specializing more in the topic than those in CE.

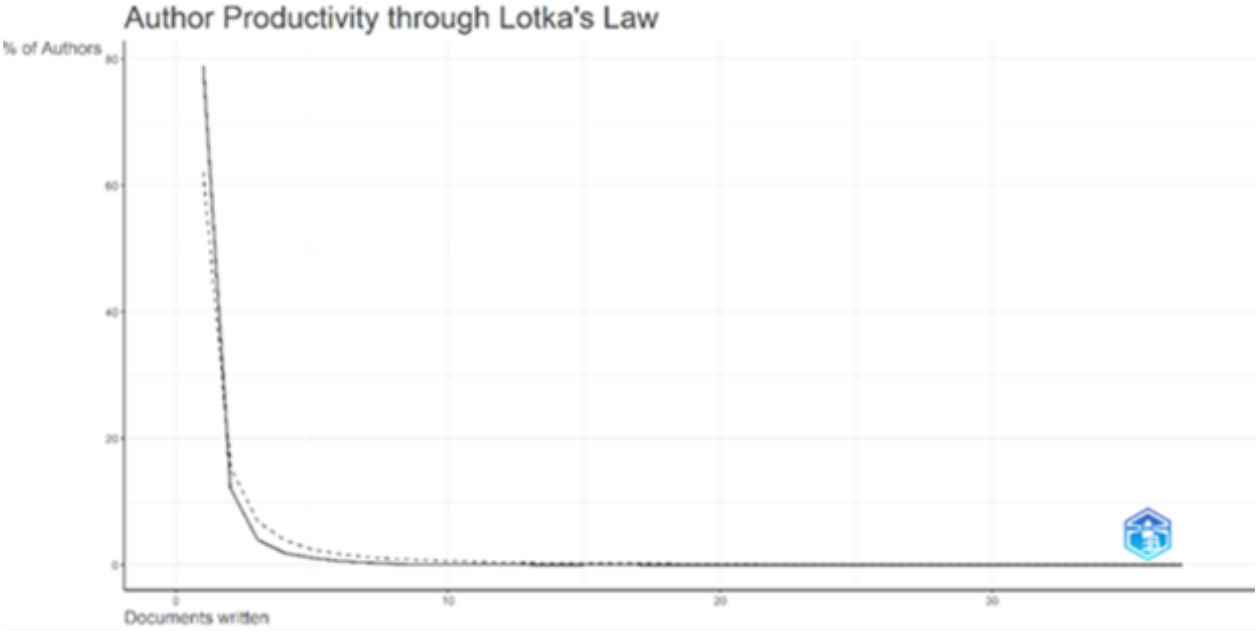


Figure 1.4 *Circular Economy. Author Productivity through Lotka's Law.*
Source: Biblioshiny

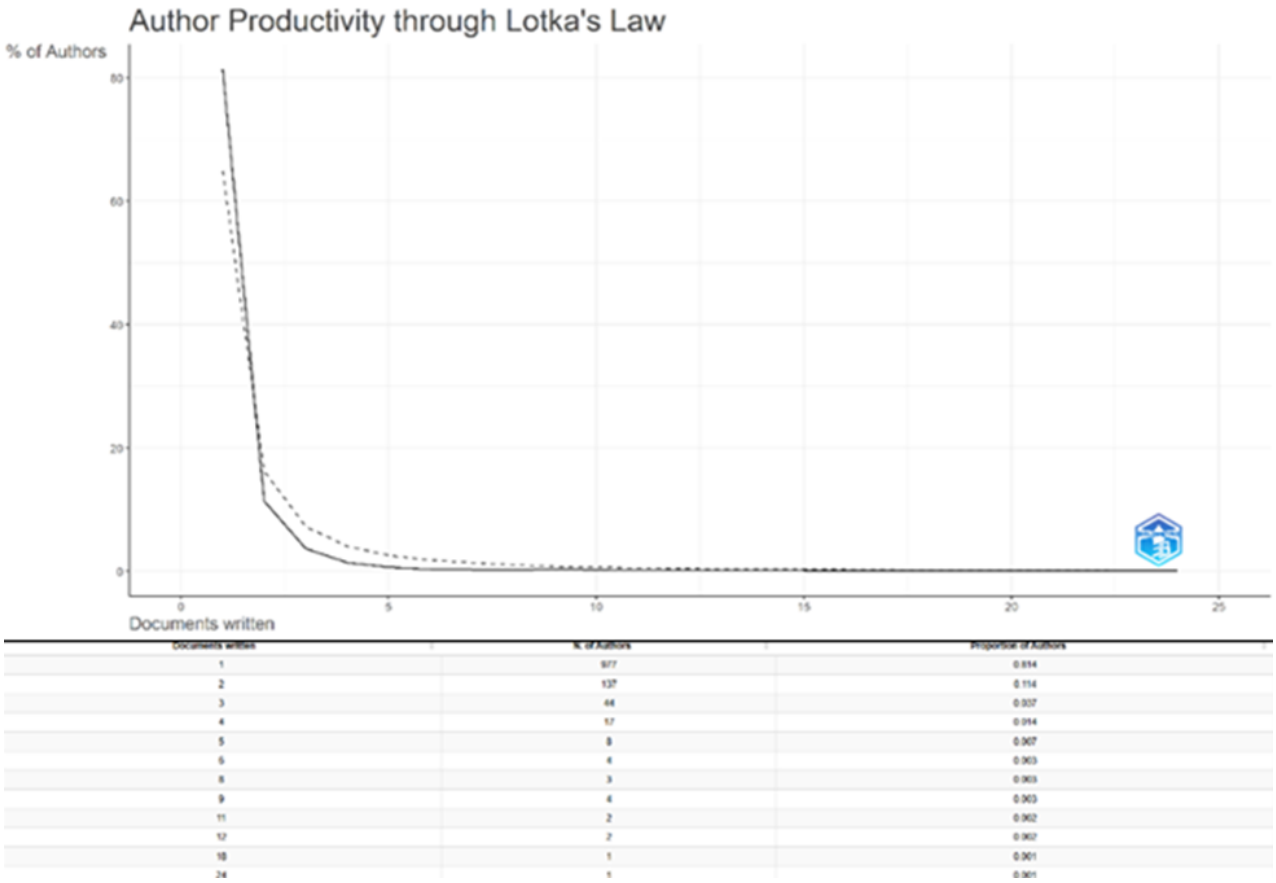


Figure 1.5 *Industrial Ecology. Author Productivity through Lotka's Law.*
Source: Biblioshiny

Countries

Figure 1.6 indicates that studies on IE originate in Western countries (mainly North America) and then spread to the rest of the world, while studies on CE originate mainly in Eastern countries (China) and later spread to the rest of the world as well, to an even greater extent than IE. It should be noted that IE is also of greater interest in China in the more recent period, while countries on the European continent (England and Italy) are prevalent for CE.

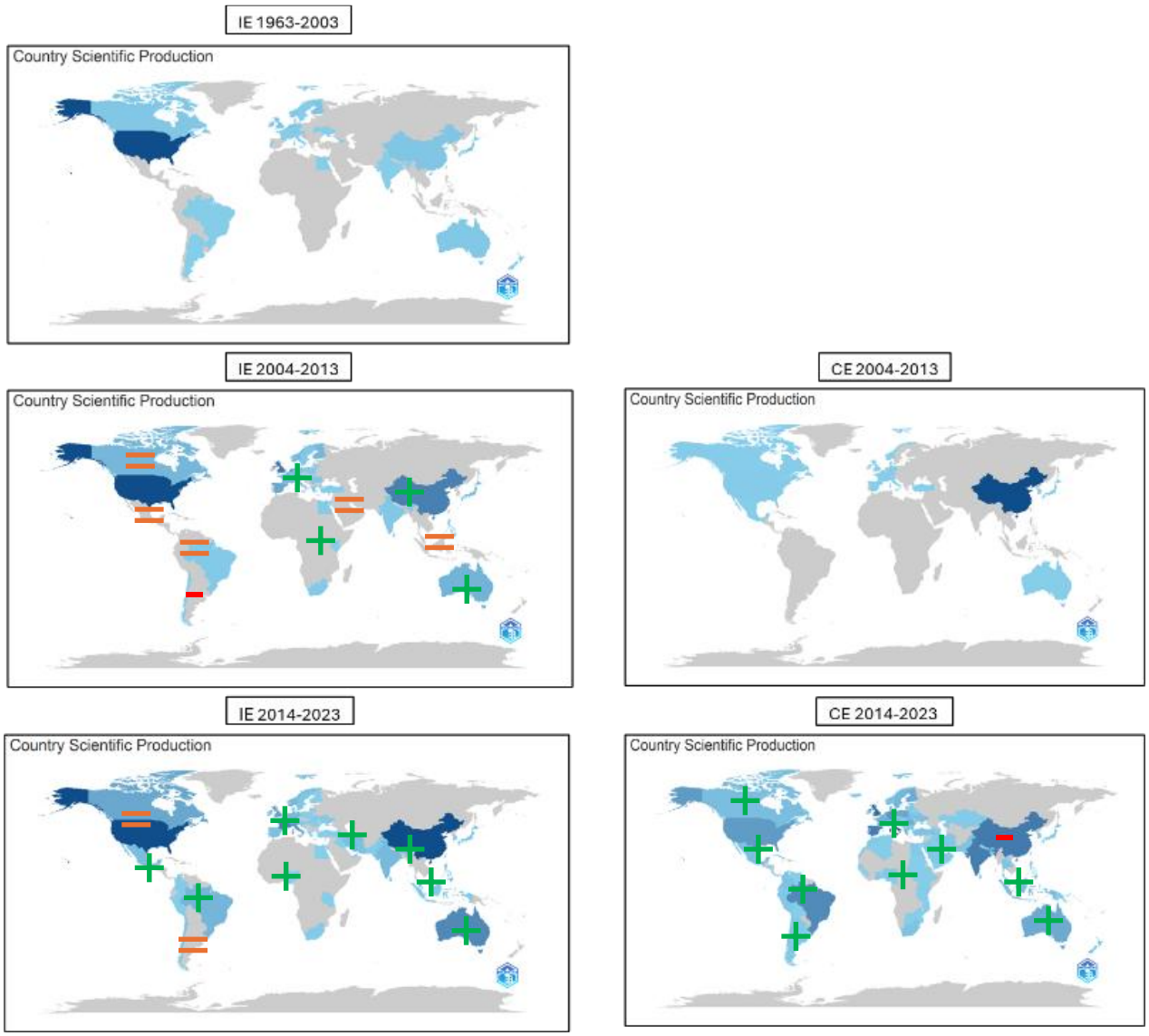


Figure 1.6. *World map - scientific production of the countries.*

Source: Biblioshiny

Keywords

All author's keywords extracted from Biblioshiny, for the IE and CE datasets, were ordered according to their absolute frequency in a first step of the analysis. It was decided to select the first 20 in relation to IE and CE. Then the keywords were merged and organized together in alphabetical order (*see Figure 1.7*). The analysis conducted in this way shows that the theme "environment" is common to both fields, as well as themes related to some methodological aspects (e.g., industrial symbiosis, life cycle assessment) and aspects more closely related to waste and its management (e.g., food waste, recycling, waste, waste management).

	anaerobic digestion	barriers	bioeconomy	biological analogy	business model	china	circular economy	cleaner production	complexity	dematerialization	eco-industrial park(s)	energy	environment	exergy	food waste	industrial ecology	industrial ecosystems	industrial metabolism	industrial symbiosis	industry 4 0	innovation	life cycle assessment	material flow analysis	metaphor	recycling	remanufacturing	renewable energy	resource efficiency	reuse	reverse logistics	urban metabolism	waste	waste management
CE	x	x	x		x								x		x	x			x	x	x	x			x	x	x	x	x	x		x	x
IE				x		x	x	x	x	x	x	x	x	x	x		x	x	x			x	x	x	x						x	x	x

Figure 1.7 *Summary table (IE and CE) – all periods.*
Source: authors' elaboration

Additional analysis was carried out by extracting the top keywords in both fields based on time periods. From this data, pie charts were constructed showing the frequency of the top 10 most used author's keywords for IE and CE (*Figure 1.8*). It was decided for the first IE period to include at least 30 keywords for a more detailed analysis. Since this number is not visible with a pie chart, a table was chosen. A "longitudinal" analysis (Analysis 1 in *Figure 1.8*) was performed for the two fields, with the purpose of understanding the evolution of keywords within the individual fields; and a "cross-sectional" analysis (Analysis 2 in *Figure 1.8*), with the purpose of highlighting the keywords that the two fields have in common. It can be seen that there is a consistency in evolution within IE, with many themes remaining relevant over the years (*see* light gray color). CE, on the other hand, uses only a few terms over the years, including "industrial ecology" (*see* dark gray color). The "cross-sectional" analysis reveals that many key concepts in CE studies were already key concepts of IE before 2004 and remain constant within IE over time. These are: *cleaner production*, *life cycle assessment*, and *waste* (highlighted with a circle). *Recycling* is also the most frequently used keyword in IE studies over the past 10 years. Both research fields share the keywords *industrial ecology* and *circular economy*. In CE, *industrial ecology* has been used since the beginning, while in IE *circular economy* has been used more in the last 10 years.

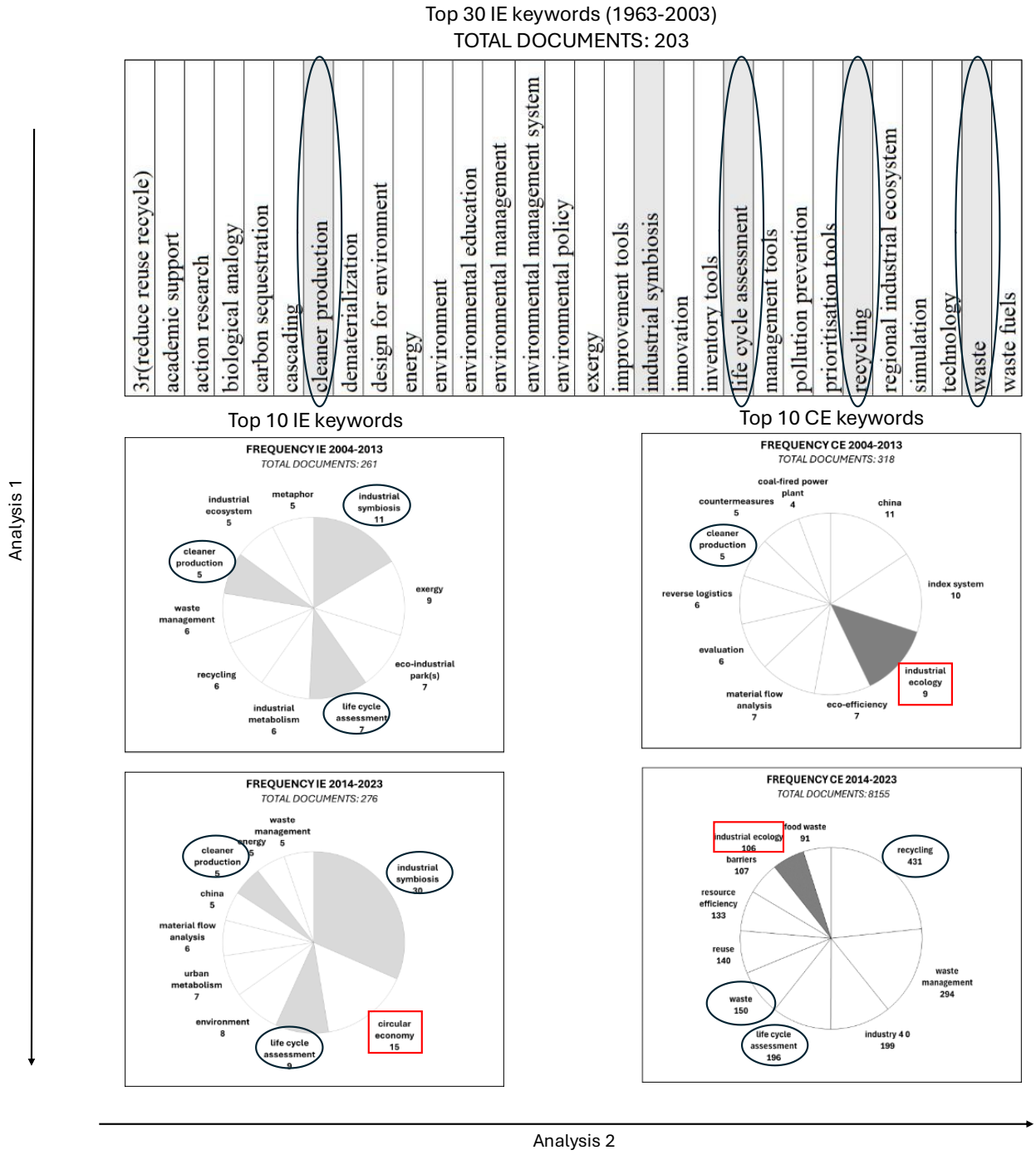


Figure 1.8 *Pie chart - 3 periods of IE and CE.*

Source: authors' elaboration

Cross-analysis

In a cross-analysis of the previous results, and with reference to the entire period of scientific production for the two fields of research considered, a three-field diagram was used to investigate which authors in the two fields are concerned with which topics of study and where they come from. The purpose was to map both the current distribution of dominant research interests and their

geographical location. *Figures 1.9* and *1.10* show the keywords with the most links. Analyzing the first four keywords in detail, two are common: *life cycle assessment* and *waste management*. On the other hand, *circular economy* and *industrial symbiosis* are the most common in IE studies, while *recycling* and *industry 4.0* are the most common in CE studies. In addition, many of the reference authors for the CE field come from Europe (England, Italy, Spain), while for IE they come from USA and China.

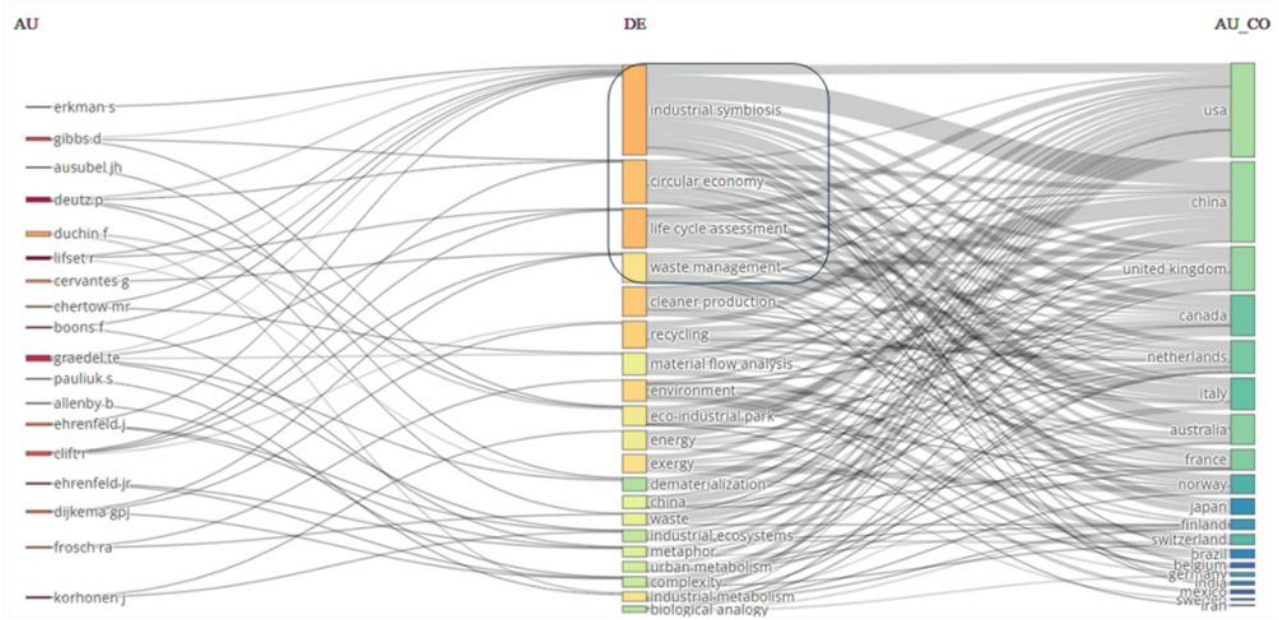


Figure 1.9 *Three-field plot – IE (1963-2023).*

Source: Biblioshiny

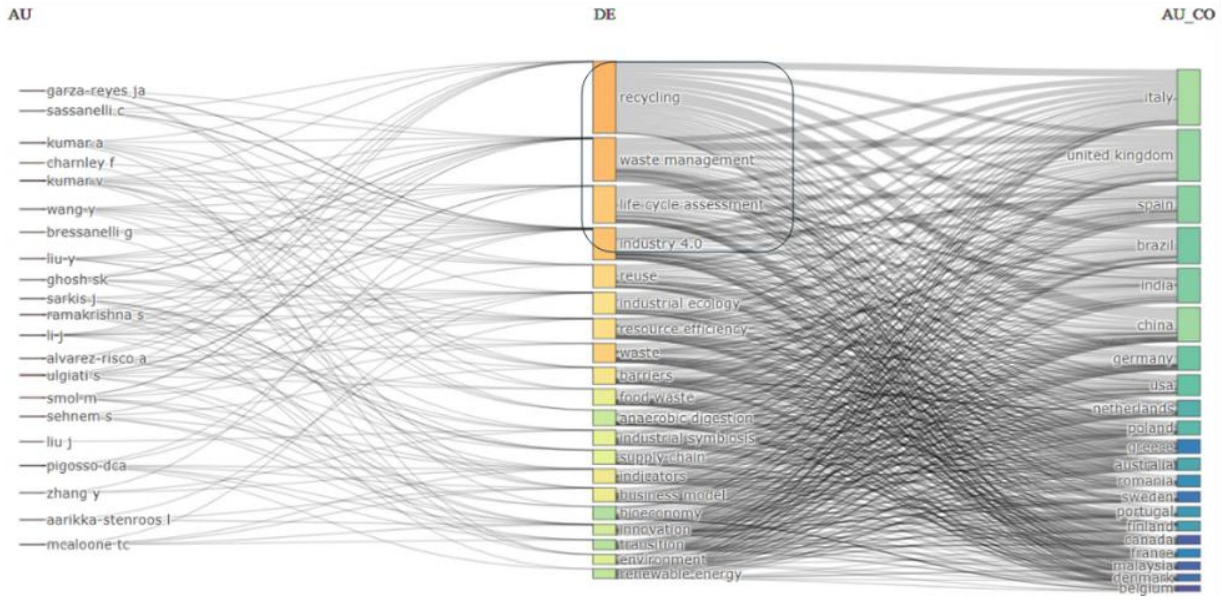


Figure 1.10 *Three-field plot – CE (2004-2023).*

Source: Biblioshiny

Relevance and centrality of the themes

In the final stage of bibliometric analysis, the respective weight of different research topics in the two fields was examined using a thematic map. The results were aggregated for the three periods considered (1963-2003; 2004-2013; 2014-2023). As can be seen from *Figure 1.11 B*, even before the birth of CE (2004), the IE field was already dealing with the concepts of "closed loops", "closed-loop systems", and the 3Rs (reduce, reuse, recycle), which later became the basis of the current CE field.

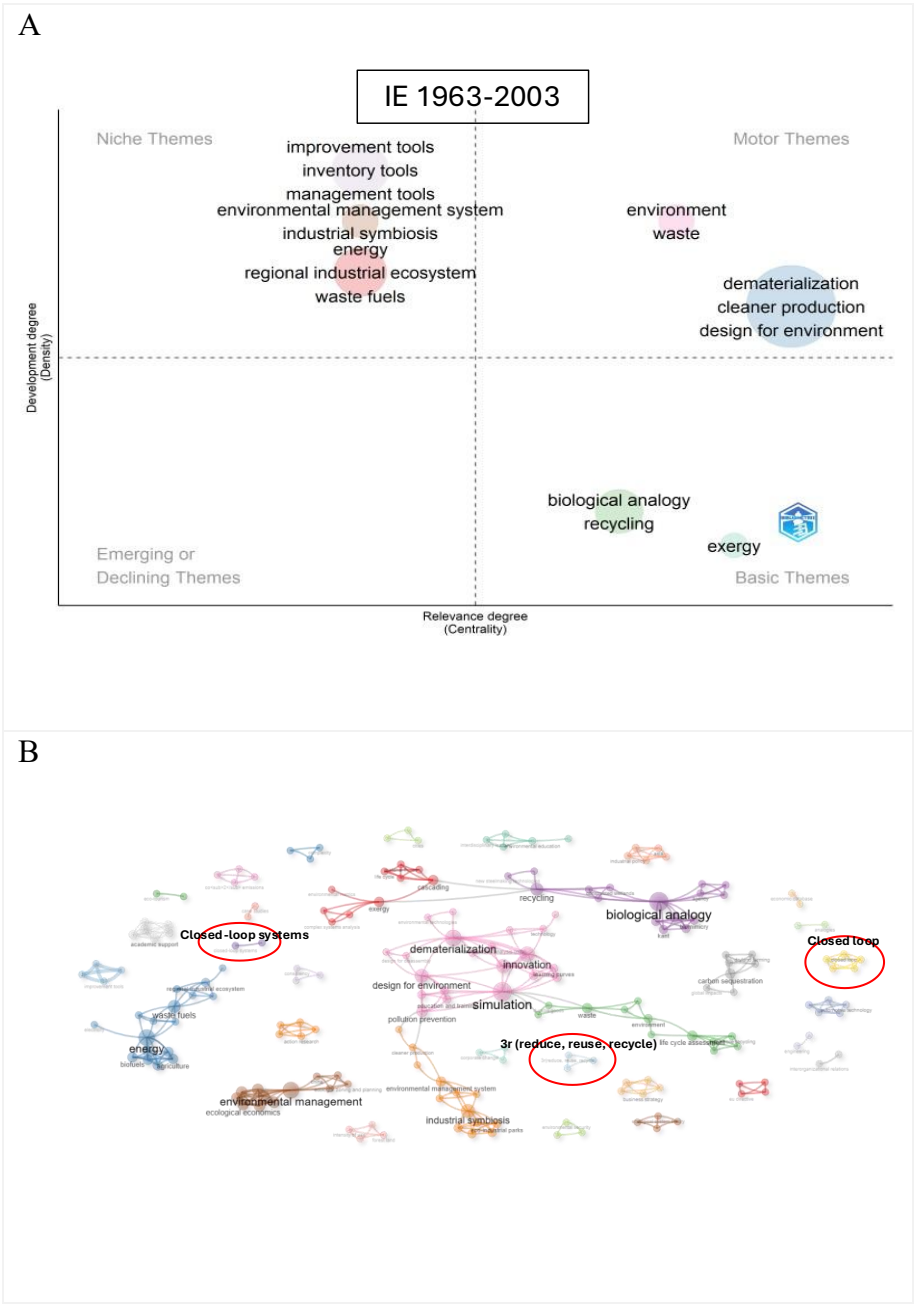


Figure 1.11 *Thematic map – IE (1963-2003).*

Source: Biblioshiny

A cross-sectional comparison of the two fields in the subsequent decades (*Figures 1.12 A* and *1.13 A*) reveals that the concept of CE was a "niche" topic for IE in 2004-2013, which then became "basic" in the next decade. The concept of IE in CE was considered "basic" in the first decade and then appears to have regressed into a state of decline. In addition to the thematic analysis, the associated network analysis (*Figures 1.12 B* and *1.13 B*) shows that the IE field is populated by more research themes (or clusters of nodes), while the CE field includes more and more concepts (nodes) within fewer themes.

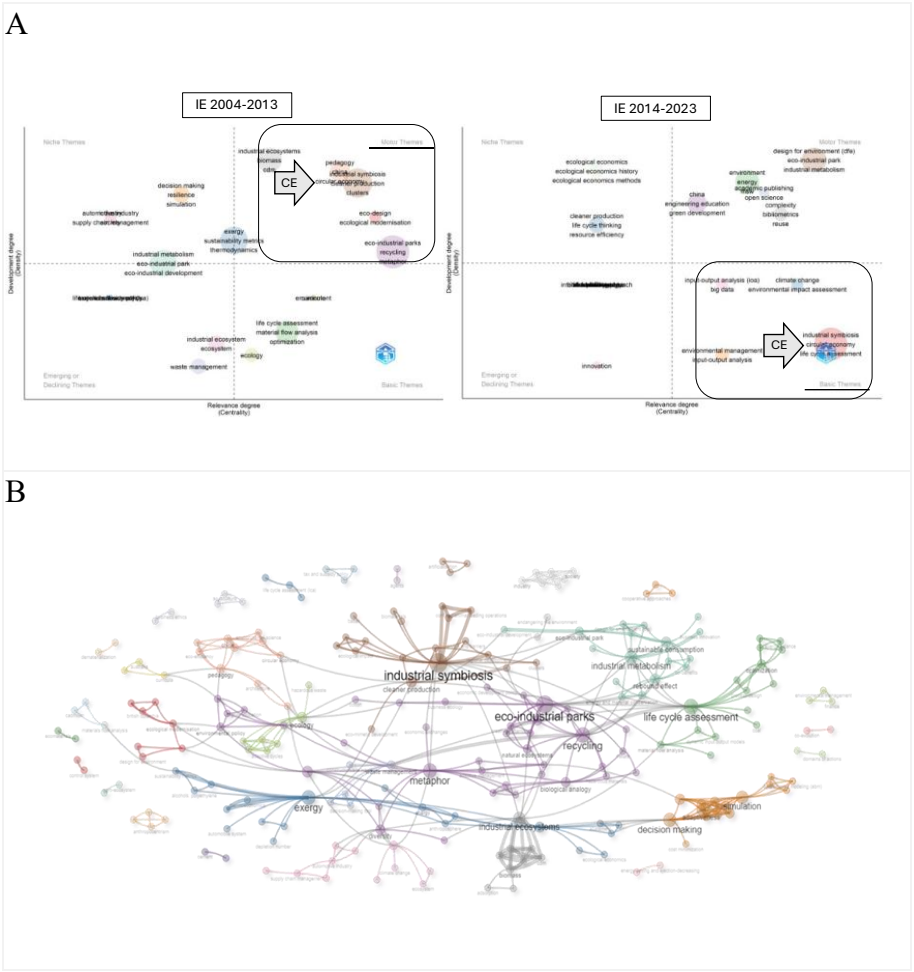


Figure 1.12 *Thematic map – IE (2004-2023).*

Source: Biblioshiny

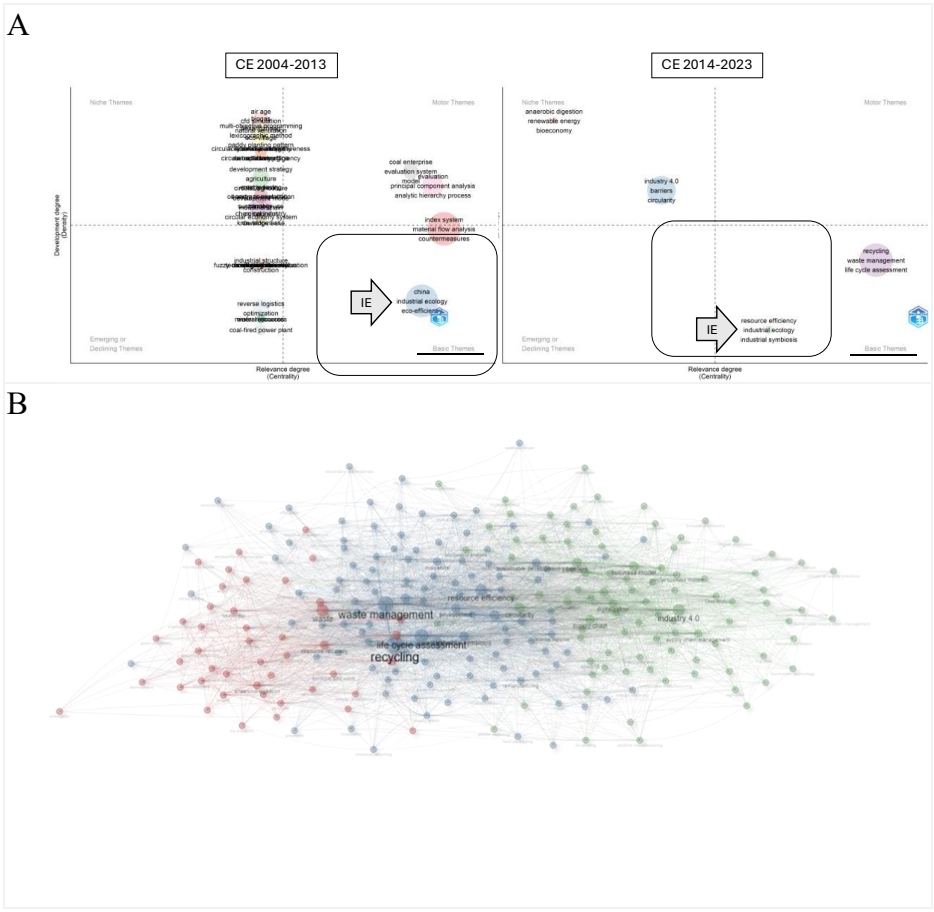


Figure 1.13 *Thematic map – CE (2004-2023).*
Source: Biblioshiny

1.4.1 Content Analysis

The results of the bibliometric analysis have led to a further step in the literature reviews in order to investigate the presence of any other relevant aspects. *Table 1.1* summarizes the results obtained from the content analysis. The 14 literature reviews included in the study were ordered chronologically, according to the year of publication. For each article, the objective was to identify the methods and tools related to CE and IE fields as reported in the text. In this work, a method or tool was considered relevant to either CE or IE when reading the articles, an association with either of the two fields clearly emerged. This connection was identified on the basis of how they were described and their use to address specific problems or to practically implement the two fields' key concepts. The results indicate that although (as can be assumed) numerically the identified methods and tools are more closely associated with the CE field, the IE field developed in an earlier period, so in many cases a certain scientific heritage between the two is evident. The concepts most frequently reported in the reviews are also consistent with those that emerged from the keywords in the bibliometric analysis phase. Highlighted in bold are the methods and tools that were already present in IE before CE (*see Figure 1.9*). In particular: 3R and subsequent declinations (6R and 10R); DFE; the role of waste - waste

management/waste recycling; industrial symbiosis; innovation; the role of technology; policy; LCA; simulation; cleaner production. As well as MFA, cleaner production and eco-industrial parks. It should also be noted that there has been an evolution over the years to include advanced dynamic simulation techniques (e.g. system dynamics and agent-based modelling), statistical tools (e.g. principal component analysis, data envelopment analysis, geographic information system and input-output analysis) and ICT tools for the development of platforms that can support data processing and visualization. Also relevant to note is the more recent interest in hybrid methods and tools.

Table 1.1 *Results of content analysis. Source: authors' elaboration*

Year	Author	IE methods and tools	CE methods and tools
2016	Ghisellini et al.	industrial metabolism	industrial metabolism, 3R: reduction, reuse and recycle, eco-design, design for environment (DFE), cleaner production, consumers responsibility, labelling systems, policy tool, waste management, eco-industrial parks, industrial symbiosis, collaborative consumption models, new business models
2017	Winans et al.		industrial symbiosis, eco-city policy instruments, eco-industrial parks, eco-industrial estates and networks, waste recycling, material flow analysis (MFA), innovation, social innovation, 3R or 6R
2017	Masi et al.		government incentives, mandatory regulation, industrial symbiosis, information and communications technology (ICT), investments to implement CE practice, development of technology, system thinking approach, environmental information disclosure, policy, eco-industrial parks
2018	Merli et al.		life cycle assessment (LCA), material flow analysis (MFA), development of a specific indicators, eco-cities or eco-provinces, circular cities, waste management, eco-industrial parks, industrial symbiosis, recycling, cleaner production, eco-design, 3R, policy, sharing economy, product-service systems, dematerialization, remanufacturing, big data and Internet

			of Things (IOT), ReSOLVE framework
2018	Kalmykova et al.	eco-industrial parks	national input-output tables, emergy-based indicators, eco-efficiency, eco-effectiveness, 4Rs principle, environmental extended input-output methods, life cycle assessment (LCA), material flow analysis (MFA), MFA-LCA method, emergy analysis, input-output analysis
2019	Walmsley et al.	life cycle assessment (LCA), environmentally extended input-output analysis (EEIOA), material flow analysis and substance flow analysis (MFA/SFA), hybrid approaches, industrial metabolism	environmentally extended input-output analysis (EEIOA), life cycle assessment (LCA), life cycle optimization, input-output analysis, carbon emissions pinch analysis (CEPA), processing pathway synthesis with total site integration, detailed process simulation and integration for optimal design
2020	Walzberg et al.	life cycle assessment (LCA), environmentally extended input-output analysis (EEIOA), material flow analysis (MFA), emergy and exergy	circularity matrix, eco-design, screening tools, serious games, system dynamics, discrete event simulation, agent-based modelling, operations research, combination of methods, backcasting techniques (qualitative), computable general equilibrium models (qualitative)
2020	Saavedra et al.		material flow analysis (MFA), eco-design, cleaner production, political and standard contribution
2020	Hossain et al.		design, material selection, supply chain, business model, policy, collaboration among actors, knowledge among stakeholders, urban metabolism, industrial symbiosis, LCA tools (SimaPro, openLCA), fuzzy analysis, statistical analysis (principal component analysis, data envelopment analysis, geographic information system), life cycle assessment (LCA), life cycle cost (LCC), life cycle sustainability assessment (LCSA), material flow analysis (MFA), material flow cost accounting, input-output analysis, indicators, questionnaire survey, mathematical modelling approach, semi-structured interviews and

			document analysis, e-Delphi technique, confirmatory factor analysis, social network analysis (SNA), observation, material flow analysis (MFA)
2020	Turken et al.		closed loop supply chains, industrial symbiosis, eco-industrial park
2021	Al-Thani and Al-Ansari		life cycle assessment (LCA), diversification, dematerialisation, lean principles, collection and recycling, remanufacturing and resuse, waste management, lean manufacturing, energy recovery perspective, waste management and prevention, reverse supply chain, global level, reuse and recycle, urban metabolism, industrial symbiosis, MFA and data envelopment analysis (DEA), eco-industrial parks
2021	Ogunmakinde et al.	inter-firm industrial symbiosis, eco-industrial parks	life cycle cost (LCC), life cycle analysis, material passports, reverse logistics, extended producer responsibility
2021	Walker AM et al.	industrial symbiosis, eco-industrial parks, indicators, LCA-LCT-based methodology, input-output analysis, scenario analysis, material flow analysis and substance flow analysis (MFA/SFA), ecological footprint, cost-benefit analysis, fuzzy cognitive mapping combined with sensitivity analysis, multi-integer programming model	industrial symbiosis, eco-industrial parks, life cycle thinking (LCT), product-cycle perspective, indicators
2021	Singh et al.		life cycle assessment (LCA), material flow analysis (MFA), reuse and recycling, input-output models, stakeholder engagement, innovation, business models

1.5 Discussion and conclusions

The outcomes of the comparative bibliometric analysis reveal that, from a time perspective, the concept of IE appears significant at least 15 years before CE (1990-2004) and follows a steady trend over time. CE, on the other hand, shows a publication trend similar to that of IE from 2004 to 2014, but at some point, it starts to grow exponentially and then diverges completely in terms of number of publications. A bibliometric analysis conducted showed that IE comes mainly from Western countries, while CE comes from Eastern countries, especially China, and moves globally equally with IE. In terms of "constancy of academics", IE shows greater stability over time, while CE shows great unevenness. In terms of topics, the concept of sustainable development and sustainability is definitely a reference for both, but there are also topics related to the environment, waste management, and specific methodological approaches such as life cycle assessment and industrial symbiosis. The keywords "industrial ecology" and "circular economy" are undoubtedly mutually recognized. Analysis of the key themes of the first IE period shows that some key concepts of the CE have been transferred and have always been present as key concepts in the 60 years of IE. Also interesting is that the theme of Industry 4.0 emerges as one of the key themes of CE, representing the link between the ecological and digital transition. From the thematic map, it appeared that the CE had already started to incorporate IE studies as a core theme and appeared to be declining in the second period (2014-2023). In contrast, in IE, CE studies are initially (2004-2013) an underdeveloped niche theme and then evolved as a core theme here as well. While in CE there is a gradual specialization, which is also physiological in the early stages of research, this is not the case in IE, which seems to be a more open field with a more exploratory nature and thus remains a field that aims to study as many aspects as possible from a methodological perspective. The content analysis is coherent with the bibliometric analysis based on authors' keywords, confirming the presence of numerous links between IE and CE and a kind of "scientific heritage" form IE in respect of CE and even if not always openly declared, IE may have often been a source of inspiration for CE scholars. This preliminary study highlights interesting insights for discussion, some of which are certain to have limitations and require further investigation. Quantitative analysis, in particular, provides results that may be influenced by less than three aspects: i) subjectivity in the selection of data and algorithms, ii) parameters used, and iii) potential limitations related to the chosen tools. However, such first result obtained motivates further investigation of the theme, especially the presence of possible synergies and spaces of integration between the two fields not yet fully explored.

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CHAPTER
2

The role of external variables: Extended Producer Responsibility in the circular transitions of the textile supply chain

The content of this chapter refers to an article presented at the SUN network conference during Ecomondo 2023 ("Toward a National Program for Industrial Symbiosis: Perspectives and Opportunities for Italy", Rimini, November 7–10, 2023) and later published in the conference proceedings. The article examines the recent evolution of regulatory frameworks on Extended Producer Responsibility (EPR) and circularity in the textile sector, considering the policy transformations introduced by European Union.

TITLE:

EXTENDED PRODUCER RESPONSIBILITY AND CIRCULARITY IN THE TEXTILE SECTOR: STATE OF THE ART AND FUTURE DIRECTIONS

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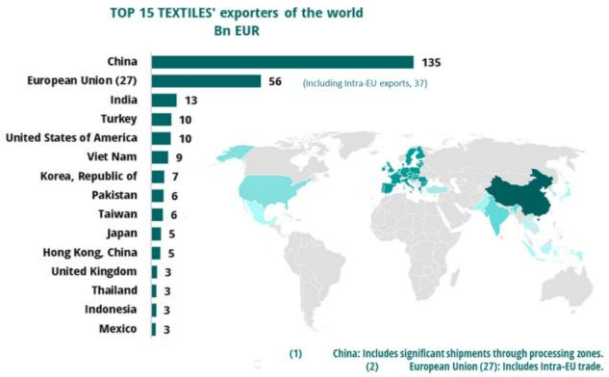
Abstract

Circular Economy (CE) has progressively established itself as a reference paradigm for transitioning to more sustainable socioeconomic systems. The textile sector is among the industries receiving the greatest regulatory and policy attention. The European Union, in particular, has defined the s.c. EU Strategy for Sustainable and Circular Textiles which calls for a profound redesign of production processes and life-cycle management along the entire value chain. Implementing this strategy requires a complete review of production methods and life cycle management along the entire supply chain to fully implement eco-design and environmental assessment approaches and tools. This article provides an evolutionary analysis of recent regulatory provisions on Extended Producer Responsibility (EPR) and circularity in the textile industry, highlighting potential synergies and critical issues of their prospective application.

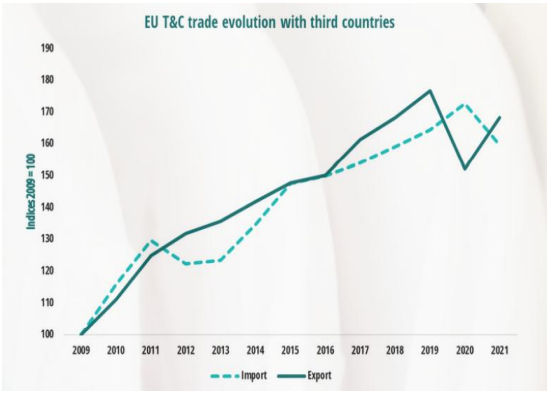
2.1 Introduction

The textile sector includes manufacturing activities dedicated to the production and processing of textile fibers, inputs for the clothing and textile products industry, and technical materials for use in sectors extending from fashion to interior design. It has a very long history, having driven the First Industrial Revolution thanks to the major innovations introduced during that period. Today, the textile industry contributes significantly to the national economies of many countries; in terms of production and employment, it is one of the largest sectors in the world. In Europe, the textile industry employs around 1.3 million people in 143,000 companies, with a total turnover of €147 billion. The sector is mainly based on micro, small, and medium-sized enterprises: 88.8% are companies with 0 to 9 employees, 11% have 10 to 249 employees, and only 0.2% are large companies with more than 250 employees (Euratex, 2022). Europe is also the world's second largest exporter. In recent years, commercial performance has increased, making the textile and clothing sector the second most export-intensive sector in the entire European economy (*Figures 2.1a* and *2.1b*). The main component in the overall production of the textile industry is the manufacturing of clothing and accessories, with a production share of 31%, followed by technical and industrial textiles (17%), fabrics (15%), and home textiles (14%) (Euratex, 2022). However, dependence on foreign countries (imports and exports) has made the textile supply chain one of the most vulnerable; moreover, the Covid-19 pandemic has redefined the import strategies of many countries. In fact, companies operating in the textile sector are among those that have encountered the most supply problems (along with electronics and automotive companies) (Istat, 2022).

(a)



(b)



Figures 2.1(a) e 2.1(b) *(Euratex, 2022)*

In Italy, the textile and clothing sector comprises almost 50,000 companies, employing approximately 400,000 people, with a turnover of €45 billion in 2020 (in 2019, turnover was €56 billion) and is a fundamental component of the national economy and manufacturing sector (Sistema Moda Italia, 2021).

2.2 Technological, production, and environmental characteristics of the textile sector

The textile sector is divided into a series of segments which, taken together, define highly ramified and now globalized supply chains. Production processes begin with the production of fiber to be used, which can be of natural origin (e.g., animal fibers, such as wool and silk, or plant fibers, such as cotton and linen) and/or artificial (e.g., synthetic or semi-synthetic fibers such as nylon and rayon). The long and complex value chain continues with the following stages: i) fabric production and finishing (aimed at giving the fabrics their visual, physical, functional, and aesthetic properties); ii) transformation of fabrics into finished products through manufacturing processes (clothing, home textiles, or technical textiles); and finally, iii) retail activities (*Figure 2.2*).

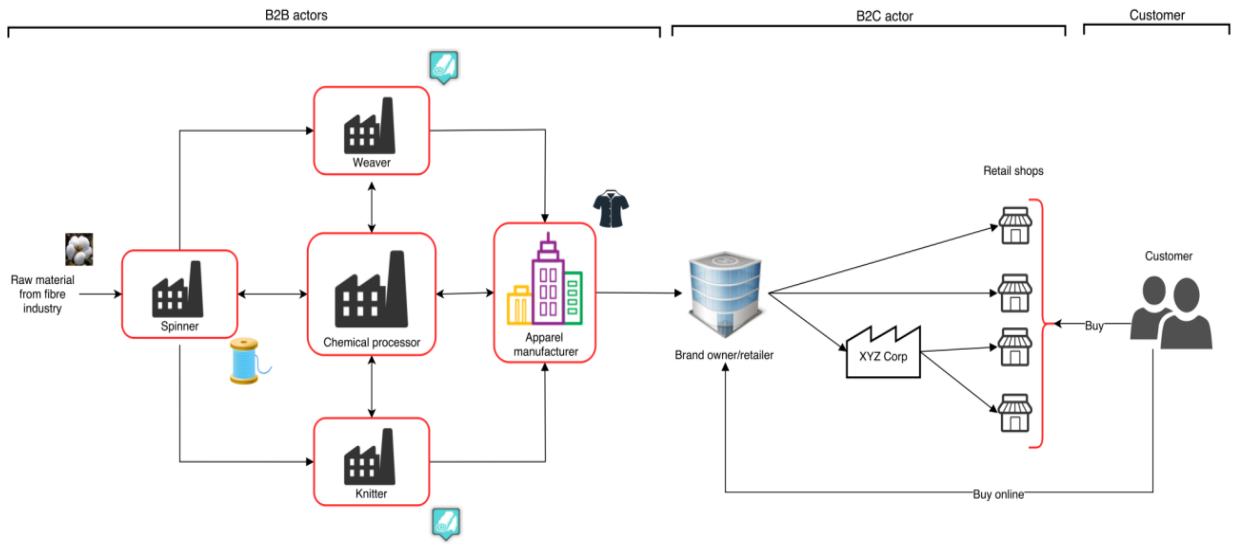


Figure 2.2 *Textile Supply Chain Network (Kumar, et al., 2017)*

Environmental and social sustainability is a critical issue in the textile sector. From a life cycle perspective, the main problems in the production phase are: i) in the fiber production phase, where various production techniques are used with massive resource, water, energy, and chemical consumption; ii) in the use of land for natural fiber cultivation (a prime example is cotton cultivation); iii) in the fabric processing stage, which generates a significant amount of solid waste and wastewater; iv) in energy use, which is common to all stages of the life cycle (Moazzem et al., 2022). As highlighted in the Circular Economy Action Plan published in 2020 by the European Commission (European Commission, 2020), textiles are the fourth largest sector in terms of raw material and water use (after food, construction, and transport) and the fifth largest in terms of greenhouse gas emissions. The main inputs it uses are mainly non-renewable, such as petroleum for producing synthetic fibers, fertilizers for cotton cultivation, or chemicals for producing, dyeing, and finishing fibers and fabrics. Textile production also uses approximately 93 billion cubic meters of water per year, causing serious problems in regions where this resource is scarce. In 2018, the fashion industry was responsible for approximately 2.1 billion tons of greenhouse gases, equivalent to 4% of global emissions. Of these, approximately 70% can be attributed to upstream activities, such as the production and processing of materials. In 2020, textiles was on average the fifth largest sector in terms of raw material use and CO_2 emissions and the third largest in terms of water and land use (European Environment Agency, 2022). To the consumer use phase, energy and water consumption related to washing, drying, and ironing can be attributed (Moazzem, et al., 2022). The impacts related to the use phase are also considered to be one of the causes responsible for the microplastics released into the oceans, mainly due to clothing made of synthetic fibers, such as nylon, polyester, and acrylic, which are released

during washing (European Commission, 2022). Regarding the end-of-life phase, the textile product supply chain model is still predominantly linear at a global level: according to the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2017), only 13% of clothes that reach the end of their life are recycled, and less than 1% of this material is reused to produce other clothing (Circular Economy Lab, 2022). Most of them (between 50 and 75%) are destined for reuse, while the majority of the rest are recycled into lower quality products (e.g., insulation material in the construction sector, or mattress padding), effectively losing value. The remaining two-thirds of textile waste generated is assumed to end up in mixed urban waste streams for incineration or landfill (Fondazione per lo sviluppo sostenibile, 2022). More recently, the environmental and social sustainability of the textile supply chain has been further and severely compromised by the spread of the 'fast fashion' phenomenon, which has radically transformed production and sales trends. This is a production and distribution approach based on the rapid creation and immediate availability of clothing at minimal cost. The low selling price is the result of unsustainable and highly impactful choices, mainly due to the use of labor in developing countries, where workers' rights are often ignored and there are no effective environmental regulations (European Commission, 2022).

2.3 Extended Producer Responsibility and Circularity in the Textile Industry

2.3.1 The European regulation approach

The consideration of impacts arising from the textile production and consumption on the environment and human health has played an important role in the extensive reference legislation, especially in recent years. In general, Regulation (EU) No 1007/2011 concerning textile labeling and transparency of information should be noted; Regulation (EC) No. 1907/2006 (better known as the REACH Regulation) governing the use of chemicals; Directive 2008/98/CE on waste, which specifically requires Member States to adopt a system for the separate collection of textile waste by 2025. This Directive, amended in 2018 by EU Directive 2018/851, had, among its major changes, the addition of Article 8 bis concerning the general minimum requirements for "Extended Producer Responsibility," a fundamental principle for ensuring the reorganization of the supply chain in a "circular" perspective (Euratex, 2022). The European Green Deal, the Circular Economy Action Plan, and the 2020 Industrial Strategy also assessed the high potential for circularity in the textile sector (Bour et al., 2023), particularly considering the serious repercussions of the Covid-19 pandemic on the European economy, and the 'Next Generation EU' instrument identified the resources for its sustainable recovery. On the basis of these measures, on May 30, 2022, the European Commission adopted the Strategy for Sustainable and Circular Textiles, which provides a framework aimed at

making, by 2030, textile products placed on the European market *"durable and recyclable, largely made from recycled fibers, free from hazardous substances and produced in compliance with social and environmental rights..."* (European Commission, 2022). Specific measures include: i) Introduction of mandatory eco-design specifications; ii) Ending the destruction of unsold or returned textiles; iii) Combating microplastic pollution; iv) Introduction of information requirements and a digital product passport; v) Environmental self-declarations for truly sustainable textile products; vi) Extended producer responsibility and promotion of reuse and recycling of textile waste. Despite the considerable efforts being made by the EU and Member States, textile waste production is tending to grow (European Environment Agency, 2022). In this regard, the European Commission intends to propose a new directive that more strongly regulates the end of life of textile products. The proposal aims to remove regulatory barriers and address market failures by making the requirements clearer, more specific, and more harmonized (European Commission, 2023).

2.3.2 The EPR principle and its application in the EU

The principle of Extended Producer Responsibility (EPR) was first introduced in 1990 (Lindhqvist and Lidgren, 1990) and describes an environmental protection strategy aimed at reducing the product's environmental impact by making the producer responsible for its entire life cycle, including the so-called take back phases, i.e., collection, recovery, and final disposal. The EPR system requires the "Producer" to take responsibility for its products from the moment they are placed on the market until they become waste, through a financial contribution known as an eco-contribution. The Producer must comply with this obligation by financing and organizing a system for the collection, recovery, and recycling of waste generated by the end consumer. The strategy underlying the EPR principle is implemented through the use of administrative, economic, and informational instruments; their synergistic implementation determines its effectiveness. *Table 2.1* summarizes the EPR implementation progress for textiles in some European countries.

Table 2.1 *EPR progress in some European countries*

	Italy	France	Germany	Sweden	Netherlands
National Regulations	NO Draft decree under review	YES Code de l'environnement	NO Position Paper	YES SOU 2020:72-Statute in force since 01/01/2022	SI Decree 14/04/2023 132 – in force since 01/07/2023
Operative EPR system	NO	YES	NO	NO Authorized collection systems starting from 01/01/2024	YES
Textile categories included	Clothing, footwear, accessories, leather goods, and home textiles (draft decree)	Clothing, footwear, household underwear (excluding furnishings, protection, and decoration)	-	Clothing, accessories, products for free time (sleeping bags)	Clothing, products for free time (blankets, sails, and tents)

2.4 Critical aspects, future prospects, and conclusions

Based on the analysis conducted, the two most significant regulatory issues in terms of circular transition in the textile sector are related:

- defining the scope of EPR and identifying the entity responsible for placing products on the market and managing them. One example of this is the extension of responsibility to e-commerce sites, i.e., considering "merchants," or sellers who place a product on the market for the first time, as "producers" as well;
- identifying the owner of second raw materials, which is currently difficult to manage but could become a valuable resource in the coming months.

There are also "structural" issues specific to the sector, such as:

- lack of awareness among certain categories of consumers regarding the sustainability aspects of products (to which the phenomenon of fast fashion continues to contribute);
- lack of/difficulty in controlling products imported from low-cost countries (supply chain fragmentation);
- large number of environmental and social certifications (high degree of heterogeneity);

- potentiation of the sorting phase, since, according to industry estimates, 60% of textile waste can still be reused.

The revision of EU Directive 2018/85 aims to establish mandatory and harmonized EPR systems for all EU countries, with tariffs that will differ based on the level of pollution caused. The goal is to use the contributions paid to finance investments in collection, sorting, reuse, and recycling systems. It also aims to encourage research and technology development to maximize the circularity of the sector, such as fiber-to-fiber recycling, or solutions that can limit the export of textile waste disguised as reusable materials to countries that are not equipped for proper management. In this regard, there are various possibilities for upcycling and downcycling, while as far as waste management is concerned, the sorting phase plays a fundamental role, as reusable garments must be correctly separated from the mainstream, elements such as zips and buttons removed, and garments sorted according to color and/or fiber type. Most of the sorting processes are still carried out manually, but there are also innovations in automatic sorting, with the introduction of machines that operate using spectrometry or artificial intelligence techniques. Among recycling technologies, the most established are mechanical and thermo-mechanical recycling; chemical recycling is under development, while biological recycling, which exploits the action of enzymes, is under study (European Commission, 2021). To estimate the potential environmental impacts of the waste management system, it is important to consider the life-cycle assessments, such as those proposed through the use of the LCA (Life Cycle Assessment) methodology. In scientific literature, most LCA studies on textile waste report reuse as the preferred method. In the study proposed by Sandin and Peters, 2018 which analyzed 41 LCA studies on the subject, it was found that among the main variables influencing the results of life cycle analyses of textile waste management are the efficiency of recycling processes, the modeling of the use phase (number of washes and reuses), the composition of input waste, and the substitution coefficient between recycled fibers and virgin fibers or between a used garment and a new one. In conclusion, the main challenges in circular textile waste management today seem to be linked to the exact identification of responsibilities, the establishment of efficient platforms, and the ability of the most directly involved actors to manage a mix of heterogeneous materials while maintaining the highest possible fiber quality from a circularity perspective.

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CHAPTER 3

Methods and tools for evaluating circular scenarios

The content of this chapter refers to an article presented at the SUN network conference during Ecomondo 2024 ("Supporting the Transition of Italian Industrial Areas and Brownfields into Eco-Industrial Parks and Advancing Industrial Symbiosis as a Routine Management Tool," Rimini, November 6, 2024) and later published in the conference proceedings. The article examines the methodological and operational foundations needed to analyze and model circular scenarios within local supply chains, using the MAX-SHEEP research project as a case study. The project focuses on the sheep supply chain and offers an illustrative example of how circularity must be approached within territorial and sector-specific contexts, where geographical, socio-economic, technological, and product-related conditions vary significantly.

TITLE:

ANALYSING AND MODELLING CIRCULAR SCENARIOS IN LOCAL SUPPLY CHAINS: APPROACHES AND TOOLS WITHIN THE "MAX-SHEEP" PROJECT

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Abstract

The transition towards circular and sustainable economic models (s.c. Circular Economy), requires the commitment of all the actors involved, at technological, social and political level. Although this paradigm is being established at the global level, the actions that characterize it often have local scale and impacts. To ensure that this transition process takes place in a balanced and measurable way, it is necessary to identify useful approaches and tools to define models for the implementation of potential solutions in different contexts, which may differ from a geographic, socio-economic, technological and product-related point of view. This article, through the description of the MAX-SHEEP research project, presents and discusses the results of an overview and systematization of the main tools potentially supporting the development of the different phases of an eco-industrial model of sheep supply chains.

3.1 Introduction

The Circular Economy (CE) concept is rapidly gaining attention in the international debate, having been deemed as the necessary response to the fragility and unsustainability of current economic systems. Mainly, based on reducing, reusing, repairing, refurbishing, and recycling solutions, it is intended to create a closed-loop system that decreases waste while increasing resource efficiency. The transition towards circular production and consumption models concern all actors in the economic world. In these terms, the CE can be considered a strategy and a development opportunity for local supply chains and territorial systems, as it is capable of proposing and fostering new -or renewed- paths of sustainable growth. The process behind will have to be supported by approaches and tools that enable the analysis of contexts, modelling and simulation of closed-loop/circular scenarios solutions at various levels of scale, such as products, processes, supply chains, local systems (Taddeo, 2021; Walker, et al., 2021). Although the CE is now emerging as a new economic paradigm, the strategies implemented so far are mainly sectoral. Holistic approaches and tools, which consider broader aspects as well as system-level perspectives, have been relatively disregarded. From a systemic perspective, the literature and empirical evidence point to a number of important gaps, namely: i) knowledge and representation of the technological, structural and organizational characteristics of the contexts of interest; ii) identification of the most suitable circular approaches, tools and solutions for these contexts; iii) simulation of the effects on the contexts; iv) choice of metrics and indicators to support change decisions (Ritzéna, and Sandströma, 2017). This article presents the preliminary results of the research project "MAX-SHEEP: *Modelling and assessment of circular scenarios in local*

contexts. Applications in the sheep supply chain" which aims to develop a dynamic model capable of supporting the implementation of circular solutions in local sheep supply chains. In particular, the results of a survey and systematization of the main methods and tools potentially able to support, in an integrated way, the development of the various phases of the model under study will be discussed.

3.2 Methods and findings

From a methodological point of view, the MAX-SHEEP research project uses approaches and analysis tools peculiar to Industrial Ecology (IE). The local reference contexts are economic-productive systems, specifically supply chains, whose actors and processes are represented according to a "metabolic" perspective, i.e. in the set of material-energy flows and stocks that characterize them. The aim is to develop a dynamic model that allows these contexts to be represented in an eco-industrial perspective. Furthermore, the purpose is to assess the potential and possible impacts on sustainability (environmental, economic and social), also externally, i.e. at a territorial level, circular solutions implemented in the linear system of reference. The project consists of five steps: i) analysis of the linear supply-chain; ii) identification of circular solutions; iii) modelling; iv) measurement; v) simulation. Its development necessarily requires the support of different types of analysis tools, both typically used in IE studies and borrowed from other areas of research, with multiple functionalities and often overlapping fields of operation. In addition, to the reconnaissance of existing applications, the project aims to assess the possibilities of synergic use aimed at the dynamic representation of scenarios to support change decisions in a circular perspective. The main tools identified at this stage relate to approaches and tools for mapping and representing systems (e.g., Flowchart); material flow analysis (e.g., Material Flow Analysis); methods to support the spatial representation of relationships (e.g., Social Network Analysis); tools for simulating circular scenarios (e.g., System Dynamics Modelling); and life cycle approaches used to assess the environmental, social and economic impacts of products, processes and organizations (e.g., Life Cycle Assessment). The search was conducted using a set of keywords combining the function of the methods with the software terminology (e.g. "software" AND "material flow analysis"). The search returned over 200 results. A total of 172 tools were analyzed, following a refinement phase to exclude duplications and irrelevant results. These were grouped into 11 categories, divided into 4 main fields of application, as described in *Table 3.1*.

Some of these tools were developed with a unique functionality (e.g., GIS and Social Network

Analysis), while others allow for the integration of different functions, although created for a specific purpose. Therefore, from a systemic analysis point of view, the flexibility of some of these tools makes it possible to use a single tool at the same stage, with economic (e.g., software with a license fee) and time-related (e.g., use of a single database, duplication of calculations, etc.) advantages, as well as in the training of recipients and users. In addition, some tools allow for more than one function. *Figure 3.2* shows how, for instance, some tools enable the development of Sankey Diagrams but also network analysis, or scenario simulation or impact assessment. Finally, the analysis shows how some tools are useful in three of the four application areas, while no tool is crosscutting across all of them. The possibility of using only one tool/software could further simplify the development of the model.

Some tools associated with the methods have been developed with a single function (e.g., GIS and Social Network Analysis), while others, although created for a specific purpose, allow for the integration of different functions, as shown in *Figure 3.1*. Therefore, from a systemic analysis perspective, the flexibility of some of these tools allows a single tool to be used in the same phase, with both economic (e.g., software with a paid license) and time-saving advantages (e.g., use of a single database, duplication of calculations, etc.), as well as in the user training.

Table 3.1 *Tools identified to support the project phases*

Fields of application	Tools	Description	Source
Economic-productive systems analysis and representation	Flow chart	*Graphic representation used to represent a sequence of operations. Report the temporal order of events or actions.*	Chapin, 2023
	Sankey Diagram	*It provides a representation of material flows between processes, distinguishing between different sources and their different uses/applications.*	Marques, et al., 2020
	MFA	*It quantifies how materials that feed modern society are used, reused and wasted.*	Graedel, 2019
	IS	*It describes the physical exchange of materials, energy, water and by-products/wastes between companies and/or production sectors through an integrated approach aimed at obtaining mutual competitive benefits.*	Chertow, 2000
Analysis and spatial representation of networks	GIS	*It facilitates the management, manipulation, analysis, modelling, representation and visualization of georeferenced data to solve complex planning and resource management problems through a system of hardware, software and procedures.*	Escobar, et al., 2008
	SNA	*It maps and measures relationships between interacting units (such as organizations).*	Taddeo, et al., 2019
Scenario development	ABM	*It studies the development of dynamic patterns. A way of describing a system of behavioral elements. It allows new agents to be added and behavior, learning, evolution and complexity to be modified by modifying the rules of interaction.*	Zehra, and Urooj, 2022
	SDM	*It represents the structure of complex systems through feedback loops, both material and informational, consisting of stocks, flows and auxiliary variables to explore the causes and consequences of dynamic trends causing concern and design policies to improve systems performance.*	Forrester, 2016
	Scenario simulation	*It assesses the uncertainty of future developments based on current conditions.*	Wang, et al., 2021
Impact assessment	CF, WF	*Measuring, respectively, the greenhouse gas emission that contributes to global warming and the consumption and contamination of freshwater resources.*	Ercin, and Hoekstra, 2012
	LCA, SLCA, LCC	*LCA: assesses the potential environmental impacts of a product system throughout its life cycle. S-LCA: assesses the social and socio-economic aspects of products and their positive and negative impacts along their life cycle. LCC: identifies economic hotspots to potentially reduce product life cycle costs.*	ISO, 2006; Petti, et al., 2018; Hunkeler et al., 2018

LEGEND: MFA: Material Flow Analysis; IS: Industrial Symbiosis; GIS: Geographic Information System; SNA: Social Network Analysis; ABM: Agent-Based Modelling; SDM: System Dynamic Modelling; CF: Carbon Footprint; WF: Water Footprint; LCA: Life Cycle Assessment, LCC: Life Cycle Costing, SLCA: Social Life Cycle Assessment.

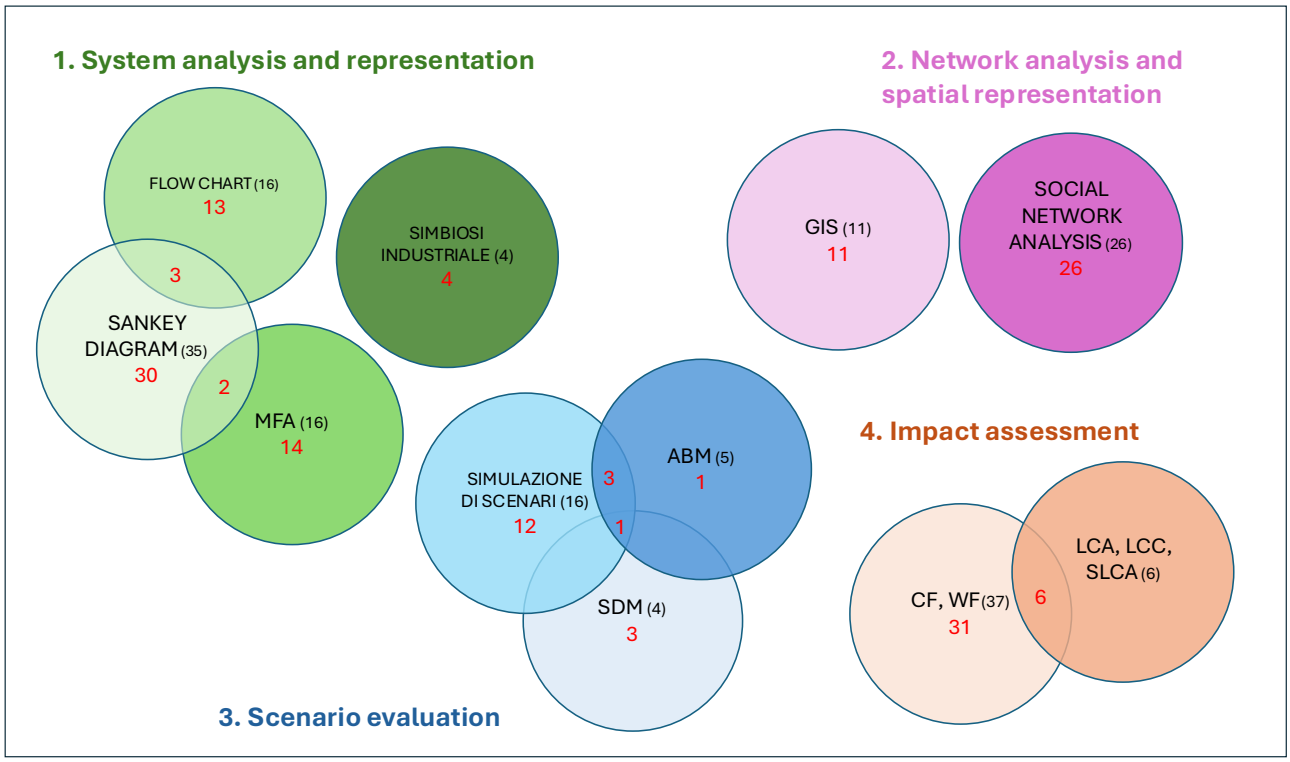


Figure 3.1 *Number of tools identified to support the four areas of operation identified in the project: 1. System analysis and representation; 2. Network analysis and spatial representation; 3. Scenario evaluation; 4. Impact assessment.*

LEGEND: The total number of tools in each category is indicated in parentheses; the number of tools that perform only one specific function or more functions in common with others is indicated in red.

Furthermore, some tools can be used in multiple areas, taking the discussion of integration to a higher and more complex level. Figure 2 shows how, for example, some tools can be used to develop Sankey diagrams, but also network analyses, scenario simulations, or impact assessments. Finally, the analysis shows that some tools are useful in three of the four areas of application, while no tool is applicable across all of them. The possibility of using a single tool/software could further simplify the development of the model.

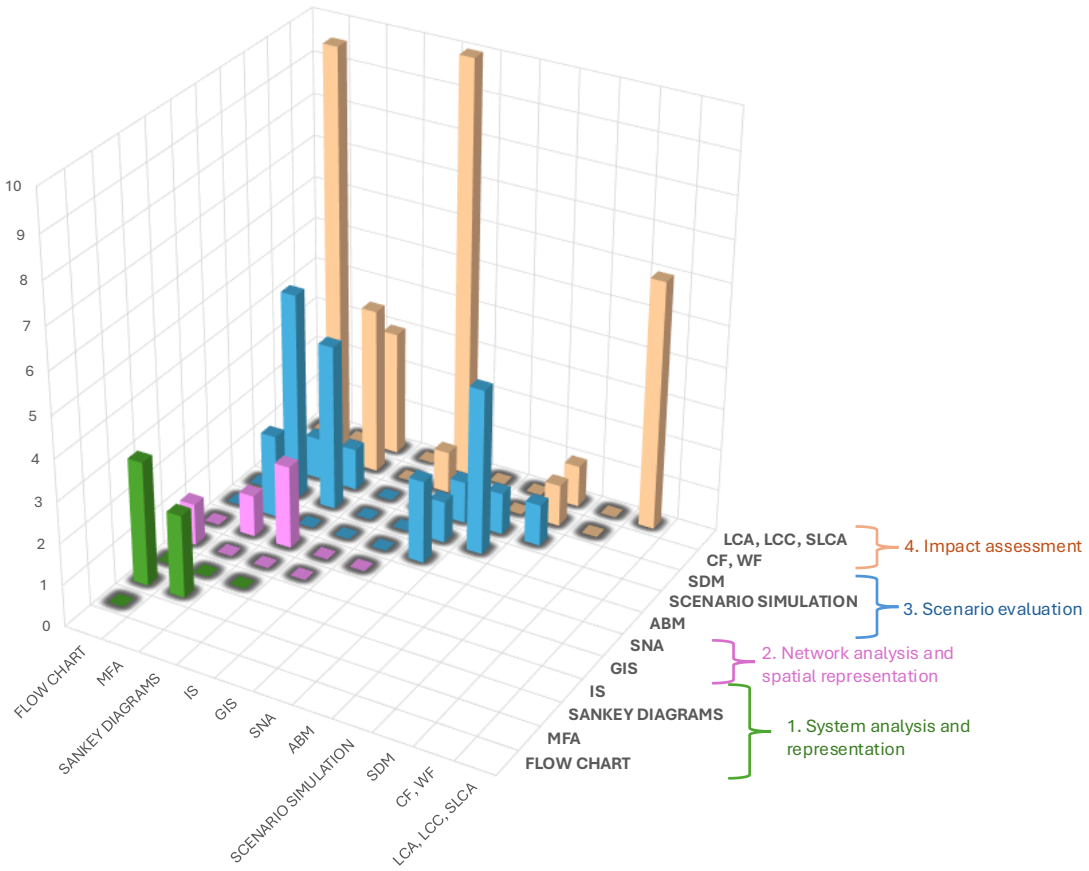


Figure 3.2 *The multifunctionality of the tools for integrated support in the four application areas.*

LEGEND: MFA: Material Flow Analysis; IS: Industrial Symbiosis; GIS: Geographic Information System; SNA: Social Network Analysis; ABM: Agent-Based Modelling; SDM: System Dynamic Modelling; CF: Carbon Footprint; WF: Water Footprint; LCA: LIfe Cycle Assessment, LCC: Life Cycle Costing, SLCA: Social Life Cycle Assessment.

3.3 Conclusions

At present, there are numerous tools from different disciplines, capable of analyzing various aspects of a given system, which can be traced back to the fields of study of CE and can highlight sustainability aspects related to products, processes and, more generally, to economic-productive systems. Several elements of interest emerge from the analysis conducted and open up for further investigation. For instance, some tools, created for different purposes, show areas of functional overlap with others. This highlights the potential with a view to the extension and integration of applications, even though these may, on the other hand, leave room for duplication of analyses. The need to use and implement dynamic tools that elaborate changing scenarios in time and space, such as circular ones, is another issue of great importance. Therefore, given the complexity of the

contexts and the characteristics of the tools analyzed, it is necessary that the models and tools also consider exogenous variables. These aspects, together with the potential for integrated use, represent one of the main areas for further investigation in the next phases of the project.

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CHAPTER 4

Comparing static and dynamic modeling approaches for circular transition

The content of this chapter is based on a paper presented at the Quality, Innovation, Sustainability Symposium, held in Urbino from May 21 to 23, 2025. The extended abstract was published in the conference proceedings, while the full paper is currently under review for publication.
This contribution represents a further step forward in the process of understanding the potential of methods and tools outlined in the previous chapters.
After identifying the main methods and tools supporting circularity (Chapters 2 and 3) and discussing their potential applications, this chapter focuses on the specific features of dynamic models used to evaluate circular scenarios.

TITLE:

MODELING AND EVALUATING CIRCULAR SCENARIOS: INDUSTRIAL ECOLOGY, AGENT-BASED AND SYSTEM DYNAMICS APPROACHES

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Abstract

The concept of Circular Economy has become increasingly popular and has established itself as a reference paradigm for the transition from linear to circular production systems, with the aim of increasing their sustainability. The complexity of such systems requires a multidisciplinary approach, with specific methods and tools to support informed decision-making and implementation of circular solutions. Industrial Ecology (IE) provides strong methodological basis for mapping systems, quantifying and optimizing material and energy flows, identifying solutions and measuring their impacts. However, conventional IE-based modeling approaches do not often capture the dynamics and the multidimensionality of the transition process. To address this limitation, IE studies are increasingly adopting advanced dynamic modeling approaches to improve decision-making. Such approaches allow for the simulation of the temporal evolution of systems and the analysis of how the interactions between external variables, components and actors influence the overall system behavior. This article presents a qualitative analysis highlights how conventional IE-based approaches can be potentially supported by two of the most popular dynamic modeling and simulation approaches in modeling and evaluating circular scenarios: Agent-based modeling (ABM) and System Dynamics (SD). The aim is to improve the exploration of complex scenarios by modeling the relationships between actors, flows and stocks involved, feedback loops and nonlinear dynamics that determine systemic behavior and critical points on which solutions should be focused and the related effects on the system.

4.1 Introduction

One of the most widely agreed definitions of Circular Economy (CE) is that provided by the Ellen MacArthur Foundation, which defines it as *"an industrial system that is restorative or regenerative by intention and design"* (EMF, 2013). This definition highlights the central role of industrial systems, which are the key role in the transition to CE. Over the years, scientific research and several case studies identified concrete strategies and solutions to promote circularity (e.g. the 10R: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover) (Reike, et al., 2022; Yin, et al., 2023). The shift from linear to circular production must be balanced with circular business model needs related to globalization, government regulations, price system, and standard of living of the consumer (Sasso, et al., 2025; Jelinski, et al., 1992). In making informed decisions, it is important to recognize that the world is made up of a set of economic, environmental and social complex systems, closely interconnected and characterized by dynamic interactions that affect their evolution over time (Davis, et al., 2009). The scenario is further complicated when the

problem is analyzed at different levels of scale: micro (company level), meso (supply chain level) and macro (territory level). In this regard, Industrial Ecology (IE) (Jelinski, et al., 1992; Erkman, 1997) provides strong approaches for mapping systems, quantifying and optimizing material and energy flows and identifying critical aspects of a system and related solutions. However, these approaches, which are essentially static, often fail to capture the dynamic complexity and patterns in circular scenarios (Walzberg, et al., 2021). The objective of this article, through a qualitative comparative analysis, is to understand if (and how) conventional IE-based approaches can be supported by dynamic modeling and simulation approaches such as Agent-based modeling (ABM) and System Dynamics (SD), in supporting decision-making related to modeling and evaluation of circular scenarios.

4.2 Methodology

The qualitative comparative analysis (Bolbakov, et al., 2020), mainly based on scientific literature, is structured in two phases: i) description of the main IE-based and dynamic modeling approaches ii) comparison between IE-based and dynamic approaches in modeling and evaluating circular scenarios. The comparison of proposed approaches is based on a set of criteria to highlight differences, complementarities and possible integrations. The criteria have been defined according to IE literature and previous studies conducted by the authors (Wiprächtiger, et al., 2022; Coban, et al., 2024). Through a comparison matrix, pairwise comparisons of approaches (IE-based and ABM; IE-based and SD; ABM and SD) has been conducted. The qualitative relationships considered are: [<] less effective, [>] more effective, [=] similarly effective. Results are discussed highlighting the capability of such approaches to support strategic decision-making in dealing with circular scenarios evaluation.

4.3 Theoretical background

4.3.1 Circular scenarios modeling and evaluation: potential features and needs

In the present study, for "modeling and evaluating circular scenarios" we intend those activities aimed at representing and measuring the effects of the transition of a reference context in which "closed-loop" solutions are implemented (or simulated). Moving on such assumption, the reference context is defined as a socio-economic system, covering the networks of actors, flows and processes involved in the extraction, production, distribution, use and end-of life of goods and services (or part of them). Such contexts may potentially move from a linear to a circular "metabolism", a concept that describes

the way in which resources (material and energy) are extracted, transformed, used and finally returned to the environment (Janssen, et al., 2001) or reintroduced within the system through circular solutions.

In this regard, the functions that a given circular scenarios evaluation approach must be able to perform are (Taddeo, et al., 2017; Simboli, et al., 2020): *identify and analyze the actors involved; map production and logistics processes; identify and quantify material and energy flows; analyze actors networks; adopt a product life-cycle perspective; adopt a multi-scale perspective; include spatial and geospatial dimensions; include time scale and time delays; incorporate internal quantitative and qualitative variables; incorporate external variables; include quantitative and qualitative indicators; import existing databases; simulate and compare short and long term scenarios (with parameters); include environmental, social and economic impacts assessment; be validate and calibrate with statistical methods; be integrated with other decision-making tools; be objective and replicable; be subjected to continuous monitoring and improvement*. Based on the above, the most promising IE-based and dynamic approaches have been selected, and are respectively described in the two following sections.

4.3.2 Static approaches supporting IE

The most popular IE-based approaches (Walzberg, et al., 2021; Wiprächtiger, 2022) selected are the following:

- **Life Cycle Assessment (LCA)**. LCA, among the s.c. life cycle-based approaches (Coban, et al., 2024), is probably the most used for detailed representation of material and energy flows of a given product-system, allowing a rigorous analysis of the potential impacts associated (Bjørn, et al., 2018). An LCA study is carried out in 4 phases (ISO 14040:2006; ISO 14044:2006): i) goal and scope definition, ii) inventory analysis, iii) impact assessment and iv) interpretation. The indicators in the LCA are not included in the basic methodology but are derived from the results of the analysis and are used to quantify the environmental impacts (such as the recycling rate or CO_2 emissions). They help to summarize the data, evaluate sustainability and identify areas for improvement. LCA metrics represent numerical values that quantify the environmental impacts and resources used during the entire life cycle of a product or service. They can be of different entities based on the objectives and context of the analysis (e.g. emissions of CO_2 (kg CO_2 equivalent), water usage (liters), energy consumption (MJ or kwh) waste generation (kg or tons)). LCA is characterized by high standardization, database availability, methodological robustness and acceptance by the scientific and regulatory community. However, it is a static approach, based on mixed data (primary and

secondary), which does not simultaneously consider all three dimensions of sustainability and often does not consider temporal variations.

- **Material Flow Analysis (MFA)**. MFA is useful for tracing material flows within a defined system, providing a detailed quantitative picture of material inputs, stocks and outputs (Baars, et al., 2022). This approach consists of several key activities, including (Khlifa, et al., 2024; Graedel, 2019): i) definition of the objectives of the study; ii) system definition (determination of system boundaries, selection of material, selection of processes); iii) determination of flows; iv) data collection and compilation; v) calculation of mass flows and stocks; vi) illustration and interpretation of results; and vii) use of statistical approaches to evaluate the uncertainty and sensitivity of the model, taking into account the availability of data. Metrics in MFA are used to measure material flows, providing quantitative data that helps identify hot-spots and evaluate opportunities for improvement in the analyzed system, in terms of efficiency. Indicators are not directly included in the MFA but are calculated from the material flows that are identified during the process (e.g. the recycling rate or the efficiency in the use of resources). MFA conventional approach often assumes steady-state conditions, without capturing dynamic changes in material flow networks (e.g. what happens if raw material prices increase) (Fischer-Kowalski, et al., 2021).

- **Environmentally Extended Input-Output Analysis (EEIOA)**. EEIOA is an approach that allows for a quantitative examination of the relationships between inputs and outputs within an industrial system, focusing on the connections between economic sectors (Leontief, 2018). This approach includes many key activities: i) definition of the objective and scope of the study; ii) collection of input-output tables; iii) collect environmental data; iv) construction of the technical coefficients matrix; v) construction of the environmental extensions matrix; vi) calculation of total environmental impacts; vii) analyzing and interpreting the results; and viii) validation of results. EEIOA is useful for evaluating environmental impacts at a macroeconomic level, considering the direct and indirect effects of one sector on others. However, the technological characteristics are aggregated, making it impossible to analyze specific products or companies in detail. There is a lack of information on time dynamics, such as the future availability of materials for reuse and databases tend to be old, excluding e.g., emerging sectors such as the sharing economy. Furthermore, the conventional EEIOA approach does not consider unexpected events such as economic or environmental shocks and focuses mainly on environmental impacts and the economic interconnection between sectors.

4.3.3 Dynamic modeling and simulation approaches

The most popular dynamic modeling and simulation approaches (Walzberg, et al., 2021) selected are the following:

- Agent-Based Modeling (ABM). The evolution of Agent-based modeling (ABM) is closely linked to the theory of complex systems, which explores how simple interactions can generate complex behaviors. This theory has allowed for a better understanding of dynamic phenomena in social, economic and natural systems. With the advent of computer simulation, it has been possible to model autonomous agents that interact with each other and with the environment. ABM has overcome the limits of traditional approaches enabling the study of emerging phenomena, such as the evolution of social norms and market dynamics, (Macal, 2016) and the analysis of emergent behavior of a system through the interaction of autonomous entities, called agents. Each agent has defined rules of behavior, can interact with other agents and with the surrounding environment and can adapt or evolve in response to changing conditions (Macal, and North, 2009). ABM consists of several key activities, including (Macal, and North, 2011; Helbing, 2012; Ding, et al., 2018): i) definition of the model purpose; ii) definition of the boundaries of the model and the main variables; iii) definition and selection of agents; iv) identification of agent data; v) formulate hypotheses on the system's mechanisms; vi) identification of the behavior of the agents; vii) definition of the interactions of the agents; viii) set the initial values for the variables; ix) simulation; x) verification, calibration and validation of the model; and xi) scenario planning. To better understand the distinctive characteristics of this approach, it is useful to examine the key elements considered in the development of an agent-based model, as reported in *Table 4.1.*

Table 4.1 *Agent-based model elements. Based on (Macal, and North, 2011; Helbing, 2012; Ding, et al., 2018)*

ABM Element	Description	Roles
AGENTS (VARIABLES)	autonomous entities that make decisions and act according to rules	role of subjects in the system
AGENT ATTRIBUTES (PARAMETERS OR VARIABLES)	specific characteristics of the agents (e.g. age, preferences) that influence their behavior	influence the decisions of the agents and their interactions with other agents
BEHAVIORAL RULES (PARAMETERS)	define how the agents make decisions and interact with each other based on internal and external variables	guide the evolution of the agents' behavior
SYSTEM VARIABLES (INDICATORS)	aggregate variables that represent the overall state of the system (e.g. population, global resources)	provide an overview of the overall behavior of the system and monitoring the evolution of the model over time
ENVIRONMENT (VARIABLES)	context in which the agents operate, which can evolve over time (e.g. resources, external conditions)	modifies the dynamics of the system, creating opportunities or limitations for the agents and influencing their actions
METRICS	quantitative measures used to monitor the progress and performance of the system or agents	used to monitor the performance of the system or the agents
FEEDBACK LOOPS	feedback mechanisms that influence behavior in the system	represent the continuous flow of information that regulates the behavior
INDICATORS	measures that represent the overall trend of the system or specific phenomena in the model	used to analyze the evolution and results of the system over time
EXTERNAL EVENTS (VARIABLES OR PARAMETERS)	exogenous factors that influence agents, but are not directly determined by the model (e.g. regulations)	create external shocks or changes in the basic conditions, which alter the behavior of the agents
PARAMETERS	fixed or variable factors that define the structure of the model (e.g. probability, growth rates)	define the basic conditions for the behavior of the agents

In its broader meaning, ABM also consists of simulating the interactions between individuals and entities, providing a framework for testing hypotheses. It is modular, flexible and expressive, and can link micro and macro dynamics, improving understanding of emerging phenomena and enabling rigorous testing, making it a useful approach for socioeconomic analysis (Helbing, 2012). However, it has disadvantages: simulation requires high energy consumption and computational power, especially with many agents or high complexity; computation time can be long; calibration and validation are costly because they require detailed empirical data and sophisticated methods; design

is complex and requires advanced skills; and uncertainty in agent behavior and environmental conditions can reduce the accuracy of predictions.

- System Dynamics (SD). Another widely used approach for studying complex systems is System Dynamics (SD), developed by Jay W. Forrester in the late 1950s and early 1960s at the Massachusetts Institute of Technology (MIT). The goal of SD is to explore the dynamics of complex systems by modeling feedback relationships between variables (Forrester, 1993). It focuses on analyzing the evolution of a system over time, assuming that behavior emerges endogenously from internal interactions. It draws on fundamental theories such as General Systems Theory, Feedback Theory, and the principles of lags and nonlinearity to identify the dynamics that cause problems in the system, providing a basis for targeted solutions. In SD, systems are generally considered causally closed, where each action is influenced by the results of previous actions, implying that the causes of behavior reside in the system itself. To represent the structure of a system, SD uses two main types of diagrams: i) Causal Loop Diagrams (CLDs), which highlight causal relationships and positive and negative feedback loops, and ii) Stock-and-Flow Diagrams (SFDs), which describe the flow of resources between accumulation (stocks). SD consists of several key activities, including (Pruyt, 2013; Meadows, 2008; Bala, et al., 2016; Ding, et al., 2018): i) problem identification and goal definition; ii) definition of the boundaries of the model and the main variables; iii) construction of the qualitative conceptual model of the system's mechanisms and feedback (CLDs) – develop dynamic hypothesis; iv) construction of the quantitative conceptual model of the system's mechanisms and feedback (SFDs); v) construction of the mathematical model; vi) simulation; vii) verification, calibration and validation of the model; viii) policy analysis. To better understand the distinctive characteristics of this approach, it is useful to examine the key elements considered in the development of an SD model, as reported in *Table 4.2*.

Table 4.2 *SD model elements. Based on (Pruyt, 2013; Meadows, 2008; Bala, et al., 2016; Ding, et al., 2018)*

SD Element	Description	Roles
CAUSAL VARIABLES	variables that represent the structure of the system	make cause-and-effect relationships explicit, identify feedback loops, support quantification in SFD and identify leverage points
AUXILIARY VARIABLES	intermediate variables that derive from other variables	provide additional details about the dynamics of the system
STOCK	variables that represent accumulations in the system	memorize the state of the system over time and influence the dynamic behavior of the model
FLOW	variables that regulate the stock change over time, defining the rates of entry and exit	determine the rate of stock change and control system transitions
EXTERNAL VARIABLES	variables that influence the system but are not determined by the model itself	define the boundaries of the system and influence internal dynamics
FEEDBACK LOOP	circular relationships between causal variables	determine the overall dynamics of the system
DELAYS	system elements that represent the time required for an action to produce effects in the system	introduce delay dynamics in system responses, contributing to behaviors such as oscillations or instability
PARAMETERS	constant or predefined values that influence the behavior of the system	define the structural conditions of the model and allow simulation of different scenarios
PERFORMANCE INDICATORS (KPIS)	synthetic measures that evaluate the effectiveness of the system	allow monitoring goal achievement and compare scenarios
LEVERAGE POINTS	variables on which a small change can have a significant impact on system behavior	tools to identify effective intervention strategies for system change
OUTPUT METRICS	values derived that quantify specific aspects of system behavior	help in interpreting simulation results

SD helps understand how small changes in a system can influence the system itself over time (feedback loops), being useful for understanding long-term effects. It facilitates the observation of the interaction between variables over time, revealing dynamics not evident in a conventional static analysis. Because it focuses on aggregate variables, large-scale, complex systems can be simulated without detailed data for each element (Ding, et al., 2018). However, creating SD models is complex and requires significant resources in terms of time and expertise, especially for highly articulated systems. The use of aggregate variables is often based on simplifications that may not fully reflect

reality. In addition, validation is difficult as it requires complete and reliable historical data which are often unavailable. Based on these considerations, it can be said that SD is effective in macroeconomic analysis, but less suitable for capturing microeconomic dynamics, such as the individual behavior of the actors involved.

4.3.4 Recent developments of ABM and SD in IE studies

Over the years, several researchers have conducted studies on the integration of traditional IE-based approaches with advanced modeling and simulation approaches, with the aim of enriching the conventional static assessment of environmental, social and economic performance and better informing decision-making (Walzberg, et al., 2023). For example, Davis et al., 2009 conducted a study on the integration of Life Cycle Assessment (LCA) into ABM to provide environmental information on the evolution of an energy infrastructure system; Baynes et al., 2009 propose to enrich IE-based approaches used for the analysis of urban contexts, with the use of dynamic approaches such as ABM and SD; more recently, Mohagheghian et al., 2021 developed a hybrid simulation-optimization approach based on systems dynamics for sustainable product design; Walzberg et al., 2023 analyzed and discussed the results obtained from the application of ABM to study the techno-economic and social conditions that favor circularity and sustainability; Anane et al., 2023 use ABM and SD to analyze the complexity of interactions between companies in industrial symbiosis, with a specific focus on the impact of transportation on resource exchange; Corona et al., 2024 combine LCA with ABM and SD to better evaluate circular packaging systems by modeling consumer behavior and the interactions between different actors; Rizzati et al., 2024 conduct a systematic review of the literature on the use of ABM in CE, identifying three key areas (producers, consumers, and the diffusion of innovation) and highlight the potential of ABM to better understand the impact of heterogeneity and behavioral interactions in CE systems; Bhanu Pratap et al., 2024 develop a SD model to analyze the complexity of raw material recovery from end-of-life lithium-ion batteries.

4.4 Comparing static and dynamic approaches

Table 4.3 shows the results of the comparative analysis. The table compares the three approaches discussed above - IE-based, ABM and SD - based on the criteria defined as the relevant aspects for the modeling and evaluation approach to circular scenarios. To facilitate understanding, the second line is explained:

- *IE-based and ABM:* IE-based > ABM means that, according to the *Map production and logistics processes* criteria, IE-based approaches (such as LCA, MFA, and EEIOA) are more effective than the

ABM approach. The IE-based approaches, in mapping production processes, offers more in-depth and precise analysis than the ABM approach.

- *IE-based and SD:* IE-based > SD indicates that IE-based approaches are more effective even than SD approaches regarding *Map production and logistics processes*. This implies that the IE-based approaches are considered more suitable for representing production processes than dynamic system models.

- *ABM and SD:* ABM < SD means that, for the selected criteria, ABM is less effective than SD. The SD approach is more useful and powerful in mapping production processes than the ABM approach (especially for the use of SFDs).

Table 4.3 *Comparison Matrix*

CRITERIA (based on Taddeo, et al., 2017 and Simboli, et al., 2020)	IE-based and ABM	IE-based and SD	ABM and SD
Identify and analyze the actors involved	IE-based < ABM	IE-based > SD	ABM > SD
Map production and logistics processes	IE-based > ABM	IE-based > SD	ABM < SD
Identify and q*uantify material and energy flows*	IE-based > ABM	IE-based > SD	ABM < SD
Analyze actor networks	IE-based < ABM	IE-based > SD	ABM > SD
Adopt a product life-cycle perspective	IE-based > ABM	IE-based > SD	ABM < SD
Adopt a multi-scale perspective	IE-based < ABM	IE-based < SD	ABM = SD
Include spatial and geospatial dimensions	IE-based < ABM	IE-based < SD	ABM > SD
Include time scale and time delays	IE-based < ABM	IE-based < SD	ABM < SD
Incorporate internal quantitative and qualitative variables	IE-based < ABM	IE-based < SD	ABM = SD
Incorporate external variables	IE-based < ABM	IE-based < SD	ABM = SD
Include quantitative and qualitative indicators	IE-based < ABM	IE-based < SD	ABM = SD
Import existing databases	IE-based < ABM	IE-based < SD	ABM = SD
Simulate and compare short and long term scenarios (with parameters)	IE-based < ABM	IE-based < SD	ABM < SD
Include environmental, social, economic impacts assessment	IE-based > ABM	IE-based > SD	ABM < SD
Be validate and calibrate with statistical methods	IE-based > ABM	IE-based > SD	ABM < SD
Be integrated with other decision-making tools	IE-based < ABM	IE-based < SD	ABM = SD
Be objective and replicable	IE-based > ABM	IE-based > SD	ABM = SD
Be subjected to continuous monitoring and improvement	IE-based < ABM	IE-based < SD	ABM = SD

The results of the qualitative comparative analysis show that IE-based approaches (LCA, MFA, EEIOA) are in general more effective for rigorous quantification, objectivity and replicability of the study and impact assessment, but lack temporal flexibility in actors modeling and interactions simulation. ABM is the best approach for modeling and simulation actors and interaction networks. However, it is focused on micro-level dynamics (actors and interactions). SD is the best approach for dynamic and temporal analysis, with a good compromise between flexibility and structure. However, it is focused on macro-level dynamics, considering aggregate variables. Furthermore, the exclusive use of IE-based approaches may be limited in the context of one specific dimension of sustainability. As socio-economic and environmental systems are characterized by non-linearity, response lags, and emergent behaviors, the support of dynamic approaches such as ABM and SD becomes crucial to capture the complexity and temporal variability of the phenomena under analysis. While IE-based static approaches provide an accurate and comparable picture of a system at a given point in time, ABM and SD approaches enable the modeling and simulation of future scenarios, the assessment of the impact of long-term policies, and the adaptive dynamics of socio-technical and environmental systems.

4.5 Discussion and conclusions

The results of this qualitative analysis provide further insights, highlighting the potential and limitations of the IE-based approaches conventionally used to model and evaluate circular scenarios. The evaluation of circular scenarios requires a systemic and integrated approach. Only through a holistic perspective is it possible to identify effective strategies and promote a balance between economic efficiency, environmental protection and social well-being. To identify where and how to implement “closed-loop” solutions and measure the effects of such transformations, appropriate approaches, methods, tools and indicators are needed to support decision-making. An effective approach must be able to consider several key aspects, which determine its ability to provide a comprehensive and operational analysis. In the literature, the integration of ABM and SD approaches is an area of growing interest, because it combines the advantages of macrostructural modeling with the ability to represent emerging behaviors at the micro level. This leaves space to analyze in depth how IE-based, ABM and SD approaches can be considered simultaneously, overcoming the limits of each approach and promoting a more dynamic and complete analysis of the issues related to circular scenarios modeling and evaluation. The same applies to some digital transition approaches and tools. For example, recent studies aim to understand also how to integrate Artificial Intelligence (AI) techniques with ABM and SD. Platas-López et al., 2023 propose the integration of Machine Learning (ML) tools in the different phases of the ABM modeling and simulation process as a solution to

critical steps, such as design complexity, difficulty in parameter calibration and interpretation of results. Rahmandad et al., 2025 instead propose an innovative approach to estimate the parameters in complex systems dynamics models, integrating the Amortized Bayesian Inference (ABI) methods with SD. Using Neural Posterior Estimation (NPE), the authors train neural networks on synthetic data to estimate the parameters of the models. AI proves to be a very powerful support not only for simplifying and optimizing the phases of model construction and simulation, but also for the continuous improvement in the application of CE strategies, thanks to its ability to manage and analyze large volumes of data from heterogeneous sources in real time. In this context, AI can improve the accuracy of forecasts, identify hidden critical environmental, social and economic issues and dynamically adapt to changes in the data, allowing for more effective and proactive management of the simulated systems. Furthermore, the use of advanced ML techniques can significantly reduce the margin of error in simulations and improve the understanding of the interactions between variables in the long term. The analysis conducted has some limitations, mainly related to the qualitative nature of the study. To overcome these limitations, future research developments could include an in-depth quantitative study, aimed at comparing the approaches examined in this article in a more systematic and analytical way.

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CHAPTER 5

An integrated decision-support framework for circular transition

The content of this chapter is derived from an article developed during the third year of the PhD program, conceived as a final contribution to the research project. The first part of the chapter, up to the presentation of the theoretical framework for a CE-oriented Decision Support System, has been accepted as a contribution to the 7th International Conference on Quality Innovation and Sustainability (ICQIS 2026), held at South East Technological University (SETU), Waterford, on June 10th–12th, 2026. The remaining part of the chapter extends this contribution and is structured as a scientific article with the aim of future submission.
The chapter proposes a reference framework that illustrates how Information and Communication Technology (ICT), Artificial Intelligence and static and dynamic methods explored in previous chapters, can be integrated to provide an overview of the information flow management required for simulation-based decision support systems in circular scenario evaluation.

TITLE:

TOWARDS CLOSED-LOOP PRODUCTION SYSTEMS: THE ROLE OF ICT AND ARTIFICIAL INTELLIGENCE TECHNOLOGIES IN SUPPORTING DECISIONS THROUGH CIRCULAR TRANSITION

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Abstract

The transition to a Circular Economy (CE) requires a redesign of production systems, a process that introduces a high degree of complexity in decision-making and requires the integrated management of various types of variables such as technical, economic, environmental, and social ones. This complexity makes information flow an essential component of eco-industrial systems, since the management of this information ensures transparency, traceability, coordination among the actors involved, and data-driven decision-making. In this regard digital infrastructures that can manage information flows and support -data-driven, adaptive, and circular-oriented- decision-making becomes crucial. Information and Communication Technology (ICT), particularly that of Industry 4.0, plays a strategic role in the collection, integration, and valorization of data throughout the entire product life cycle. Artificial Intelligence (AI) further contributes by enabling advanced data-analysis and interpretation capabilities that can support informed and timely decision-making processes. A complementary role is played by methodologies and tools for modeling and simulating production systems, including Life Cycle Assessment (LCA), Material Flow Analysis (MFA), System Dynamics, and Agent-Based Modeling, which support the representation of system complexity and the evaluation of alternative scenarios. However, it remains unclear how Industry 4.0 enabling technologies and scenario evaluation methodologies can be effectively integrated into a circular-transition-oriented Decision Support System (DSS). With the aim of understanding how Industry 4.0 technologies and well-established methodologies for evaluating production systems can be integrated, this article investigates how these can interact to enable more informed and circularity-oriented decisions. After an initial literature review aimed at analyzing how information flow can be managed and improved through Industry 4.0 ICT technologies, the article proposes a theoretical reference framework for a CE-oriented Decision Support System. It also presents a practical test on the use of AI integrated into advanced dynamic modeling software to highlight the role of technology in supporting decision-making.

5.1 Introduction

In recent years, growing awareness of environmental challenges and the urgent need to reduce the impact of human activities have led researchers, policymakers, and businesses to explore new possibilities for more sustainable economic development. In this context, the interdisciplinary field of Industrial Ecology (IE) has established itself as a systemic approach aimed at optimizing the management of material and energy flows within production systems, inspired by the functioning of natural systems, which are extremely efficient and in which the concept of waste does not exist (Graedel and Allenby, 2010). In this perspective, concepts such as Industrial Symbiosis (IS) and,

more recently, Circular Economy (CE) aim to promote a regenerative economy through more efficient resources use and increased interconnection between businesses, sectors, and territories, promoting closed-loop cycles and waste reduction (Chertow, 2000; Saavedra, et al., 2018; Casolani, et al., 2025a). In this context, the units of analysis are defined as eco-industrial systems, i.e., complex industrial systems in which strategic and operational decisions relating to designing, managing, and optimizing material, energy, and information flows play a crucial and highly complex role in addressing sustainability challenges. They require the concurrent consideration of multiple variables -economic, environmental, technological, and social- and the ability to assess the interdependencies between systems and actors at various levels of scale (micro, meso, and macro) (Geissdoerfer et al., 2025). This complexity inevitably requires an interdisciplinary and systemic approach, as well as the adoption of technologies, methods, and tools that contribute to informed decision-making regarding the implementation of certain CE solutions. From this perspective, information flow management plays a strategic role as a structural component of the eco-industrial system. This component directly influences the system's capacity for learning, adaptation, and innovation. Thus, there is a need to define integrated information architectures that can connect and transform heterogeneous data from different sources into useful information. This information can then support the identification and implementation of context-specific CE solutions. In this regard, Industry 4.0 digital technologies play a very important role. The essence of Industry 4.0 is the integration of data originating from people, machines, and systems throughout the entire supply chain, made possible by intelligent, real-time interconnection between physical objects, and digital environments. This integration is enabled by the combined use of technologies such as the Internet of Things (IoT) and Cyber-Physical Systems (CPS), which enable autonomous communication between devices, products and services. In this context, the products themselves become active players in the production process, equipped with detection, processing, and decision-making capabilities, able to monitor their own status and interact with the surrounding environment. The result is the continuous synchronization of the virtual and real worlds (Kagermann et al., 2011; Stock et al., 2018). This synchronization enables the optimization of processes, increased production flexibility, and the development of new business models based on data value and system autonomy in decision-making (Oztemel and Gursev, 2018; Kumar et al., 2021). Industry 4.0 ICT also enables the collection and processing of large volumes of data, modeling and simulating alternative scenarios, and providing quantitative and qualitative information to facilitate the transition to more circular and sustainable production models. In fact, at the European level, the importance of Industry 4.0 ICT is part of the broader twin transition framework, combining the green and digital transitions (European Commission, 2020; Arnold et al., 2023). In this framework, digitalization is recognized as a key driver that accelerates the ecological transition, positioning

sustainability as the primary strategic objective toward which technological innovation should be directed. In the twin transition, eco-industrial systems become a privileged field of application, where technologies such as Artificial Intelligence (AI) and machine learning, IoT, and big data analytics can support the redesign of more efficient, interconnected, and resilient industrial systems and support data-driven decision-making processes that advance CE, digital innovation and sustainability. Among the various emerging technologies, AI plays a central role in enhancing decision-making capabilities, as it can support modeling complex scenarios, analyzing predictive material flows, optimizing symbiotic networks, and assessing environmental, economic, and social impacts. Through machine learning techniques and optimization algorithms, it is possible to identify patterns of interaction between companies, suggest Industrial Symbiosis (IS) strategies, or predict the effects of applying certain circular solutions at different levels of scale. At the same time, AI-based modeling approaches can benefit from being combined with System Dynamics approach, which is specifically aimed at representing how interconnected variables evolve and influence each other within different scenarios.

After conducting a literature review (*Section 5.3.1*) to understand how ICT-based decision-making support is addressed in IE, CE, and IS studies, and to examine the role of modeling and simulation (*Section 5.3.2*), the work focuses on analyzing AI applications and their potential contribution (*Section 5.3.3*). Based on this review, an interpretative framework for integration is proposed (*Section 5.3.4*). Finally, *Section 5.3.5* presents an application example developed with proprietary System Dynamics software, which is useful for discussing the potential and limitations of AI-based modeling approaches in supporting decisions.

5.2 Methodology

The research was divided into three main phases: (i) in the first phase, a literature review was conducted with the aim of identifying the main reviews on the topic. The search was carried out using the Scopus database (Elsevier, 2025), applying the following query: ((“industrial ecology” OR “circular economy” OR “industrial symbiosis”) AND (“ICT” OR “information communication technology” OR “digitalization” OR “digitalization” OR “industry 4.0”) AND (“decision support” OR “decision making” OR “decision support system”)). The search was conducted on titles, abstracts, and keywords and returned a total of 248 documents published between 2014 and 2025. Among these, documents classified as review articles (28 in total) were selected (*see Table 5.1*); (ii) the second phase explored the role of AI by adding the search criterion ‘AND (“artificial intelligence”)’ to the previous query. This extension returned a total of 53 documents, including 10 review articles. The latter were analyzed in detail to identify the main approaches, methods, and applications of AI in decision support in eco-industrial systems. All selected literature reviews were analyzed to

reconstruct the proposed theoretical framework. Finally, (iii) the third phase presents an example of an AI-based decision-making software, with the aim of showing how such technologies can be applied. By combining dynamic modeling with the predictive and adaptive power of AI, the software enables the creation of a tool capable of learning from data, continuously validating its assumptions, and supporting more informed decisions. This approach facilitates scenario analysis and the evaluation of alternatives.

5.3 Results

5.3.1 Digital technologies and decision-making processes

The literature studies analyzed (*Table 5.1*) highlight how strategic decisions towards circularity depend strongly on the system being analyzed (reference production sector, technological maturity, socio-economic context, etc.) (Oyedun et al., 2025; Madkhali et al., 2025; Beducci et al., 2025; Wagner et al., 2025; Bevere and Daccilongo, 2024; Gibbin et al., 2022; Roy et al., 2021). This makes the collection, integration, and interpretation of real-time data essential to obtain useful knowledge for making informed and timely decisions. In fact, in the context of CE, information refers to processed and accessible data that decision-makers can use to make informed decisions and evaluate different CE solutions across multiple scenarios (Wagner et al., 2025; Yu et al., 2022(a); Sahu et al., 2021). Industry 4.0 technologies facilitate the creation and management of this information (Ramirez-Marquez et al., 2024; Akbari et al., 2023). For example, Tavana et al. (2022) show through text mining and semantic network analysis that the most common digital technologies associated with CE are *big data analytics*, *blockchain*, *Internet of Things*, *artificial intelligence*, and *machine learning*. These technologies promote transparency, integration, and flexibility in supply chains (Provensi et al., 2024), improving demand forecasting, inventory management, and resource optimization. IoT, in particular, enables connectivity and traceability, while blockchain ensures security and trust in distributed information flows. According to Ciano et al. (2025), Industry 4.0 technologies support the circular transition through two complementary paths, one managerial and one operational. At the managerial level, technologies such as simulation, IoT, cyber-physical systems, big data analytics, and AI support the choice of the most appropriate CE solution (e.g., 10R). At the operational level, on the other hand, technologies such as augmented reality, virtual reality, and additive manufacturing enable the concrete implementation of CE strategies, e.g., for repair or recycling. The authors emphasize that digital technologies can simultaneously contribute to testing multiple circular solutions, reinforcing synergies between production processes and sustainability objectives. Sajadieh et al. (2025) expand this horizon by presenting Digital Twin (DT) as an advanced technology for informed decision-making in CE contexts. DT, thanks to their ability to create dynamic virtual

replicas of physical systems, enable real-time monitoring, forecasting, and optimization. The authors introduce the concept of "lifecycle intelligence" enabled by DTs, which, unlike traditional methodologies such as Life Cycle Assessment (LCA), provides continuous feedback that can improve circularity choices in relation to the responsiveness of the production system. Integration with generative AI opens the way to automated design and the production of synthetic data for training predictive models, accelerating innovation and reducing costs (Sajadieh and Noh, 2025; Cortes Pellicer et al., 2025; Okafor et al., 2025; Mannan et al., 2025). Furthermore, Akbari et al. (2023) explore the fundamental role of Edge Computing as an emerging technology that represents a significant change from traditional cloud computing, introducing a new paradigm of distributed processing operating at the edge of the network. The principle behind this approach is to bring computing capabilities closer to the source of the data. In traditional computing architectures, data is sent to centralized processing centers, resulting in latency issues, increased bandwidth consumption, and high costs. Edge Computing aims to overcome these challenges by enabling real-time data processing directly at the edge of the network, where the data originates. This is a potential solution for handling the enormous amounts of data created by IoT devices and sensors.

5.3.2 Modeling and simulation

Some authors show how the integration of modeling and simulation with digital technologies improves the resilience of supply chains. For example, Yuniarti et al. (2025) highlight that decision-making systems based on IoT and metaheuristic optimization algorithms enable the adaptive reconfiguration of supply chains, while requiring reliable data flows and robust algorithms in conditions of uncertainty. In the context of waste management according to CE principles, Seyyedi et al. (2024) propose a conceptual simulation model that integrates IoT and digitalization. The waste management system is modeled as a set of interconnected processes whose evolution over time is influenced by variables such as sensor accuracy, recycling capacity, and waste generation rate. Sensors are modeled using probabilistic parameters, allowing for the simulation of realistic scenarios and for assessing the impact of real-time data collection on strategic decisions. This approach provides a virtual decision support platform that is useful for testing alternative strategies before their actual implementation. In the construction sector, Yu et al. (2022b) propose an integrated approach that combines Building Information Modeling (BIM), Geographic Information System (GIS), IoT, big data, blockchain, LCA, Material Flow Analysis (MFA), and Agent-based Modeling, creating a predictive simulation and decision support framework. This approach enables the exploration of hypothetical scenarios and the evaluation of the evolutionary performance of systems, providing a quantitative basis for CE planning and strategies. In this study, we share the approach of Yu et al.

(2022b) and define modeling as an activity aimed at mapping and representing a system, highlighting its constituent elements and the relationships between them. On the other hand, simulation refers to techniques that make it possible to analyze the evolution of a system over time and make predictions by integrating the dynamic component. These include Agent-based Models and Simulations and System Dynamics (SD), which enable "what-if" analyses, testing alternative scenarios, and assessing impact of different variables on system behavior. (Casolani, et al., 2025b). Also, Mustafee et al. (2021) highlight how simulation supports complex decisions, enabling sensitivity and "what-if" scenario analyses on key performance indicators, and emphasize the importance of hybrid approaches that integrate simulations with engineering methods, soft operations research, and software engineering, considering the life cycle of distributed models, reusability, agile development, and documentation. For supply chain stakeholders, the use of distributed simulation systems enables the selective sharing of data and models. This approach protects the privacy of sensitive information while leveraging non-sensitive data to improve overall supply chain management. However, except for a few studies that consider these aspects as parameters within their conceptual models, the way in which variables of different types can be integrated, and analyzed simultaneously, remains largely unexplored. This aspect is particularly relevant in highly dynamic contexts, where decisions must be continuously adapted to sudden changes, such as regulatory changes, variations in raw material prices, or fluctuations in market demand, which require a high capacity for adaptation and systemic management of economic, environmental, and social variables. In this regard, SD makes it possible to represent and understand the interaction and evolution of these variables over time (Ciano et al., 2025). This enables the modeling of complex systems through causal relationships and feedback mechanisms, providing effective support for the analysis and simulation of different CE solutions (Casolani, et al., 2025b).

Table 5.1 *Overview of reviewed studies, including references and key focus areas*

Documents	*Study Focus*
Sajadieh and Noh, 2025	*Adoption of Digital Twins in CE strategies through two interrelated frameworks: one enabling data acquisition, real-time monitoring, and AI-enabled decision-making aligned with CE principles and Industry 4.0 capabilities; the other structuring the integration of enabling technologies such as AI, IoT, and edge/cloud computing to support closed-loop control*
Oyedun et al. 2025	*Technological advancements in circular manure management practices*
Yuniarti et al., 2025	*Design of sustainable and resilient supply chain networks*

Madkhali et al., 2025	*Exploration of electronic waste inventory and management practices through the use of distributed systems*
Beducci et al., 2025	*Identification and characterization of the linkages between digital technologies, services, and sustainability strategies within the context of servitization*
Wagner et al., 2025	*Analysis of circular economy barriers in the electronics sector, identifying information gaps along the product lifecycle and discussing the potential and limitations of digital product passports to overcome these barriers*
Ciano et al., 2025	*Development of a comprehensive integration framework based on the 10R principles, providing practical guidance on how Industry 4.0 technologies can support the full range of circular economy strategies*
Cortes Pellicer et al., 2025	*Exploration of the integration of AI into reverse logistics processes to enhance decision-making, operational efficiency, and resource recovery.*
Keles et al., 2025	*Identification of ten key digital technologies to enable circularity in the building sector, including discussion of their integration, alignment of technology opportunities with CE barriers, and mapping of applications across the building lifecycle*
Okafor et al., 2025	*Review of publications on AI applications in the environmental research field, focusing on trends, methodologies, and impacts of artificial intelligence on environmental monitoring, management, and sustainability*
Mannan et al., 2025	*Investigation of collaborative AI integration in ERP system implementation, examining its impact on business growth and long-term organizational sustainability*
Seyyedi et al., 2024	*Digitalization in waste management processes, using simulation methodologies to predict the potential impacts of digital technologies on waste handling*
Provensi et al., 2024	*Supply chain stakeholder engagement and network formation*
Bevere and Faccilongo, 2024	*Analysis of current ecological and digital transition scenarios in the healthcare sector, with particular attention to its high energy consumption*
Ramirez-Marquez et al., 2024	*Overview of current technological advancements and their potential applications in Society 5.0, with a literature review focusing on the roles of AI, IoT, and other emerging technologies in enhancing resource efficiency, particularly in the water and energy sectors, to reduce environmental impact*
Mastrucci et al., 2023	*Review of building sector models, from subnational to global scales, aimed at identifying best practices and critical gaps in representing*

	transformations toward low energy demand (LED) futures
Akbari et al., 2023	*Examination of how edge computing implementation can advance circular economy practices within supply chains, including associated challenges and best practices*
Gibbin et al., 2023	*Investigation of the thematic evolution linking sustainability and project management, with a focus on developing research agendas to enhance understanding and application in this field*
Tavana et al., 2022	*Digital transformation of supply chain processes using Industry 4.0 technologies and text mining to identify trends and key technologies*
Esenreich et al., 2022	*Analysis of the potential implications of CE solutions on a company's value chain processes*
Yu et al., 2022	*Application of information and communication technologies (ICT) to support circular construction practices across the building lifecycle*
Yu et al., 2022	*Review investigating circular economy practices in the construction industry, analyzed through the lens of the five-stage policy cycle developed in public policy research*
Cagno et al., 2021	*Review exploring the role of digital technologies in facilitating and operationalizing the transition to a CE*
Sahu et al., 2021	*Literature review on the adoption and implementation of Industry 4.0 and CE practices.*
Roy et al., 2021	*Literature review on mitigation actions*
Mustafee et al., 2021	*Design and analysis of supply chains using simulation techniques*
Romero-Silva and de Leeuw, 2021	*Overview of the evolution and state-of-the-art in Operations Research and Management Science, analyzed using text mining techniques*
Coroama and Hilty., 2014	*Review of methodological approaches used to assess the average energy intensity of internet transmissions*

5.3.3 The role of Artificial Intelligence

The literature analysis shows that AI is a cross-cutting technology in the main digitization processes, providing important decision support. In the context of supply chains, AI is used for forecasting and optimization, data fusion to integrate different information sources, machine learning algorithms to support the raw material selection process, cooperative waste prevention systems, flow tracking in real time, and return forecasting models to predict returns along the logistics chain (Cortes Pellicer et al., 2025; Tavana et al., 2022; Gebhardt et al., 2021). In livestock waste management, it is integrated

into digital monitoring systems to estimate quality parameters, process data from sensors, and support decisions on collection, storage, and emissions (Oyedun et al., 2025). In the environmental field algorithms, such as neural networks and support vector machines, are used to model complex phenomena and feed predictive systems for ecosystem monitoring (Okafor et al., 2025). In the construction sector, AI is incorporated into BIM, digital twins, and digital platforms to classify materials, support design, and manage lifecycle information from a circular perspective (Keles et al., 2025). Within 'circular supply chains', it contributes to collaborative mechanisms by analyzing shared data and integrating with IoT, blockchain, and cloud computing to structure inter-organizational information flows (Gebhardt et al., 2022). In reverse logistics, AI is involved in network planning, automated classification of returns, and decision-making processes related to recovery using predictive models (Cortes Pellicer et al., 2025). On a broader level, in 'Society 5.0' models, it operates as a pervasive technology within IoT and cyber-physical ecosystems, coordinating data flows and optimizing resources in complex digital systems (Ramírez-Marquez et al., 2024). Finally, in Enterprise Resource Planning (ERP) systems, AI acts as an intelligent layer that integrates predictive analytics, computational automation, and natural language interfaces (Mannan et al., 2025). Analysis of the contributions highlights some recurring strengths, including AI ability to process large amounts of unstructured data, automate highly complex activities, and enhance digital infrastructures such as BIM, ERP, and digital twins (Okafor et al., 2025; Keles et al., 2025). The most frequently mentioned challenges, on the other hand, concern implementation costs, the lack of specialist skills, cybersecurity risks, limited interoperability between digital platforms, and the lack of shared standards for AI-based models and procedures (Keles et al., 2025; Gebhardt et al., 2022).

5.3.4 An interpretative framework

Figure 5.1 summarizes the role of Industry 4.0 digital technologies in managing information flow to support decisions in the circular transition. The proposed framework aims to hypothesize the structure and functioning of a possible 'CE Simulation-based Decision Support System', a framework designed to facilitate informed decisions on the implementation of CE solutions.

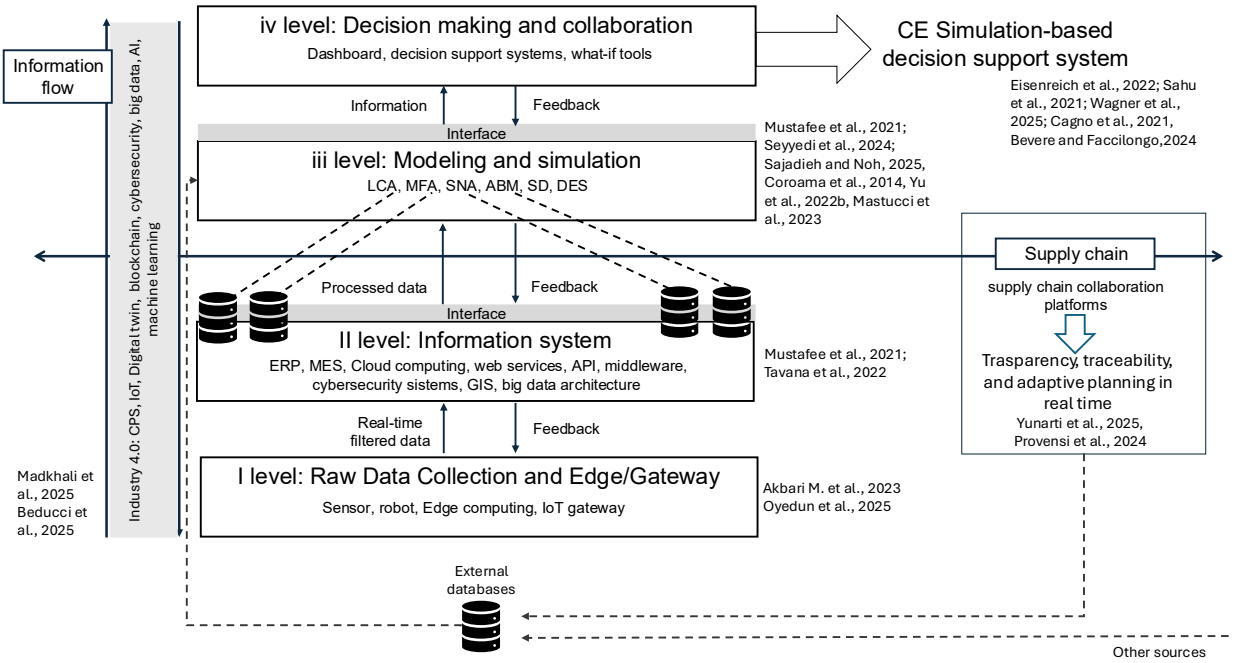


Figure 5.1 *Schematic representation of information flow management to achieve a simulation-based decision support system for circular transition leveraging Industry 4.0 technologies*

LEGEND: ERP: Enterprise Resource Planning; MES: Manufacturing Execution System; GIS: Geographic Information System; LCA: Life Cycle Assessment; MFA: Material Flow Analysis; SNA: Social Network Analysis; ABM: Agent-Based Modeling; SD: System Dynamics; DES: Discrete Event Simulation; CPS: Cyber-Physical Systems; IoT: Internet of Things; AI: Artificial Intelligence.

The framework is divided into four main levels, connected by bidirectional information flows:

i) *Raw data collection* (Edge/Gateway): this level concerns the collection, management, and quality of data within production processes. This level represents the primary data source as technological infrastructures, such as sensors, IoT, and monitoring and control systems, are the information basis for performance evaluation and subsequent decision-making. Raw data is filtered and made available in real time to higher levels for processing.

ii) *Information System*: the collected data (from the i. level) is organized and transformed into processed information, accessible for analysis and modeling. This level includes internal and external databases and requires intuitive and easy-to-use user interfaces, so that the information is immediately usable by stakeholders and facilitates access to processed data for simulation and decision-making.

iii) *Modeling and Simulation*: at this level, the processed data feeds into modeling and simulation methodologies, such as LCA, MFA, ABM, SD, and other dynamic and predictive approaches. External data from shared platforms along the supply chain can also be integrated. The goal is to explore "what-if" scenarios, evaluate alternatives, and support strategic decisions based on solid data.

iv) *Decision Making and Collaboration*: the final level concerns decision making and collaboration between stakeholders. Here, information and simulation results are presented through intuitive dashboards, decision support tools, and user-friendly interfaces, enabling informed and participatory decision making.

The information flow moves vertically, from raw data to information and simulation, and vice versa through feedback that continuously updates data and models. Industry 4.0 enabling technologies (such as CPS, IoT, Digital Twins, blockchain, AI, machine learning, big data, and cybersecurity) are integrated both vertically and horizontally, supporting internal information management as well as data sharing along the supply chain. This approach facilitates the creation of collaborative platforms, improving information flows across external databases and promoting shared modeling and joint decision-making processes. Level iii) represents an interesting area of study for the integration of AI and machine learning techniques, opening the possibility of developing a 'digital decision ecosystem', in which data feeds predictive models and decision support scenarios. These technologies make it possible to transform large volumes of heterogeneous data into operational knowledge and adaptive strategies. Dynamic methodologies such as SD and ABM, integrated with AI and big data analytics tools, represent promising approaches for understanding emerging behaviors, simulating scenarios, and evaluating the effects of alternative strategies throughout the entire life cycle.

5.3.5 Application example: STELLA Architect software

As highlighted, modeling and simulation play a crucial role in supporting decision-making in the transition toward the CE. In this context, System Dynamics (SD) emerges as a fundamental methodology for addressing the complexity of production systems, as it enables the analysis of feedback loops, time delays, and nonlinear relationships, features that are intrinsic to circular systems. Through the development of Causal Loop (CLD) and Stock-and-Flow (SFD) Diagrams, SD makes it possible to visualize system structure and to simulate the impacts of alternative scenarios over time. Among the software platforms commonly used for building and analyzing dynamic models, STELLA Architect (Isee systems) offers advanced simulation capabilities and integrates optimization and decision support functionalities. These features focus on assistance in conceptual modeling (leveraging generative AI) and analytical decision support (using optimization and sensitivity analysis). Recent versions of STELLA Architect (Isee systems) include an assistant based on Large Language Models (LLMs), functioning as a co-pilot throughout various phases of model development. To illustrate these aspects, an SD model was developed in collaboration with an electronic engineer and under the supervision of SD experts, focusing on the topic of plastic waste management. The experiment consisted of completing, within eight hours, the main phases of

building a dynamic model: 1) Verbal model and objective, 2) Definition of system elements, 3) Stock-and-Flow diagram and quantification, and 4) Simulation results and discussion. Subsequently, the experiment was replicated using AI within STELLA Architect software (Isee systems), following the same steps performed manually. In this second case, the process started directly from the SFD, since the qualitative model (CLD) had already been defined during the human experiment, with the aim of observing how AI would interpret and expand the model. Two versions of the model were therefore developed. The first ("human model") was created manually during the expert-supervised experiment, while the second ("artificial model") was generated entirely by the AI. The development of the project is retraced below through the phases followed in each version.

- Human Model

Phase 1) Verbal Model and objective

The first phase focuses on verbally explaining how system works and on defining the purpose of the model. The text as written during the experiment is reported below:

"The recycling process of plastic waste is described. The production of plastic manufactured goods generates ready-to-use plastic products. The use of these products, after a certain period, generates waste. The generation of plastic waste is a problem of environmental degradation. In fact, plastic waste can follow two paths: properly disposed or dispersed into the environment. Properly disposed of plastic waste, it can be recovered to a certain %, or it can end up in landfills (and therefore not recovered)-depending on the type of material processed. Plastic materials cannot be 100% recycled, so even for properly disposed and valued waste, there will always be some % of waste, which will end up in landfills. In addition, plastic materials, cannot be recycled indefinitely, so they still contribute to the generation of new plastic waste. Technology and innovation play an important role, as the amount of waste that can actually be recovered depends on them. But people's environmental awareness, too, contributes to the decrease in environmental degradation generated by plastics. The objective of the model is to assess what possible actions a policy maker should put in practice to improve plastic waste management. The spatial boundaries are for a country system (EU), and the effects are evaluated on a time scale expressed in years."

Phase 2) Definition of system elements

The second phase involves identifying the key elements of the system (main variables), and representing their interactions through a causal loop diagram, which forms the basis of the dynamic structure. *Figure 5.2* shows the variables identified and the CLD created.

Elements
annual production of virgin plastic
use of plastic products
volume of plastic waste **(Stock)**
waste out of the system
environmental sensibility
waste correctly disposed **(Stock)**
waste to landfill **(Stock)**
non-recycled plastic waste
waste from the recycling process
recycled plastic waste
recycling process efficiency

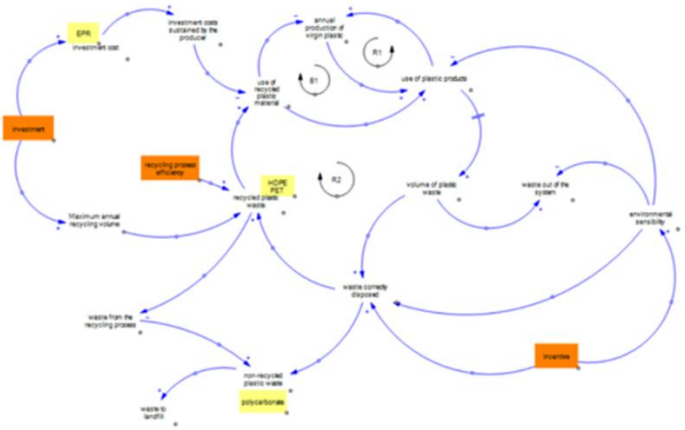


Figure 5.2 *Plastic waste system elements and CLD*

Phase 3) Stock and Flow diagram and quantification

The third phase translates the qualitative understanding of the system into a SFD representation and assigns numerical values to the parameters for simulation. *Figure 5.3* shows the SFD model created, and *Figure 5.4* shows the simulation results.

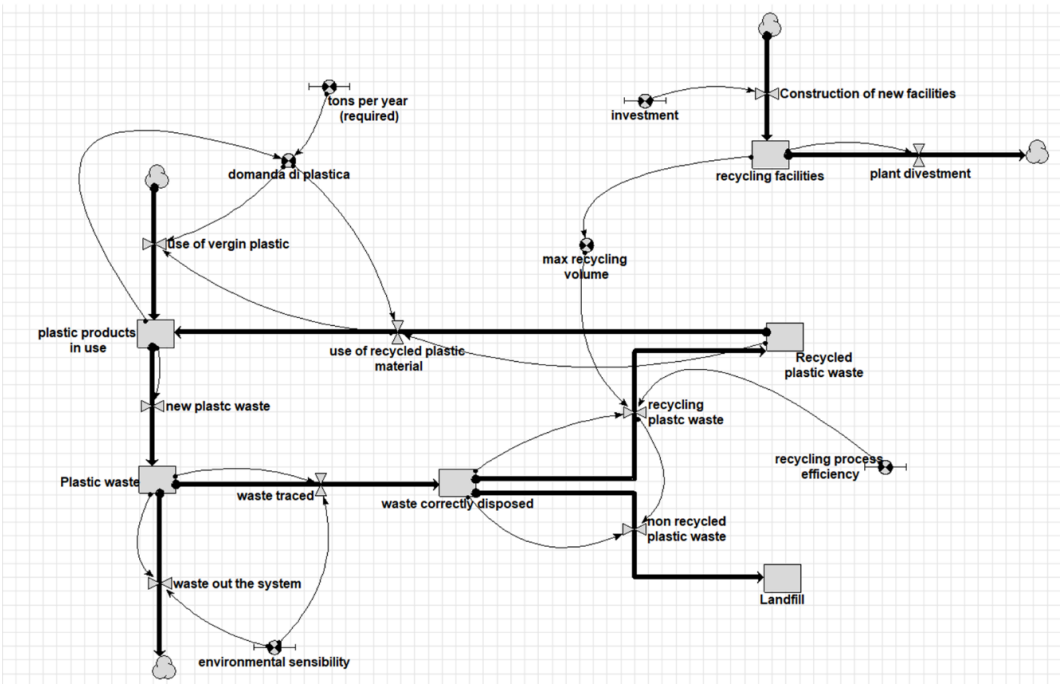


Figure 5.3 *Plastic waste Stock and Flow Diagram (SFD)*

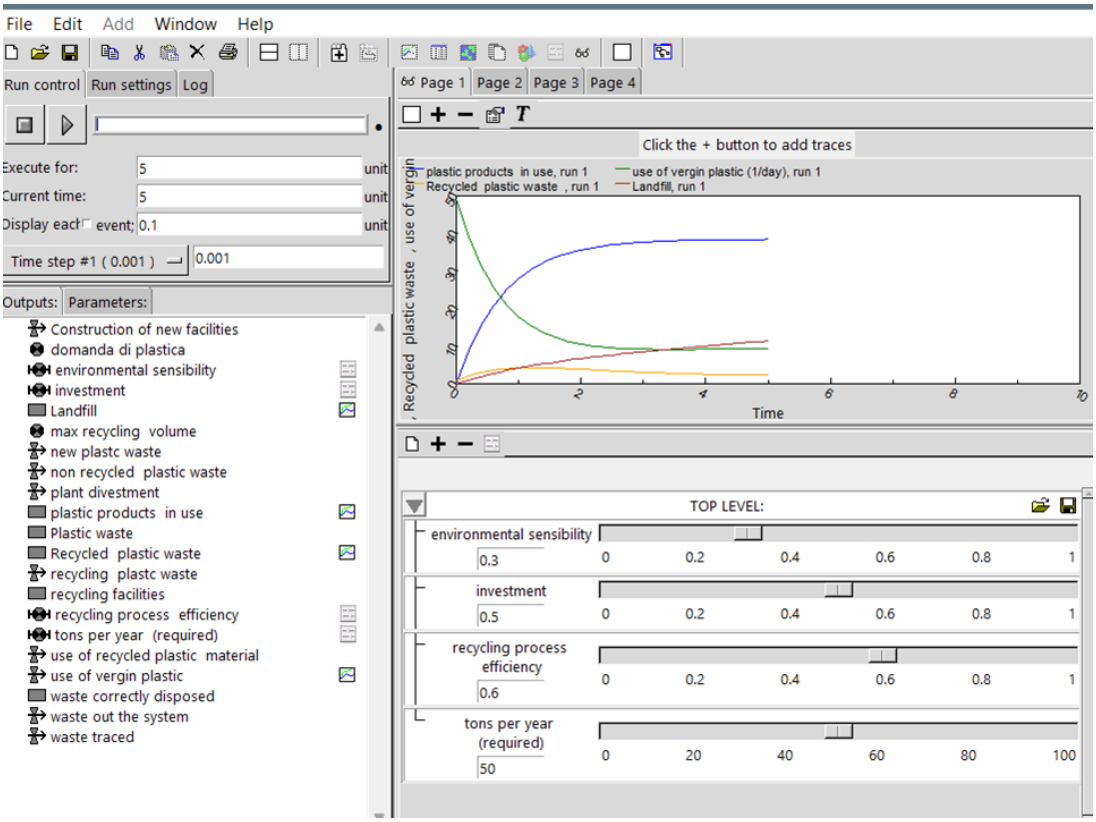


Figure 5.4 *Plastic waste Model Simulation*

Phase 4) Simulation Results and Discussion

The final stage consists of discussing the results of the simulation. The text as written during the experiment is reported below:

"The model includes several critical variables, such as plastic products in use, recycled plastic waste, the use of virgin plastic, and the amount of material sent to landfill. These are influenced by a set of parameters, including environmental sensibility, the level of investment, the characteristics of the recycling process, and the required tons per year. Changes in these parameters affect the system in different ways. When recycling efficiency increases, the slope of the landfill curve decreases. For the same amount of plastic waste generated, the share of non-recoverable material becomes smaller, because a more efficient recycling process increases the portion of waste that can be converted into recycled plastic rather than disposed of. Environmental sensibility also plays an important role: as it increases, the amount of waste leaving the system (through improper disposal or dispersion) decreases. As a result, a larger volume of waste enters the formal treatment system and is processed either through recycling or landfill. Since the recycling efficiency stays constant, both correctly recycled waste and waste sent to landfill increase. A material substitution strategy, instead, reduces the amount of virgin plastic entering the market and, as a consequence, decreases the stock of plastic products in use".

- Artificial Intelligence Model

Starting from the qualitative model (verbal model and CLD) developed in collaboration with experts, the subsequent phases were carried out using AI. *Table 5.2* shows the results generated by AI in response to specific prompts. Subsequently, starting from phase 3 of the construction of a dynamic model, the responses produced by AI are reported.

Table 5.2 *AI Assistant (Prompt)*

Results	Mode and Assistant	Prompt
1	Build – quantitative	This is the verbal model [*Verbal Model and objective*]; transform it into Stock and Flow Diagram
2	Build – quantitative	Show me how the results change under different intervention policies
3	Build – quantitative	Run a simulation using real data on the stock of plastic products in Europe. Perform the simulation considering the most important parameters
4	Discuss-seldon	Discuss the main drivers of this model
5	Discuss-seldon-experimental	What are the levers of change?
6	Discuss-seldon-experimental	Discuss the main results of this model for policy makers
7	Discuss-seldon	Discuss the model and the simulation and suggest improvements

Phase 3) Stock and Flow diagram and quantification

- Prompt: "This is the verbal model [Verbal Model and objective]; transform it into Stock and Flow Diagram".

- AI Result 1

AI generated:

The model was constructed based on the verbal description, focusing on material flows and closing key feedback loops related to environmental management and resource cycling.

Material Flow Structure: The core structure follows the product lifecycle: Production -> Products (Stock) -> Usage (Flow) -> Waste (Stock). Waste is then split into two paths: Proper Disposal and Dispersal, leading to Landfill/Recycling or Environmental Degradation, respectively.

Closed Feedback Loops:

1. Balancing Loop (B1: Environmental Awareness): Increased Environmental Degradation drives up Environmental Awareness, which in turn increases the Proper Disposal Fraction. A higher Proper Disposal Fraction reduces Dispersed Waste, thereby mitigating Environmental Degradation. This is a self-correcting mechanism.

2. Balancing Loop (B2: Technology Investment): Increased Environmental Degradation drives Investment in Technology. Higher Technology Level increases the Recovery Fraction, leading to higher Waste Recovery and less waste going to Landfill/Dispersal (indirectly mitigating degradation). This represents a policy response mechanism.

3. Reinforcing Loop (R1: Recycling/Production): Waste Recovery generates Recycled Plastic Material, which is fed back into the Plastic Production Rate. Increased production leads to more Ready-to-Use Products, eventually generating more Plastic Waste, which fuels further recovery. This loop represents the potential for exponential growth in the circular economy if recovery rates are high, but also accelerates the overall material throughput.

1. Ready to Use Plastic Products -->(+) product usage rate

A larger stock of products in use leads to a higher rate of products reaching the end of their life and becoming waste.

2. Plastic Waste -->(+) properly disposed waste

A larger stock of plastic waste increases the potential volume available for proper disposal.

3. Plastic Waste -->(+) dispersed waste

A larger stock of plastic waste increases the potential volume available for dispersal into the environment.

4. proper disposal fraction -->(+) properly disposed waste

An increase in the fraction of waste properly disposed increases the flow into the formal waste management system.

5. proper disposal fraction -->(-) dispersed waste

An increase in the fraction of waste properly disposed means a smaller fraction is dispersed into the environment.

6. Environmental Degradation -->(+) awareness increase rate

Higher environmental degradation increases public concern and drives the rate of increase in environmental awareness.

7. Environmental Awareness -->(+) proper disposal function

Increased environmental awareness leads to better behavior, resulting in a higher fraction of waste being properly disposed.

8. proper disposal function -->(+) proper disposal fraction

The output of the lookup function determines the proper disposal fraction.

9. properly disposed waste -->(+) waste recovery rate

The amount of waste recovered depends on the amount of waste properly disposed of.

10. properly disposed waste -->(+) waste to landfill from disposal

The amount of waste sent to landfill from disposal depends on the total amount properly disposed of.

11. recovery fraction -->(+) waste recovery rate

A higher recovery fraction means a larger percentage of properly disposed waste is recovered.

12. recovery fraction -->(-) waste to landfill from disposal

A higher recovery fraction means a smaller percentage of properly disposed waste ends up in landfills.

13. Recycled Plastic Material -->(+) recycled material input to production

A larger stock of recycled material allows for a higher rate of input into new production.

14. recycled material input to production -->(+) plastic production rate

Recycled material is a component of the total plastic production rate.

15. recycled material input to production -->(-) virgin plastic input

Using more recycled material substitutes the need for virgin plastic input, assuming total demand is constant.

16. Environmental Degradation -->(+) investment in technology

High environmental degradation pressures policymakers to invest more in technology and innovation to improve recovery rates.

17. Technology Level -->(+) recovery function

Higher technology levels enable better recovery processes, increasing the potential recovery fraction.

18. recovery function -->(+) recovery fraction

The output of the lookup function determines the recovery fraction.

19. Technology Level -->(+) technology depreciation

A higher stock of technology leads to a higher rate of depreciation/obsolescence.

20. Environmental Awareness -->(+) awareness decay rate

A higher level of awareness means there is more awareness to potentially decay over time.

21. recycling efficiency -->(+) waste recovery rate

Higher efficiency means more recovered waste is successfully converted into usable recycled material.

22. recycling efficiency -->(-) non recoverable recycling residue

Higher efficiency means less waste residue is generated during the recycling process.

23. properly disposed waste -->(+) non recoverable recycling residue

The total amount of residue generated is proportional to the amount of waste entering the recovery process.

24. Environmental Degradation -->(+) degradation mitigation

The rate of natural mitigation is proportional to the current level of degradation.

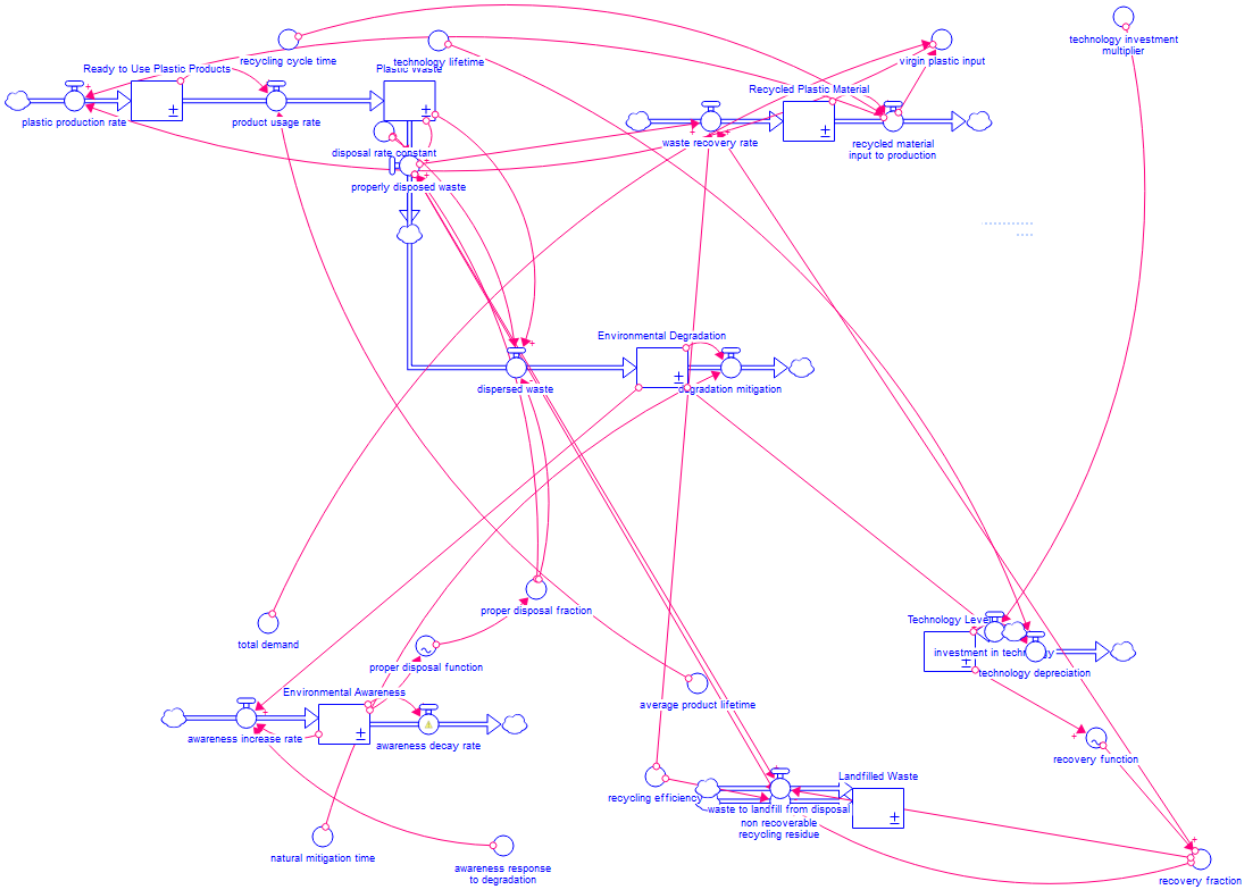


Figure 5.5 *SFD generated by AI based on the human verbal model*

- Prompt: Show me how the results change under different intervention policies

- AI results 2

Text AI generated:

1. Technology Level -->(+) technology impact on disposal

Higher technology level increases the effectiveness multiplier for disposal infrastructure.

2. technology impact on disposal -->(+) effective proper disposal fraction

The technology multiplier directly increases the effective disposal fraction.

3. proper disposal function -->(+) effective proper disposal fraction

The awareness-driven potential fraction is a component of the effective fraction.

4. Recycled Plastic Material -->(-) production cost reduction

A larger stock of recycled material leads to greater cost reduction (lower multiplier value).

5. production cost reduction -->(-) demand stimulus

A lower cost reduction multiplier (meaning lower costs) stimulates higher demand (higher stimulus multiplier).

6. demand stimulus -->(+) total demand

The stimulus multiplier directly increases the total demand.

7. total demand -->(+) plastic production rate

The production rate must meet the total demand.

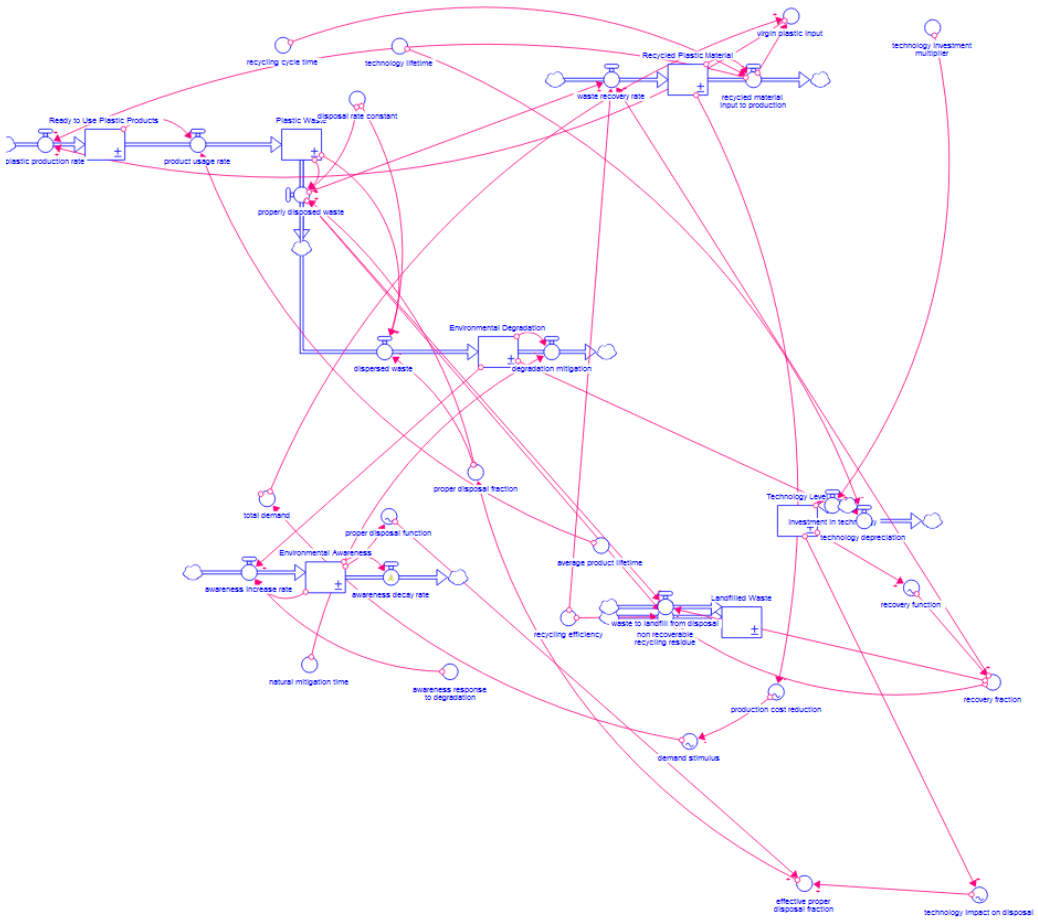


Figure 5.6 *SFD after different intervention policies*

4) Phase 4 of model construction: Simulation Results and Discussion

- Prompt: Run a simulation using real data on the stock of plastic products in Europe. Perform the simulation considering the most important parameters

- AI Result 3

Text AI generated:

To ensure the model accurately reflects system dynamics principles, I explicitly closed all implied feedback loops by adding relationships between stocks and their corresponding flows. This is crucial for tracing the reinforcing (R) and balancing (B) mechanisms. Specifically, I added relationships defining how production adds to the product stock, usage adds to the waste stock, recovery adds to the recycled material stock, and how dispersed waste accumulates as environmental degradation. I also added the necessary variable, 'Awareness Decay Time', to complete the calculation of the 'awareness decay rate'. Finally, to align the simulation with real-world data (European plastic stock), I adjusted the units of mass-related variables from 'Index'/'Tonnes' to 'MT' (Million Tonnes) and updated the initial stock values and the baseline 'total demand' accordingly. The graphical function for 'production cost reduction' was also rescaled to reflect the new MT units.

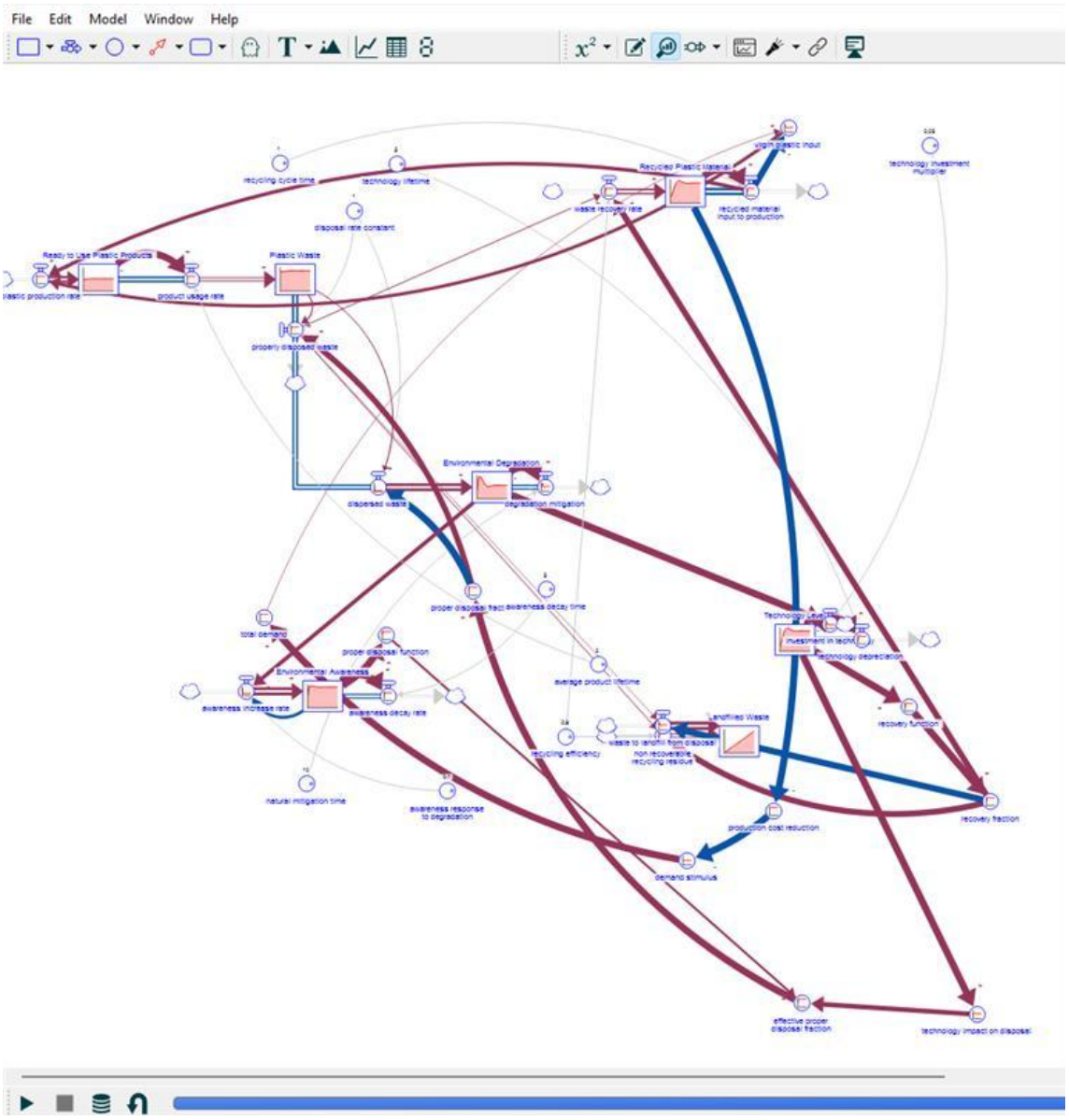


Figure 5.7 *Quantified AI SFD and AI simulation*

- Prompt: Discuss the main drivers of this model

- AI Result 4

Text AI Generated:

The model's behavior is overwhelmingly dominated by Balancing (B) loops, which appear in nearly every time step of the simulation. This indicates that the system is highly constrained and self-regulating, constantly seeking equilibrium or oscillating around limits imposed by resource availability, decay rates, and environmental feedback. The brief dominance of Reinforcing (R) loops suggests temporary growth spurts quickly constrained by these balancing mechanisms.

1. Primary Environmental Control and Feedback (B4, B2)

The most consistent drivers relate to how the system responds to and manages environmental degradation:

- ***B4 (Awareness/Disposal/Degradation): This loop is highly dominant throughout the simulation (appearing in 27 time steps). It represents the core environmental feedback mechanism: increased Environmental Degradation drives higher Environmental Awareness, leading to a greater proper disposal fraction, which reduces dispersed waste, thereby mitigating Environmental Degradation. This loop is crucial for constraining the environmental impact.***
- ***B2 (Awareness Decay): This loop (dominant in 30 time steps) acts as an internal constraint on the effectiveness of environmental efforts. It dictates that Environmental Awareness naturally decays over time (via awareness decay rate), meaning continuous environmental pressure (via B4) or external intervention is required to maintain high disposal rates.***

2. Material Flow and Waste Management Constraints (B5, B3, B1)

These loops govern the physical limits and flows within the production and waste cycles:

- ***B5 (Waste Disposal): This fundamental balancing loop (dominant in 25 time steps) ensures that the stock of Plastic Waste is drawn down by the properly disposed waste flow, preventing runaway accumulation of waste.***
- ***B3 (Recycling/Virgin Input Stabilization): This complex loop (dominant in 23 time steps) stabilizes the overall production rate. When recycling increases, it reduces the need for virgin plastic input, thereby balancing the total plastic production rate and constraining the growth driven by reinforcing loops.***
- ***B1 (Recycled Material Consumption): This loop (dominant in 22 time steps, and solely dominant during 2030.75–2032.5) represents the consumption limit of the recycled material stock. It ensures that the rate of recycled material input to production draws down the Recycled Plastic Material stock, imposing a constraint on how quickly recycling can fuel new production.***

3. The Role of Reinforcing Loops (R1, R3)

The system experiences a temporary shift to growth dynamics between 2022.75 and 2025, driven by the core recycling loops:

- ***R1 (Core Recycling Growth): This loop drives the circular economy aspect, where increased recycling leads to more recycled material, boosting production, increasing the stock of products, and eventually generating more waste available for recycling.***
- ***R3 (Degradation-Driven Recycling Growth): This loop links environmental pressure (Environmental Degradation) to technological investment, boosting recovery rates, and feeding the positive growth cycle of R1.***

The dominance of these reinforcing loops is short-lived, suggesting that while recycling efforts successfully initiate a growth phase in material circulation, the inherent balancing constraints (such as decay, depreciation, and the limits on virgin input substitution) quickly reassert control over the system's trajectory.

- Prompt: What are the levers of change?

- AI Result 5

Text AI Generated:

The levers of change are the parameters or auxiliary variables that, when adjusted, can significantly alter the behavior of the system by influencing the strength and speed of the dominant feedback loops. Based on the model structure and dynamics, the key levers fall into three main categories:

1. Product Design and Consumption Levers

- ***Average Product Lifetime: This parameter controls the rate at which products become waste (product usage rate, B7). Increasing the average lifetime slows down the inflow to the Plastic Waste stock, reducing pressure on the entire waste management system and weakening the reinforcing loops (R1, R3) that drive production volume.***

2. Waste Management and Technology Levers

- ***Recycling Efficiency: This parameter directly determines how much recovered waste successfully becomes Recycled Plastic Material (R1, R3). Increasing efficiency strengthens the circular economy loops and reduces the flow to Landfilled Waste (non recoverable recycling residue).***
- ***Recycling Cycle Time: This controls how quickly recycled material re-enters the production stream (R1, R3). Decreasing this time strengthens the reinforcing loops, making the circular economy faster and more competitive against virgin plastic input.***
- ***Technology Investment Multiplier: This controls the rate at which Environmental Degradation drives investment in Technology Level (B6, B8, B15, R3, B10). Increasing this multiplier strengthens the balancing loops that improve recovery infrastructure and disposal effectiveness.***
- ***Technology Lifetime: This parameter influences the depreciation rate of the Technology Level (B6). Increasing the lifetime ensures that technological improvements (which boost recovery and disposal fractions) remain effective for longer, sustaining the strength of balancing loops B8, B10, and B15.***
- ***Disposal Rate Constant: This controls the overall speed at which Plastic Waste is processed (either properly disposed or dispersed). While increasing it speeds up the system (B5, B14), its effectiveness depends entirely on ensuring the proper disposal fraction is high.***

3. Social and Behavioral Levers

- ***Awareness Response to Degradation: This parameter dictates how strongly Environmental Degradation drives the increase in Environmental Awareness (B2, B4, B9, B12). Increasing this strengthens the social balancing loops that lead to better disposal behavior.***
- ***Awareness Decay Time: This controls how quickly Environmental Awareness fades (B11). Increasing this time ensures that positive behavioral changes (higher proper disposal***

fraction) are sustained over longer periods, reinforcing the effectiveness of loops B4, B9, and B12.

- Prompt: Discuss the main results of this model for policy makers

- AI Result 6:

Text AI Generated:

The simulation results reveal a dynamic system characterized by an initial growth phase driven by recycling, followed by persistent constraints imposed by material flow limits and reactive environmental feedback.

1. The Double-Edged Sword of Recycling (R1 Dominance: ~2023-2025)

The early dominance of the Reinforcing Loop R1 (Recycling → Production → Products → Waste → Recycling) indicates that initial investments successfully establish a circular flow. However, this loop acts as a growth engine, suggesting that increased availability of recycled material lowers production costs (via the production cost reduction variable) and stimulates overall demand (via demand stimulus), potentially leading to higher total plastic production and consumption.

- ***Policy Implication: Decoupling Growth. Policymakers must implement measures to decouple recycling success from overall production growth. This could involve setting absolute caps or taxes on virgin plastic input, ensuring that recycled material substitutes virgin material rather than fueling net demand increase.***

2. Critical Bottleneck in Material Throughput (B1 Dominance: ~2030-2032, and recurring)

The strongest long-term constraint is represented by Balancing Loop B1 (Recycled Material Stock limit), which dominates the system during key periods of correction. This loop stabilizes the stock of recycled material by limiting the rate at which it can be fed back into production (recycled material input to production).

- ***Policy Implication: Focus on Throughput. Policy efforts should shift beyond merely collecting waste to aggressively improving the efficiency and speed of the recycling infrastructure. Reducing the recycling cycle time and increasing recycling efficiency are crucial levers to overcome the B1 constraint and maximize the utilization of recovered material.***

3. Reactive Environmental Management (B4, B8 Dominance: Persistent)

Balancing loops related to environmental feedback (B4: Degradation → Awareness → Disposal; B8: Degradation → Investment → Technology) are consistently active throughout the simulation. These loops demonstrate that the system relies on environmental degradation to trigger corrective actions (increased awareness and technology investment).

- ***Policy Implication: Proactive Investment. Relying on reactive balancing loops means environmental damage must occur before corrective action is taken. Policymakers should***

mandate sustained, proactive investment in technology (Technology Level) and public awareness (Environmental Awareness) independent of current degradation levels to maintain high disposal and recovery fractions, preventing environmental overshoot.

4. Long-Term Dynamic Equilibrium

The overall simulation trend shows that the system settles into a dynamic equilibrium or oscillation dominated by balancing loops (B1, B2, B4, B9) in the later decades (2030-2050). This suggests that without significant structural changes, the system will not achieve a sustainable collapse of plastic waste or runaway growth, but rather a continuous struggle to manage waste within existing limits.

- ***Policy Implication: Structural Change. To achieve true sustainability, policies must aim to fundamentally weaken the reinforcing loops (R1, R3) that drive production and strengthen the balancing loops (B4, B8) that reduce degradation and waste generation, moving the system away from its current constrained equilibrium***

COMPARING: HUMAN MODEL VS AI MODEL

The comparison reveals a marked difference between the time needed for manual model construction and the much shorter time in which the AI can generate a SFD enriched with a greater number of variables and relationships. While the human team required approximately eight hours to develop a very simple verbal model, CLD, SFD, and discussion of the main results, AI was able to reconstruct the same phases, enriching the model with additional causal relationships, variables, and feedback analyses (in less than an hour). A further relevant element emerged in step 3 of the AI results, where the AI was asked to run a simulation using real data on the stock of plastic products in Europe. The AI adapted the model to real measurement units. This result highlights the potential of AI to rapidly connect dynamic models with real-world data, paving the way for integration with continuously updated information flows and, in the future, with real-time data from IoT systems, industrial platforms, or digital infrastructures. It was also observed that, in the AI-generated model, quantification does not occur as a separate step prior to the simulation, but takes place directly within the simulation phase itself. The final quantification is produced at the moment the user runs the model rather than being explicitly prepared in advance. Overall, this comparison underscores the potential of AI to accelerate conceptual modeling, strengthen preliminary simulation activities, and facilitate integration with operational data. At the same time, it confirms the necessity of human oversight to ensure conceptual coherence, the correctness of causal relationships, and the interpretability of results for decision-making purposes.

5.4 Discussion and conclusions

The review conducted shows that, although digital technologies have significantly increased the availability and quality of data, their capacity to support CE systemic decision-making remains limited. The proposed framework interprets digitalization as a multi-level cognitive model in which Industry 4.0 technologies provide the connecting link between operational data and strategic decision-making. The goal is to transform the growing variety of data generated by production systems into structured information, enabling the comparison of circular scenarios while improving environmental, economic, and social performance. In this perspective, digitalization acts not only as a technical enabler but as an engine capable of converting data into useful information that can be used to define circular strategies. External databases also play an important role, as they can provide useful information when integrated. The main challenges identified concern the management of heterogeneous and distributed data, the lack of analytical structures capable of integrating interdependent variables, and the difficulty of anticipating the dynamic effects of decisions in evolving contexts. The conceptual framework proposed in this study addresses these issues by integrating data collection, information processing, modeling, simulation, and collaborative decision-making processes. Based on bidirectional information flows and interoperability between digital technologies and both static and dynamic methods, the framework represents a step forward in the development of simulation-based decision-support systems for CE. System Dynamics and simulation-based approaches play a central role within this framework. The plastic waste management case study demonstrates how such methods enable the transformation of available data into a structured representation of the system, the exploration of alternative scenarios, and the evaluation of strategies over long-term horizons. The comparison between the manually developed model and the AI-generated model further highlights the potential of AI in supporting dynamic modeling. The AI rapidly constructed SFDs, identified feedback cycles, suggested structural improvements, and analyzed system drivers. Moreover, when asked to simulate the system using real European data on plastic stocks, the AI adapted the model's units. These results show the potential of AI to accelerate conceptual modeling and scenario generation while enabling rapid integration with real-world data. Nonetheless, the need for human checking remains essential to ensure conceptual coherence, accurate causal representation, and interpretability of results. Although the study provides a structured contribution to understanding how digital technologies, Dynamic modeling and simulation, and Artificial Intelligence can support CE decision-making, several limitations must be acknowledged, which in turn open promising avenues for future research. A first limitation concerns the predominantly conceptual nature of the proposed framework. While framework integrates data acquisition, information processing, simulation, and AI-based decision-support functionalities, its

validation remains theoretical. The lack of large-scale empirical applications limits the generalizability of the findings and underscores the need for implementation and testing in real industrial settings. A second limitation relates to data availability, quality, and interoperability. Most industrial ecosystems continue to rely on fragmented datasets, heterogeneous digital infrastructures, and incomplete or non-standardized information. These conditions constrain the operational application of integrated dynamic models, particularly those that depend on automatic calibration, real-time data collection, or AI-driven scenario generation. Building robust, interoperable data architecture therefore remains a critical challenge. A further limitation concerns the use of AI within the modeling process. Although the AI demonstrated the ability to construct SFDs, identify feedback loops, suggest structural improvements, and integrate real-world data, issues remain regarding transparency, explainability, reproducibility, and user supervision. Model outputs depend strongly on prompt design, the characteristics of the AI training data, and the user's capacity to critically evaluate and validate AI-generated structures. Finally, the very simple test focused on plastic waste management, which, while illustrative, does not capture the heterogeneity of CE configurations. Different sectors such as textile, construction, electronics, food systems, and industrial symbiosis networks present distinct systemic structures, feedback mechanisms, and data requirements. These differences may necessitate customized modeling approaches and sector-specific adaptations.

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CONCLUSIONS

The PhD research project summarized in the present thesis was developed within the IE framework with the broad intention of understanding how to support the transition of production systems towards CE, which cannot be understood as a simple technological replacement or an optimization of production processes but involves the redesign of complex systems at various levels of scale, including the dynamics of contexts characterized by regulatory pressures, market and technological developments, and behaviors that are often non-linear and difficult to predict.

During research, it became clear that the *CE and IE* are not just two closely related theoretical frameworks but two perspectives that, together, offer a language and a set of approaches, methods, and tools useful for reading and interpreting the complexity of the ecological transition. The historical reconstruction of their evolution has shown that many of the concepts now attributed to CE were significantly derived from IE, suggesting the existence of a shared scientific heritage that can serve as a reference for methodological integration. This integration has proved particularly useful in defining a clear methodological framework and in making critical considerations regarding the management of the complexity of production systems.

The case of the *textile supply chain* has shown how deep the impact of regulatory drivers is in defining the directions of change. At the same time, regulation is not the only variable that can facilitate (or hinder) the circular transition, but a whole series of internal and external variables (e.g., technological change, consumer behavior, raw material prices, etc.) must be considered, making CE choices extremely complex.

The review and classification conducted highlighted the presence of a wide range of *methods and tools*, often heterogeneous, sometimes overlapping, capable of operating at different levels: representing systems, analyzing actor networks, building scenarios, and assessing impacts. However, none of these tools, taken individually, can capture the intrinsic complexity of systems. An important result resides in their complementarity and in the possibility of combining them to obtain a systemic interpretation, capable of recognizing both structural and evolutionary dynamics. This theme refers to the distinction, central to the work, between *static and dynamic approaches*. Static approaches, which include many established IE methodologies, are indispensable for description of industrial systems' metabolism, for measurement of environmental, economic, and social impacts, and for comparison of different scenarios. However, they show limitations when simultaneously considering the different variables that characterize production systems, such as environmental, economic, and social variables, as well as regulatory and behavioral ones. For this reason, they are unable to capture

and represent the dynamics of change, feedback loops, the role of actors, and the evolution of systems over time.

Dynamic approaches, such as *System Dynamics and Agent-Based Modeling*, respond to this need and open the way to more advanced forms of circular scenario evaluation, more consistent with the systemic and dynamic (non-static) nature of the circular transition. The emergence of integration between these approaches, also supported by *Artificial Intelligence technologies*, suggests that the modeling of circular systems can move towards new, more complex but more effective phases. The work therefore focused on studying how all these elements, static and dynamic methods, digital technologies, and information flows, can interact within an integrated decision-making framework. The analysis showed that digitalization is not just a set of operational tools, but can be interpreted as the cognitive infrastructure of the circular transition, the space where data becomes knowledge and knowledge can be translated into decision-making value. The integration of ICT, dynamic modeling, and AI, opens up the possibility of building decision support systems capable of adapting, predicting, simulating, and evaluating circular alternatives in a transparent, collaborative, and sustainability-oriented way. The research, of course, does not ignore the limitations that still exist. In particular, the scarcity and heterogeneity of available data, the incompleteness of infrastructure, the loss of transparency in AI-based models, the scarcity of large-scale empirical applications, and the environmental footprint of the most advanced digital technologies.

These elements make it clear that the circular transition cannot be entrusted exclusively to tools, but requires a parallel evolution of organizational capabilities, information infrastructures, governance, and decision-making processes. Despite these limitations, the thesis shows that it is possible to build an integrated path to analyze, model, and evaluate different circular scenarios. The combination of theoretical frameworks, analytical tools, dynamic models, and Industry 4.0 digital technologies is one of the most promising areas for supporting decisions in complex contexts. This work fits into this perspective, helping to define a possible direction for the development of a 'CE Simulation-based Support System' to assist decision-makers in the transition to the CE. The circular transition requires, prior to anything else, the ability to interpret complexity. This thesis proposes a way to do this: not a single method, not a single technology, but an integrated set of perspectives, approaches, methods, and tools that, together, can help build more resilient, intelligent, and sustainability-oriented production systems. In this way, the general research question - how to efficiently and effectively support the transition of a production systems to CE - is answered by an integrated process that starts with understanding the system under analysis and leads to the construction of a simulated decision-making system based on analytical methods, modeling and dynamic simulation, coherent parameters

and indicators, and enabling technological tools capable of comparing different circularity scenarios.

This result was achieved by revisiting the critical stages (gaps) in addressing decision-making towards circularity, the explanation of which satisfies the general demand of the project. The first stage involves identifying the morphological and operational characteristics of the context, with the aim of identifying the main gaps in circularity. At this stage, IE provides tools to describe industrial metabolism and represent process structures, such as Flowcharts, Sankey diagrams, and Material Flow Analysis (MFA), which enable the visualization of material and energy flows, the calculation of mass balances, and the analysis of relationships between processes, making hotspots and inefficiencies, throughout the life cycle, immediately recognizable. Experience gained in case studies shows that this analysis requires reliable data and a strong grounding in the actual functioning of the system. The collection of primary data, supplemented by interviews and structured discussions with practitioners, is essential for validating the process representation, interpreting the morphology of the system, and combining the technical and operational perspectives to accurately outline the starting conditions with respect to circularity objectives. Starting from this basis, the choice of methods and tools for analyzing the system and designing circular solutions becomes central. Research highlights the need to combine approaches related to IE, System Thinking, and Information and Communication Technologies (ICT) in order to have an integrated framework capable of representing and redesigning complex economic and production systems. Static tools related to IE - Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Carbon and Water Footprint - enable the quantification of material and energy inputs, outputs, and stocks; the estimation of environmental and economic impacts; and the comparison of current configurations with alternative solutions. Other methods such as GIS and SNA enable the analysis of how the level of the system analyzed is established at the highest level (e.g., a supply chain in the territorial context) and analysis of the relationships between the actors involved. System Thinking provides a way to interpret the complexity of systems, in particular System Dynamics, through Causal Loop Diagrams (CLDs) and Stock and Flow Diagrams (SFDs), makes it possible to construct dynamic models that make explicit the causal structures, feedback mechanisms, and adaptive behaviors of the system. Agent-Based Modeling (ABM) complements this perspective by representing actor heterogeneity and the dynamics emerging from their interactions. The enabling ICT of Industry 4.0 complete the picture, offering the ability to collect, integrate, and process heterogeneous data in almost real time and to feed advanced analytical models, including Artificial Intelligence (AI) algorithms for modeling optimization and scenario generation. Direct experimentation has demonstrated the usefulness of software: LCA software for MFA and environmental impact assessments; GIS applications for integrating the spatial dimension; SNA software for analyzing actor networks; data analysis software for processing structured datasets; SD

and ABM software for dynamic modeling and simulation. In this last case the integration of AI functionality has shown how it is possible to automate part of the model construction process (variable identification, causal relationships, diagram structure) and link models to empirical datasets. This suggests an evolutionary direction in which dynamic tools equipped with AI capabilities can accelerate model construction and updating, increasing the ability to analyze complex scenarios in a short time. At the same time, the combined use of heterogeneous software highlights significant limitations in terms of interoperability, workflow continuity and traceability indicating the need for more integrated digital architectures. The management of internal and external influencing variables finds its methodological focus in dynamic modeling within the proposed framework. Through System Dynamics, it is possible to distinguish internal variables (production efficiency, recovery rates, waste management strategies) from external variables (regulatory trends, resource prices, technological innovation, market demand) and represent them consistently within causal and temporal structures. ABM models enable a deeper understanding of micro-behavioral dimensions by simulating the decisions and interactions of individual actors (companies, consumers, institutions) and observing their emerging effects on overall circular performance. In this context, the construction of a baseline scenario describing the pre-existing linear structure is a key step. The levers of change identified from the hotspots and opportunities that emerged in the initial analysis are grafted onto the baseline: recycling and reuse strategies, industrial symbiosis, eco-design, increased collection and treatment rates, changes in management and consumption practices. The simulation of alternative scenarios makes it possible to evaluate their effects over time, capturing delays, rebound effects, and potential trade-offs between objectives. In this process, metrics, parameters, and indicators play a central role because they make the results of the simulated scenarios measurable and comparable. In SD models, indicators are incorporated as output variables (stocks, flows, composite indicators) that summarize the evolution of the system in terms of dimensions such as the use of virgin raw materials, waste generated, recycling rates and environmental impacts. In ABM, specific indicators measure the evolution of behaviors and interactions (rates of adoption of circular practices, configuration of cooperation networks, critical thresholds of diffusion). Impact assessment methods - particularly LCA, which can be integrated with LCC and Social LCA - enable the translation of scenarios into environmental, economic and social sustainability indicators, linking system dynamics to performance outcomes. These are complemented by circularity indicators developed by institutions such as the European Commission and the JRC (e.g., Circulating Material Use Rate, material footprint, recycling yield, secondary raw material share), which can be integrated into models to assess progress toward macro-level circularity targets. However, the systematic integration of these indicators into quantitative models is hindered by the lack of harmonized datasets, the absence of

standard interfaces between tools and the fragmentation of databases, suggesting the need to develop interoperable toolkits capable of linking dynamic modeling, stakeholder analysis and impact assessment through consistent and replicable sets of indicators. Finally, digital technologies are a cross-cutting and enabling element throughout the entire process. IoT, sensors, ERP systems, blockchain, and data integration platforms make it possible to collect large amounts of granular data in real time throughout the product lifecycle, ensuring traceability, continuous updating and the possibility of direct flow control. This data can feed into simulation models transforming the information assets into structured representations of the system on which to test and compare different circular scenarios. The integration of AI functions in such environments strengthens the ability to build adaptive, updatable models and to support decision-making processes in uncertain and rapidly changing contexts. In this perspective, ICT, databases and modeling and simulation methodologies converge in the construction of a *'CE Simulation-Based Decision Support System'*, capable of processing large amounts of data, representing the complexity of eco-industrial systems, simulating the effects of circular solutions and returning readable outputs for decision-makers. At the same time, technological and organizational barriers remain, including limited interoperability, complex information architectures, need to install and manage heterogeneous tools, lack of standards and structured data along supply chains and user-friendly interfaces, which hinder the full exploitation of this capability.

Overall, the research suggests that effective support for decision-making in the transition to the CE requires an integrated framework, built on a set of integrated methods and tools that meet the guiding criteria that emerged from the research process and that constitute the basic requirements for robust, replicable and evidence-based decision-making processes: *identifying and analyzing the actors involved; mapping production and logistics processes; identifying and quantifying material and energy flows; analyzing stakeholder networks; adopting a life cycle perspective; taking a multi-scale view; integrating spatial and geographical dimensions; considering the temporal evolution of systems and lag effects; including internal quantitative and qualitative variables; incorporating variables external to the production system; adopt consistent quantitative and qualitative indicators; import and integrate existing databases; simulate and compare short- and long-term scenarios; assess environmental, economic, and social impacts; be validated and calibrated with robust statistical methods; integrate with other decision support tools; ensure objectivity and replicability; provide for continuous monitoring and progressive updating*. The integration of methods and tools that meet these requirements, when implemented in a single, interoperable operating environment, can support decision-makers in the complex transition from linear to circular production models. This involves the design of an integrated tool based on an IT architecture capable of managing bidirectional

information flows, combining static and dynamic data from heterogeneous sources, and updating them in real time. This digital infrastructure becomes the connector between the operational and strategic dimensions, transforming raw data into useful knowledge to guide action. The effectiveness of the proposed path therefore depends on the ability to integrate ICT, analytical methods, and modeling and simulation in a modular, adaptive, and continuously updatable digital system that is truly capable of supporting the transition to a fully CE, based on systemic analysis, transparency, and measurable impacts.

FUTURE RESEARCH DIRECTIONS

The results of this thesis confirm that the transition to CE cannot be addressed solely on a theoretical level. Concepts, methods, and models must be translated into operational tools that can be applied to concrete systems. Based on the findings, several areas of future research have been identified that could reinforce the results obtained.

1. Integrated decision-making framework empirical validation

The proposed methodological framework (chapter 5) needs to be tested on field, through experimental applications in real and diversified production supply chains. Empirical validation is essential to verify its operational effectiveness, but also to assess its scalability, adaptability and ability to generate decision-making value in heterogeneous contexts from a technological, organizational and regulatory point of view. Although the thesis focused particularly on textile and sheep (involvement in the MAX-SHEEP project, which has led to the development of some software tests) supply chains, numerous other industrial sectors have different systemic configurations, requiring specific approaches. Applying the framework to sectors such as construction, electronics and mobility would make it possible to test its adaptability, identify recurring patterns, and highlight sector-specific requirements. It will be essential to explore participatory co-simulation methods, collaborative tools, and techniques to make the models accessible, understandable and useful to the various actors involved.

2. Development of interoperable data infrastructures

One of the most critical elements that emerged from the research concerns the absence of integrated IT architectures and databases. Future developments should focus on defining common standards for data collection, management and interoperability, ensuring quality, accessibility, sharing and traceability throughout the various stages of the supply chain. Only based on reliable data is it possible to build coherent dynamic systems and fully exploit the potential of 4.0 digitalization.

3. Advancement of dynamic models and their integration

Dynamic modeling represents a promising frontier but still partly unexplored. It will be necessary to further investigate:

- the integration between System Dynamics and Agent-Based Modeling;

- the adaptation of models to different sectors (e.g., textiles, construction, electronics, agri-food);

- the construction of multi-scale models capable of connecting micro-behaviors and macro-dynamics;

- the simulation of interactions between regulatory, technological, economic and social variables;

- the development and integration of circularity and sustainability indicators and metrics to support model calibration and scenario evaluation.

4. Further exploration of the role of IT and Artificial Intelligence in modeling processes

Initial experiments show that AI can accelerate model construction and calibration, facilitate scenario development and suggest structural improvements. However, important questions remain regarding the transparency, explainability, reproducibility and governance of these tools. Future research should promote the adoption of interpretable and reliable forms of AI that support decision-making without replacing it. The high energy and water consumption associated with advanced digital technologies raises questions that have yet to be fully explored about the sustainability of digitalization itself. Future studies could help quantify the trade-offs between the benefits in terms of decision-making and the environmental costs generated using ICT 4.0 infrastructure, data centers, AI and complex modeling and simulation tools.

5. Assessment of environmental, economic, and social impacts

A further line of research concerns the development of integrated impact assessment methodologies capable of combining environmental, economic and social dimensions. Although the thesis focused mainly on modeling processes and scenario exploration, future studies should investigate how the proposed models can be linked to Life Cycle Assessment (LCA). The integration of these dimensions would enable the quantification of trade-offs, the identification of undesirable consequences and the design of circular strategies that are not only environmentally beneficial but also economically sustainable and socially equitable.

APPENDIX

This section provides a critical analysis of the features offered by the software tested during the PhD program. For each software identified (*Figure A.1*), the following information was collected and systematized: area of use (i.e., the reference method), name, brief description and type, website link, availability and price, developer, date or version of the latest update, type of availability (open source or paid), language, free demo availability, main features, tutorials or training materials, supported file formats, export and sharing options, local or cloud use. For the testing phase, open-source software was primarily selected, as it proved to be applicable to the methods outlined in Chapter 3 and suitable for supporting the various operational phases without licensing or sharing restrictions. A few proprietary software solutions were also tested to provide a more comprehensive comparative evaluation of different tools and their performance.

Based on the experience gained through participation in projects such as "MAX-SHEEP" project, the considerations presented in this section evaluate the positive and negative aspects of each tool in relation to the objectives of *analysis, representation, modeling, circular scenario simulation, and assessment* (phases outlined in the methodological design) as well as their potential for joint use.



AMBITO	NOME	BREVE DESCRIZIONE E TIPOLOGIA	LINK WEB	Disponibilità/prezzo	PRODUTTORE	AGGIORNAMENTO (versione e anno)	DISPONIBILITA' (open o a pagamento)	LINGUA	DEMO GRATUITA	FUNZIONI	TUTORIAL	CORSO FORMAZIONE	FORMATO FILE	ESPORTAZIONE CONDIVISIONE	LOCALE O IN CLOUD
METODATA BASE	Ribo	3R SINNER SOLUTIONS - E' possibile compilare la lista dei componenti di varie attrezzat	https://mattonali.ribo.it/cart/cart.php?view=base	Contattare il produttore	Ribo S.R.L.	?	Contattare il produttore	Ita	?	https://mattonali.ribo.it/cart/cart.php?view=base	si	si	?	?	?
METODATA BASE	MON AME 5000	SOFTWARE GESTIONALE - Mon Ame 5000 è il programma customizzato per aziende, negozi, artigiani e liberi	https://www.monamet5000.it/	https://www.monamet5000.it/softwa re-gestionale-base.php	IDEA SOFTWARE s.r.l.	versione 8.0	A canone: Produzione base. A richiesta:	Italiano	si	https://www.monamet5000.it/softwa re-gestionale-base.php	si	si	PDF	si	Entrambi
METODATA BASE	CLOUDSENS	Cloudsens è un'applicazione web fra personale di campo e ufficio tecnico per la gestione delle	https://www.cloudsens.it/dotnetn uke/Default.aspx?ReturnUrl=%2f	https://www.cloudsens.it/dotnetn uke/Default.aspx?ReturnUrl=%2f	metmarprla	29/9/2022	A pagamento.	Italiano	si	https://www.cloudsens.it/dotnetn uke/Default.aspx?ReturnUrl=%2f	si	no	?	si	cloud
METODATA BASE	WINFAST	3R SINNER SOLUTIONS - Suite software gestionale Winfast specifica per la	https://www.winfast.com/Menu/Menu-area-unica-dirittifa-.html	https://www.winfast.com/Menu/Menu-area-unica-dirittifa-.html	Adriatica Sistemi Soc. Coop.	10.03.0 - 30/03/2022	A pagamento.	Italiano	si	https://www.winfast.com/Menu/Menu-area-unica-dirittifa-.html	si	no	?	?	Entrambi
METODATA BASE	BRAVO MANUFACTURING	MES - Bravo Manufacturing è il sistema MES che permette di monitorare tutte le fasi di	https://www.bravomanufacturing.it/software-mes-produzione-macchine/	https://www.bravomanufacturing.it/software-mes-produzione-macchine/	Anton S.r.l.	5.7.3. - 5/10/2022	Open e a pagamento	Italiano	si		si	si	pdf	si	locale
METODATA BASE	ATLANTIS ENO	SOFTWARE GESTIONALE AZIENDALE - Il modulo Outcome Base permette creare in diverse fasi	https://www.atlantisweb.com/portal/it/outcome-distinta-base	Chiamare: 0541-1647432. Mail: info@atlantisweb.com	Eco-Solution	20.0 - 15/09/2021	A pagamento.	Italiano	si	https://www.atlantisweb.com/portal/it/outcome-distinta-base	si	no			Entrambi
FLOW CHART DI PROCESSI/ATTIVITA'	darTertain Logical per reti informatiche (cookie se si può definire il principio produttivo)	Tipo di software: IT - applicazione software per reti	https://graphicsbuster.info.com/darterlain-logical-per-reti-informatiche-cookie-se-si-puo-definire-il-principio-produttivo/	GraphicsBuster.info.com/darterlain-logical-per-reti-informatiche-cookie-se-si-puo-definire-il-principio-produttivo/	Graphical networks	?	A pagamento. Chiedere il prezzo al produttore.	Inglese	si	Scoprire e mappare i network; Connettere e risparmiare gli strumenti; Visualizzare future infrastrutture;	No	No. Sul sito è presente il Blog e il supporto.	PDF export; PowerPoint; Visio export; KML export	condivisione in tempo reale	Cloud
FLOW CHART DI PROCESSI/ATTIVITA'	Creately - MINDMAPPING	Tipo di software: mappamentale. Complesso. Permette per il disegno di diagrammi per progettazione di	https://app.creately.com/diagram/ZzdpdmRzZ2Rp/edit	https://app.edraw.com/it-it/editor?id=5f4e6d1b1e7ae70a6c2e3f4a&type=mindmap	CAD Schroer GmbH	?	A pagamento.	Italiano/inglese/tedesco	si		si	si	Importa/esporta esportazione file in formato DXF e DWG	condivisione in tempo reale/ si con licenza di rete	Cloud. Scaricabile anche in locale
FLOW CHART DI PROCESSI/ATTIVITA'	Terrastruct	Tipo di software: IT - architettura software. media-alta difficoltà. Complesso	https://www.terrastruct.com/#Terrastruct	https://www.terrastruct.com/#Terrastruct	Terrastruct	?	A pagamento	Inglese	si - 7 giorni	https://play.terrastruct.com/diagrams/1011967206#board=2049178249	no - solo dei documenti informativi ed esempi	no	?	?	App in cloud
FLOW CHART DI PROCESSI/ATTIVITA'	Visual Paradigm	Tipo di software: media difficoltà. Semplice la creazione di diagrammi anche più complessi	https://www.visual-paradigm.com/	https://www.visual-paradigm.com/download/?gclid=Cj0KCQjwwJ-SBhCoARIsAIJ3Ce_Ze2qnCSeiwm_0mjmDmO	Visual Paradigm	versione 17.0	A pagamento.	Inglese	si	https://www.visual-paradigm.com/guide/uml-unified-modeling-language/what-is-uml/	si	si	Supporta: UML, BPMN, ArchiMate, DFD, IDEF, SysML, C4, Mockup	si, condivisione real-time	in cloud
FLOW CHART DI PROCESSI/ATTIVITA'	GitMind	Tipo di software: media/bassa difficoltà. Software pensato per disegnare flowchart e altre tipologie	https://gitmind.com/	https://gitmind.com/it/	WANGJU TECHNOLOGY (HK) CO., LIMITED	?	A pagamento.	Italiano/inglese/altre lingue - a scelta	si	GitMind permette di creare diverse tipologie di mappe, diagrammi e flowchart: mappe mentali,	si	no	Esporti in JPG, PNG, PDF, WORD, SVG, TXT, GITMIND	condivisione in cloud, Collaborazione in team - si può condividere con un link modificabile	Cloud. Scaricabile anche in locale
FLOW CHART DI PROCESSI/ATTIVITA'	EdrawMax - EdrawPdf	Tipo di software: media/bassa difficoltà. EdrawMax – permette la creazione di diverse tipologie di	https://www.edrawsoft.com/it/edraw-pdf.php?ref=ad_search_edrawpdf_it_text&gclid=Cj0KCQjwwJ-SBhCoARIsAIJ3Ce_Ze2qnCSeiwm_0mjmDmO	https://www.edrawsoft.com/it/mindmap.html	Edraw	Versione: 11.5.4 per Windows. Versione: 11.5.5 per Mac. Versione:	Canone/abbonamento annuale - per le funzioni più avanzate a pagamento	Italiano - è comunque possibile selezionare la lingua	si	Grafici e diagrammi di flusso- Progettazione di Planimetrie - Rappresenta elettrica - Pianificazione	no	no	Esporti in immagine (JPG, PNG, BMP, SVG, EMF, TIFF), PDF, WORD, EXCEL, PPT, SVG, HTML, VISIO, PSD,EPS	Su cloud condivisione con il team.	Locale/ Cloud e locale
FLOW CHART DI PROCESSI/ATTIVITA'	Gaudi Suit	Tipo di software: media/bassa difficoltà. Permette la creazione di diagrammi semplici, mappe	https://lucidchart.com/pages/it?gclid=Cj0KCQjwwJ-SBhCoARIsAIJ3Ce_Ze2qnCSeiwm_0mjmDmO&utm_source=google&utm_medium=cpc&utm_campaign=1120_Search_Brand_Exact_IT&utm_term=lucidchart&utm_content=Lucidchart_Exact_IT	Gaudi Software Inc.	?	Versione gratuita e A pagamento.	Italiano, inglese e molte altre lingue	si - studenti e insegnanti possono usufruire del piano education	si	Collaborazione in team nella realizzazione dei diagrammi (in tempo reale). Integrazione con altre	si	si	Importazione ed esportazione di Visio; Importazione Omni (in Suite); Importazione Cloud (suffic	Si, condivisione	in Cloud
FLOW CHART DI PROCESSI/ATTIVITA'	Google Drawings	Tipo di software: bassa difficoltà. Google Drawings è una forma a diagrammi semplici	https://docs.google.com/drawings/u/0/?tgif=d&gclid=Cj0KCQjwwJ-SBhCoARIsAIJ3Ce_Ze2qnCSeiwm_0mjmDmO	Gratuito	Google	25/9/2019	Gratuito	Italiano	no	Uno semplice grafici e appunge diagrammi, documenti, presentazioni e altri tool	si	no	esportazione in: PDF, JPG, PNG, svg	si condivisione in team e real time	in cloud
FLOW CHART DI PROCESSI/ATTIVITA'	Gliffy	Tipo di software: bassa difficoltà. Creazione di diagrammi semplici per: aziende, progetti di	https://www.gliffy.com/	https://www.gliffy.com/pricing/	Perforce	In locale: versione 7.13.0 - 7.20.2 dal 2022-11-07 ultimo aggiornamento in cloud: 2022-11-11	A pagamento	Inglese	si	Creazione diagramma in team, collaborazione istantanea, senza confusione di lavoro grazie alle	si (no - video introduttivi e blog	no - sono presenti dei casi studio	esportazione in: JPEG, PNG e SVG.	si. In locale esportazione e in cloud condivisione real time.	locale e in cloud: a scelta
FLOW CHART DI PROCESSI/ATTIVITA'	Cacoo	Tipo di software: bassa difficoltà. Creazione di diagrammi semplici, di modello creare anche diagrammi di	https://cacoo.com/	https://cacoo.com/it/pricing	Nulab	?	A pagamento	Inglese	si	https://cacoo.com/it/pricing	si	no	Export as SVG, PDF, PowerPoint, and more.	Share diagrams via a link, email, or social media.	in cloud
FLOW CHART DI PROCESSI/ATTIVITA'	Visme	Tipo di software: bassa difficoltà. Il software permette di creare (Visme è disponibile anche tramite un ba	https://www.visme.co/it/	https://www.visme.co/it/pricing/	Easy Web Content, Inc. (DBA Visme)	?	A pagamento e gratuito	Inglese/italiano	si - versione gratuita	Oltre alla creazione di flowchart, Visme è anche un ottimo strumento per la creazione (non) studenti)	si	si	Image, PDF, Video, GIF, Powerpoint, Keynote, HTML5	si, condivisione in cloud	in Cloud
FLOW CHART DI PROCESSI/ATTIVITA'	Miro	Tipo di software: bassa difficoltà. E' possibile creare flowchart semplici. Miro è disponibile anche per la	https://miro.com/it/diagramma-di-flusso/	Per altre soluzioni: https://miro.com/it/pricing/	Miro	?	Modulo per flowchart: Gratuito	Italiano/inglese	si - versione gratuita	Con Miro Smart Diagramming, si può disporre di macchi accesso più si ottimizzi, per AWS, Azure e Cisco, e	si	si	Image, PDF, CSV	Condivisione in tempo reale. Collaborazione a lim, GoogleDrive	in Cloud
FLOW CHART DI PROCESSI/ATTIVITA'	OmniGraffle	Tipo di software: bassa difficoltà. Disponibile solo per Mac. Strumento per disegnare diagrammi	https://www.omnigroup.com/omnigraffle	https://store.omnigroup.com/omnigraffle/	Omni Group	Versione - Mac: v7.21; iPad e iPhone: v5.19	A pagamento	Inglese	si, per 14 giorni	https://www.omnigroup.com/omnigraffle/	si	no	Esportazione: JPG, GIF, BMP, TIFF, PDF, SVG. Importazione: SVG.	Condivisione su tutti i dispositivi i MAC. Collegamento con Visio	locale
FLOW CHART DI PROCESSI/ATTIVITA'	Draw.io	Tipo di software: bassa difficoltà. Una semplice alternativa, anche per chi non ha esperienza	https://draw.io-app.com/	https://draw.io-app.com/pricing/	Sébastien Cerpentier Pte (?)	?	A pagamento	Inglese	si	Utilizzato per diverse tipologie di diagrammi: Software, Network, and Engineering, Business, Charts, and	si	no - sono presenti video e casi studio	PNG, JPEG, SVG, PDF, VSDX (beta), HTML, URL, ecc.	si	Cloud e in locale
FLOW CHART DI PROCESSI/ATTIVITA'	Creately	Tipo di software: bassa difficoltà. Una semplici diagrammi: flowcharts, Mind Maps, Concept	https://creately.com/	https://creately.com/it/plans/	Creately	?	A pagamento	Inglese/italiano	versione gratuita	https://creately.com/it/app-di-creately/	si	no	?	si	in Cloud
SANKEY DIAGRAMS	Sankey Flow Show	Tipo di software: bassa difficoltà. Una piattaforma per Sankey semplici	https://www.sankeyflowshow.com/?gclid=Cj0KCQjwwJ-SBhCoARIsAIJ3Ce_Ze2qnCSeiwm_0mjmDmO	https://sankeyflowshow.com/pricing/	FLOWTEC Software GmbH	?	Versione gratis e a pagamento	Ing	si	https://sankeyflowshow.com/pricing/	si	no	?	Salvataggio su Google Drive, possibilità di condivisione con più	cloud - online, direttamente sul browser
SANKEY DIAGRAMS	eSankey 4.0	Tipo di software: media/bassa difficoltà. Una diagramma di bandaa a partire da un fenlio di	https://www.ifu.com/e-sankey/	https://www.ifu.com/e-sankey/order/	Ifu Hamburg GmbH	24/11/2022	Versione gratuita e A pagamento.	Ita	si - versione di prova	https://www.ifu.com/e-sankey/features/	no	?	?	Commessione con excel.	Locale
SANKEY DIAGRAMS	SankeyMATIC	Tipo di software: media/bassa difficoltà. Una diagramma online molto semplice. Non	https://sankeymatic.com/build/	https://sankeymatic.com/build/	Steve Bogart	8/11/2022	open	Ing	si	Java app: https://www.npmjs.com/package/sankeymatic	no	no	PNG, SVG	esportazione in formato file.	in cloud
SANKEY DIAGRAMS	R	Tipo di software: media/alta difficoltà. è possibile utilizzare il pacchetto la lettera sankey e	https://it.sistemi.ovh/sistemi/sankey-con-r/	Gestito da « R Core Team e della R Foundation for Statistical Computing »		31/10/2022	open	ing/ita	-	Software utilizzato per la modellizzazione di dati	si	si	PNG, JPEG, TIFF, BMP. Si può	esportazione in formato file	locale
SANKEY DIAGRAMS	Qlik	Tipologia di software: media/bassa difficoltà. Una diagramma semplici, è possibile inserire più seguiti con i	https://help.qlik.com/it-IT/sense/February2022/Content/Sense_Visualizations/SankeyChart.htm	QlikTech International AB.	v9.0.2	?	A pagamento	ing/ita	si	https://help.qlik.com/it-IT/sense/February2022/Content/Sense_Visualizations/SankeyChart.htm	no	?	?	?	in cloud
SANKEY DIAGRAMS	The Sankey Diagram Generator	Tipologia di software: media/bassa difficoltà. Una diagramma semplici, è possibile inserire più seguiti con i	https://sankey-diagram-generator.acquia-pcs.com/	Acquia Procurement Services	?	open	ing	si	?	?	?	SVG	Condivisione via mail - esportazione in SVG	sul browse
SANKEY DIAGRAMS	Displayr	Tipologia di software: media/bassa difficoltà. Permette di creare diverse tipologie di visualizzazione	https://www.displayr.com/sankey-diagram/	https://www.displayr.com/pricing/	Displayr	?	a pagamento - versione base gratuita	ing	si	https://help.displayr.com/hc/en-us/articles/360039293063-Displayr-Features-Overview	no, ma ci sono molti materiali online				

Figure A.1 *Software identification*

The software was selected following a preliminary review of the main tools available for each method considered (see Chapter 3)

1. ANALYSIS

The analysis phase is the preliminary step to the representation of a system and aims to collect, organize, and interpret the information necessary to understand the production system under study. The activity is based on the integration of various sources of information, including scientific literature, secondary documentation, sector reports, available databases, and interviews with the actors involved. Through this exploration, it is possible to outline the structural and operational characteristics of the system under study, identify the main flows and processes, identify key variables, and understand the factors that can influence the application of CE solutions. The information base thus constructed constitutes the foundation on which the subsequent phases of representation, modeling, and simulation are developed, guiding the methodological choices of the entire process.

2. REPRESENTATION

The representation phase aimed to describe the functioning of the analyzed system in a clear and structured manner. Starting from the data collected in the analysis phase, Flowcharts, GIS, and SNA elaborations were developed to reconstruct the main flows, the interactions between the operating units, and the overall configuration of the system. For this phase, the following software were tested: Draw.io [2] for Flowcharts, QGIS [3] for Geographic Information (GIS) analyses, and Netdraw (UCINET)[4] for Social Network Analysis (SNA).

- Draw.io software was used to create Flowchart, as it is a useful tool for building visual maps and process diagrams. This activity made it possible to highlight key elements, interdependencies, and distinctive features of the system under study (*Figure A.2*). Compared to traditional and widely used software for presentations and creation of graphic materials, Draw.io proved particularly suitable for representing complex and larger systems, thanks to the ability to expand the workspace flexibly and place blocks in a flexible manner. However, when the diagram includes many components, the individual parts are not very visible, especially when viewed on screen or printed in a small format. To overcome this limitation, the system could be divided into separately represented subsections or explored through interactive tools that enable zooming and dynamic navigation of the diagram, for example, by exporting the file in a navigable HTML format or integrating it into digital presentations

[2] diagrams.net: https://www.drawio.com/ (Accessed on: 27/11/2025)
[3] QGIS software: https://qgis.org/download/ (Accessed on: 27/11/2025)
[4] Analytic Technologies, UCINET software: https://sites.google.com/site/ucinetsoftware/home (Accessed on: 27/11/2025)
Netdraw: https://sites.google.com/site/netdrawsoftware/download (Accessed on: 27/11/2025)

with expandable layers. In this regard, Draw.io allows users to save files on cloud platforms such as Google Drive or Microsoft OneDrive and to activate real-time collaboration features (e.g., visible user cursors, changes visible in real time) through shared access. It should be noted that for some application, especially when it is important to highlight the intensity of flows (e.g., quantity of material or energy transferred between processes), it may be useful to have tools that integrate dynamic elements or Sankey-type visualizations, where the flow density represents the quantity associated with that flow. Currently, these features are not easily accessible in the main generalist block diagram tools (as Draw.io), which nevertheless have the advantage of being free and easily accessible to anyone. On the other hand, tools that offer more advanced forms of representation, such as dynamic Sankey diagram or visual analytics tools, are generally not open source and often require payment, which limits their large-scale use.

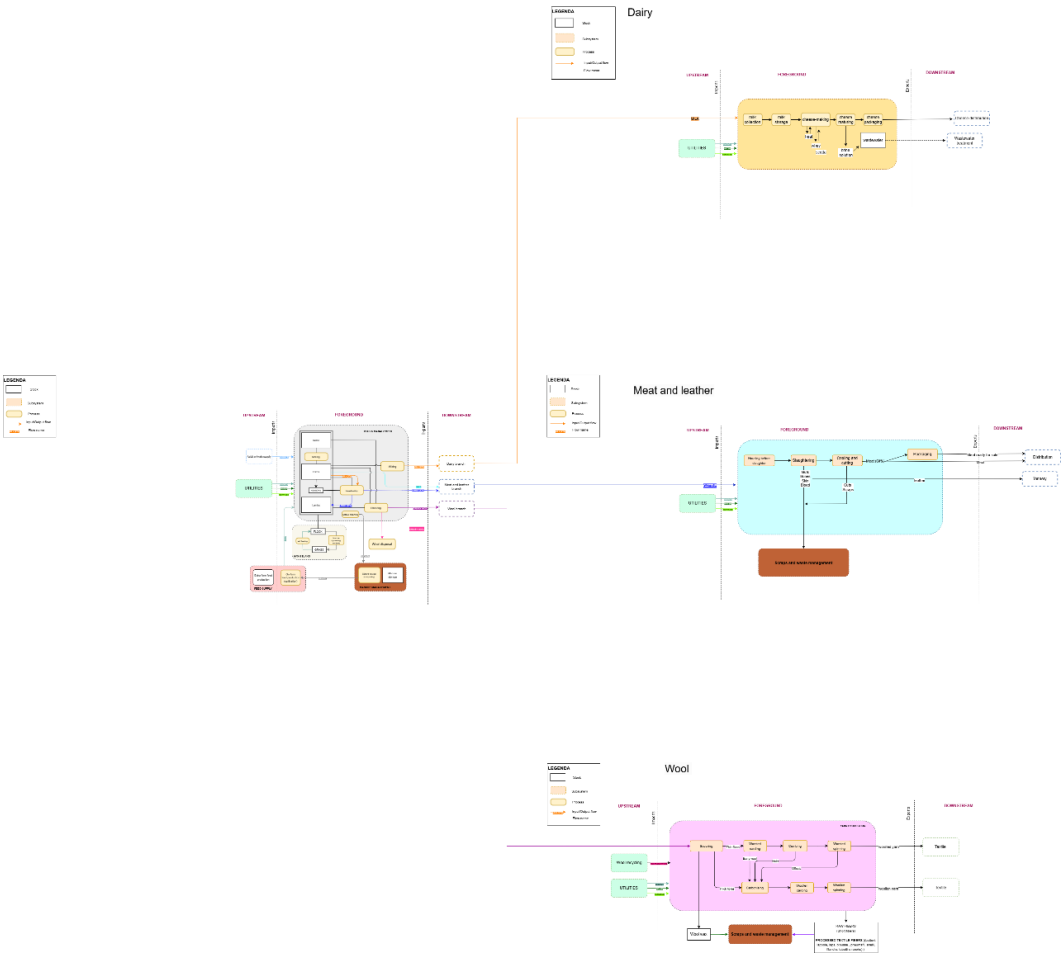


Figure A.2 *Draw.io representation*

- The use of QGIS has made it possible to geolocate the key actors in a supply chain and map their geographical distribution, integrating both quantitative and qualitative data (*Figure A.3)*. However, it proved complex to represent the physical characteristics of the territory, such as morphology, land use, or altimetry, in a concise but legible manner. Furthermore, when the number of points on the map is high, it is difficult to distinguish them visually, even when using codes for size or color. For example, an attempt was made to proportion the size of the points to a certain quantity produced, but in the presence of high density and significant volume mismatch, the representation was not very effective because the smaller points tended to disappear, while the larger ones dominated the others, resulting in a map that was difficult to read. In addition to these aspects, there are also some additional critical issues typical of the use of QGIS in this type of analysis: i) limited management of overlaps - in the presence of very close or coinciding points, the data associated with each point cannot be easily viewed in QGIS without performing manual operations or relying on dedicated plugins; ii) rigidity in advanced proportional symbology - graduated or proportional representation does not always provide a good visual balance, especially when the data has a very asymmetrical distribution (e.g., extreme values and many zeros); iii) native absence of multivariate synthetic representations - QGIS does not offer immediate tools to display multiple variables simultaneously on the same layer (e.g., combinations of quantity and quality), making it necessary to use more complex solutions such as multiple layers or pre-mapping processing in other software; iv) difficulty with interactive export - once the map has been created, its use is limited to static images or QGIS projects, while interactive exports (e.g., web maps, zoom, dynamic filters) require specific plugins (e.g., QGIS2Web). The use of plugins becomes essential, especially when geographical coordinates are not present in the database and addresses need to be geocoded using dedicated algorithms. However, free solutions have significant limitations in terms of data management, with the risk of information loss, as some points may not be geolocated correctly or may not be geolocated at all. Despite these limitations, QGIS is a valuable tool for spatial exploration and georeferencing of territorial data, especially thanks to its open-source nature and the wide availability of plugins and customization features.

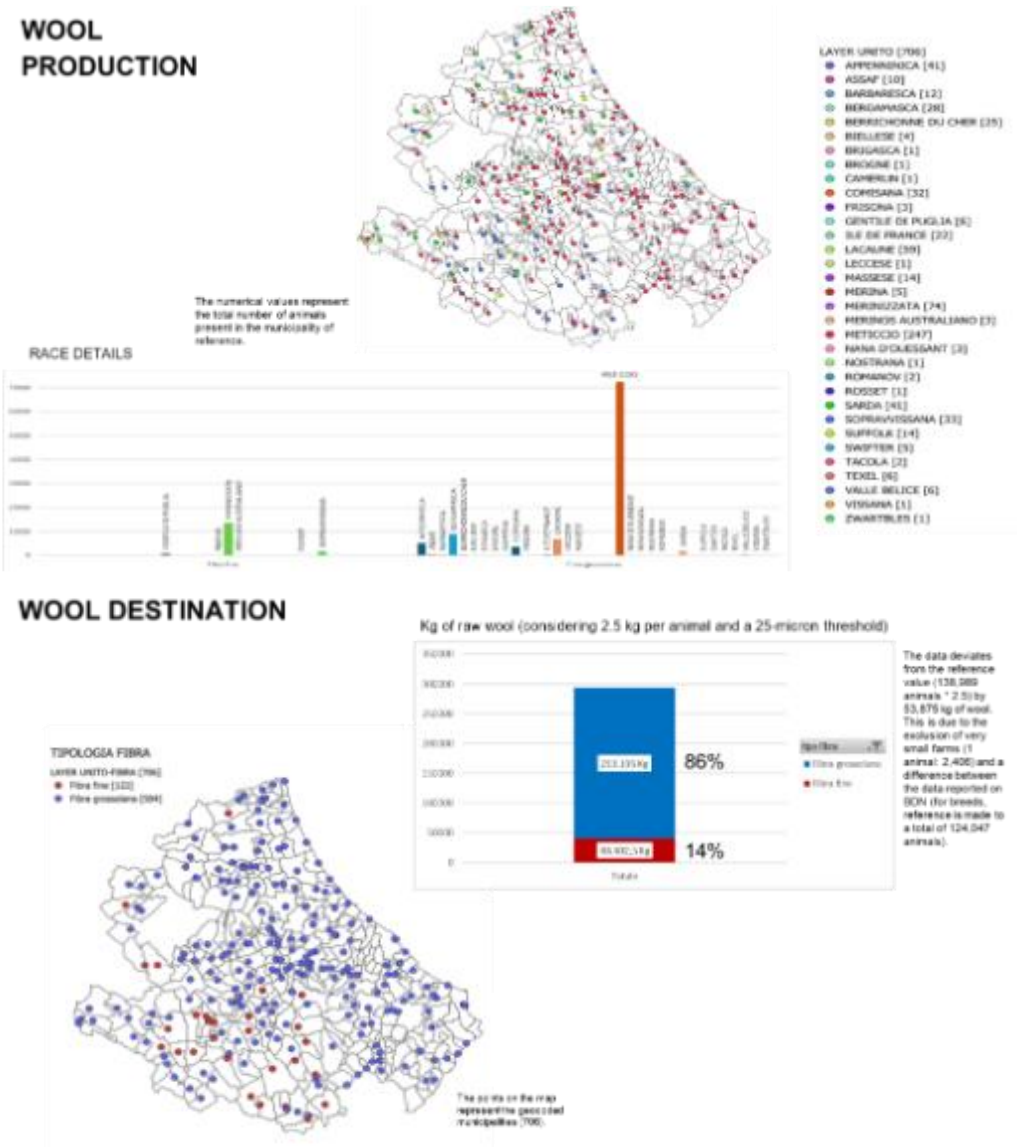


Figure A.3 *GIS analysis with QGIS software*

- The representation obtained using **NetDraw**, software integrated into the UCINET package, was used to visualize the supplier network (*Figure A.4*). The aim was to identify the relationships between the various actors, highlight direct and indirect connections, and analyze any possible concentrations or centralities along the supply chain. The software proved useful for distinguishing nodes based on size (e.g., according to the number of links or the quantity supplied) and for representing distances between nodes proportionally, facilitating visual interpretation of the network structure. The automatic layout features and the ability to apply coding for node shape, color, and size helped highlight some key patterns in the supply network. However, during use, several limitations of the tool also emerged, especially from an operational and visualization perspective: i) unintuitive and outdated interface, with some difficulty for those unfamiliar with network language or the UCINET

environment; ii) poor interactivity of the visualization, once the network has been generated, it is not possible to navigate it dynamically (e.g., zoom, filters, info on individual nodes) without exporting the data to other more advanced environments; iii) despite offering basic modification options (color, shape, size), the software has limited graphic customization capabilities and does not support the integrated representation of complex or multivariable information (e.g., quantity, category, position); iv) lack of direct integration with geographic or temporal data, networks remain nonrepresentational, with no possibility of anchoring them to space-time dimensions, unless external processing is used; v) difficulty in exporting to high-resolution vector formats, which makes it less easy to insert visualizations into documents without loss of quality; vi) limited collaboration, there are no collaborative file sharing features for network files, and visualization is restricted to the NetDraw/UCINET environment. Despite these limitations, NetDraw has proven to be useful software for synthetic representations of social or organizational networks, more appropriate in the exploratory phase or for highlighting recurring relational configurations within complex systems.

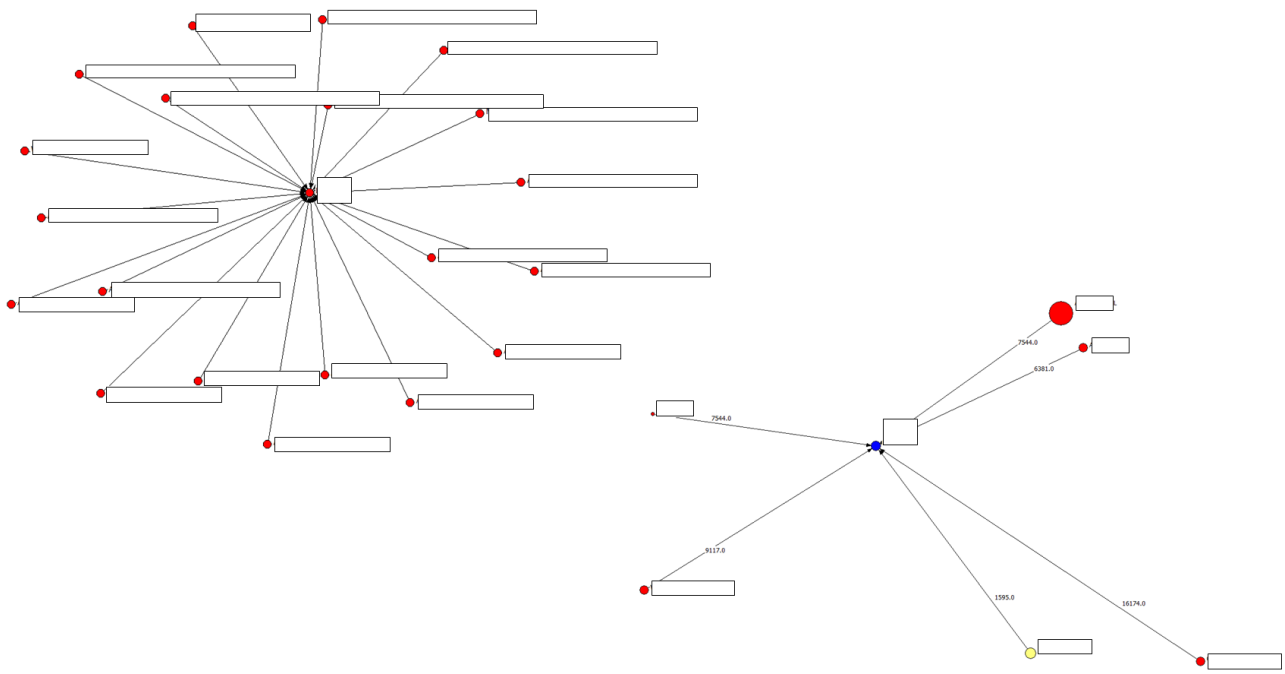


Figure A.4 *SNA with NetDraw (UCINET) software*

3. MODELING

The modeling phase involved a rethinking of the previously developed representation, with the aim of reorganizing the information into a form more responsive to the case study under analysis. The processes, flows, and relationships identified during the representation phase were reinterpreted and restructured to highlight the key elements of the system, the relevant dynamics, and the possible levers for intervention. This reworking made it possible to transform the initial description into a quantitative structure that was more focused and functional to the objectives of the analysis. This phase included several methodological activities and software such as the quantification of flows using MFA and Sankey Diagrams with LCA For Experts[5] and RStudio[6] software, the construction of Causal Loop Diagrams (CLDs) with Vensim[7], Stella Architect[8], and Simile[9], the construction of Stock and Flow Diagrams (SFDs) and simulation with Simile and Stella Architect. In this phase, it also begins to model potential CE solutions applicable to the system, verifying their actual implementation in the system under analysis.

- Sankey diagram (*Figure A.5*) representation proved particularly useful for highlighting the direction and quantity of flows, as it uses proportional arcs to visually render the order of magnitude of relationships between parties. The use of RStudio offered good flexibility in customizing the diagram, enabling the differentiation of categories through color, the orderly structuring of network levels, and the association of flow volumes with arc width, thereby improving the visual readability of quantitative information. It was also possible to export the visualization in interactive format (HTML), useful for dynamic presentations or sharing. However, the construction of the diagram required a preliminary analysis phase, necessary to select only a few significant categories within the dataset, since the presence of a large amount of data makes the representation visually ineffective. When the number of flows or categories is too high, the effectiveness of Sankey diagram is drastically reduced as the lines overlap, labels become illegible, and the overall structure loses clarity. Furthermore, the process of constructing the graph is not immediate, as it requires a specific reorganization of the data into a format compatible with the package used and every change, even the smallest, must be implemented directly in the code. Added to this is the difficulty in controlling the graphic layout which can be rigid, and the complex management of labels, especially in the presence of long names or closely spaced nodes. Finally, the interactive output is effective in digital

[5] Sphera: https://sphera.com/solutions/product-stewardship/life-cycle-assessment-software-and-data/ (Accessed on: 27/11/2025)
[6] Posit: https://posit.co/download/rstudio-desktop/ (Accessed on: 27/11/2025)
[7] Ventana Systems: https://vensim.com/software/ (Accessed on: 27/11/2025)
[8] Isee systems: https://www.iseesystems.com/store/products/stella-architect.aspx (Accessed on: 27/11/2025)
[9] Simulistics: https://www.simulistics.com/software.htm (Accessed on: 27/11/2025)

environments, but is not always suitable for printing or inserting into static documents, where it is often necessary to resort to simplified versions or high-resolution images. These limitations highlight how Sankey diagrams, while effective for visualizing proportional flows and their relative magnitudes, are less suitable when the objective is to obtain a clear and structured overview of the system's configuration. For this reason, the analysis needs to be supplemented with an MFA supported by block-based visual representations, which make it possible to organize flows into clearly defined categories and process stages. This type of visualization helps simplify complex systems and makes it easier to distinguish their main components.

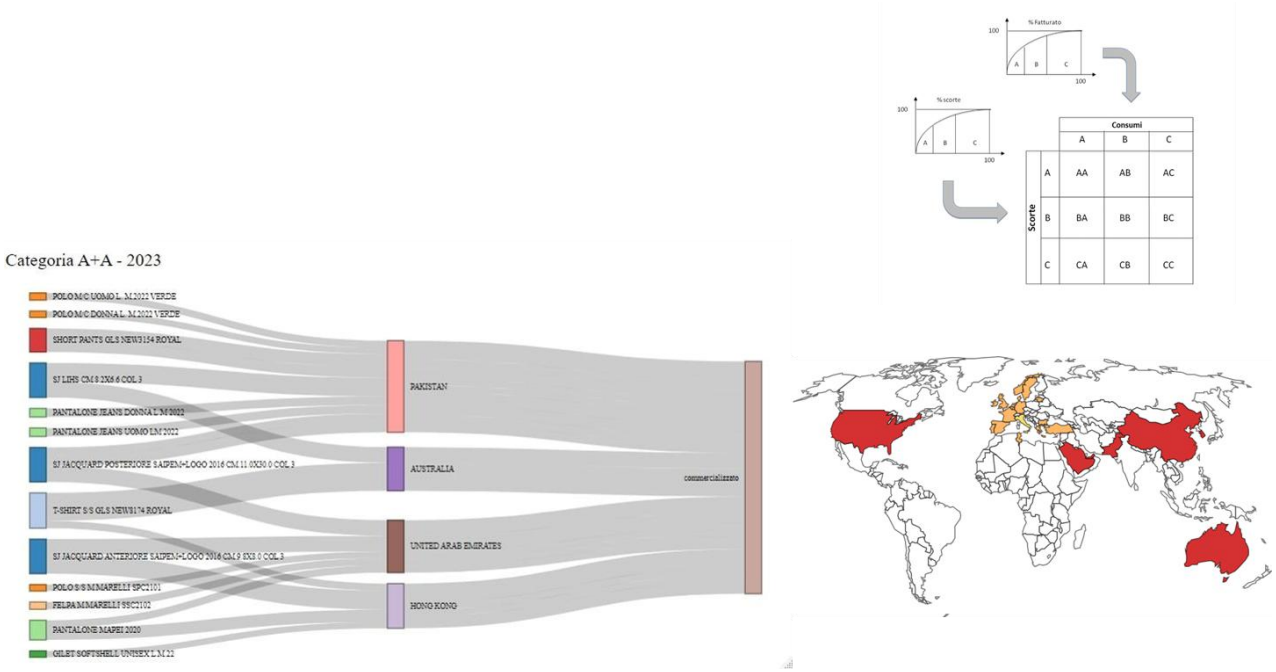


Figure A.5 *Sankey Diagram with RStudio software*

- *Figure A.6* shows the MFA of the system developed in the representation phase *(Figure A.2)*. The **LCA For Expert software** was used for this activity, which proved to be a useful tool for structuring and quantifying the flows within the analyzed system. The software enables the creation of processes and flows and their grouping into plans (sets of processes), which can represent specific segments of the system or other related supply chains. This provides additional workspace in which to build further diagrams, maintaining an organized and modular structure. Once the model has been constructed, the intensity of the flows can be viewed based on the associated quantities, enabling an immediate reading of the system's main directions. Although flows can be distinguished by color, the software represents their size correctly only when they are expressed in the same unit of measurement. Flows with different units can be displayed, but they are not directly comparable in terms of size. Furthermore, when flows have very different sizes, the smaller ones tend to become graphically uniform and

visually indistinguishable, thus reducing the communicative effectiveness of the model. It should also be noted that LCA For Expert was created as software dedicated to Life Cycle Assessment (LCA), and not as a native tool for systemic modeling activities. This leads to some critical issues when using it for modeling purposes, particularly in the management of complex structures, in the flexibility of representation, and in the customization of flows and relationships between processes, which are limited compared to other environments more specifically oriented towards system modeling. From an operational point of view, further functional limitations have been identified, for example, the elimination of a single flow automatically involves the elimination of other flows that may be connected to it, without the possibility of controlling the dependencies between nodes in detail. Furthermore, there is no undo function (such as the classic "Ctrl+Z"), making editing more rigid and increasing the risk of accidental loss of complex configurations. Also, since there is no open access or free viewer version available, it is not possible to collaborate effectively with other users who do not have a software license, effectively compromising any possibility of reviewing or co-developing the model by parties outside the direct work referent. Despite these limitations, the software provided a valuable visual tool to the supply network analysis, enabling an immediate understanding of flow concentrations, interdependencies, and potential levers for intervention.

- The first modeling of circular solutions was carried out using LCA For Expert software, with the aim of providing a preliminary representation of the effects of the proposed solutions in terms of material flows (MFA) (Figure A.7). In this context, the software made it possible to construct dedicated plans, each of which represents the development of a specific circular solution under consideration. This first phase made it possible to visualize and quantify the main effects on the material balance resulting from the introduction of the circular solution. Although this is a simplified representation, it provided a useful basis for comparing alternative scenarios.

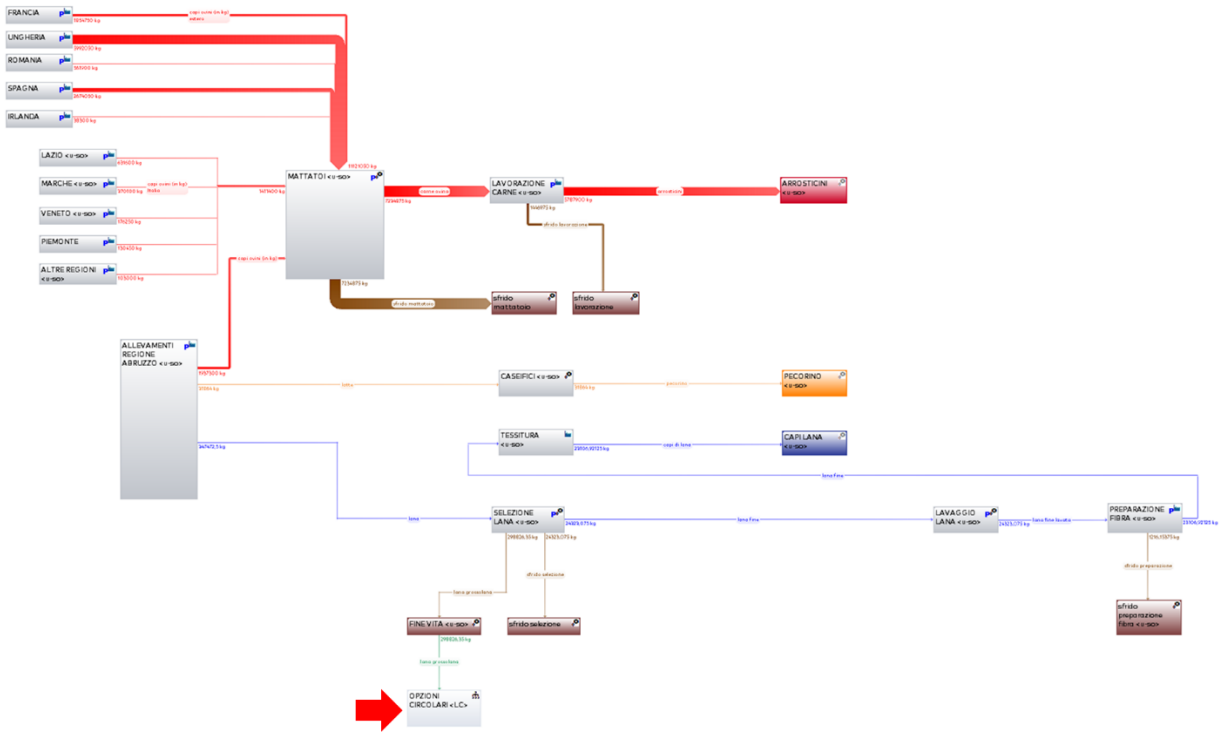
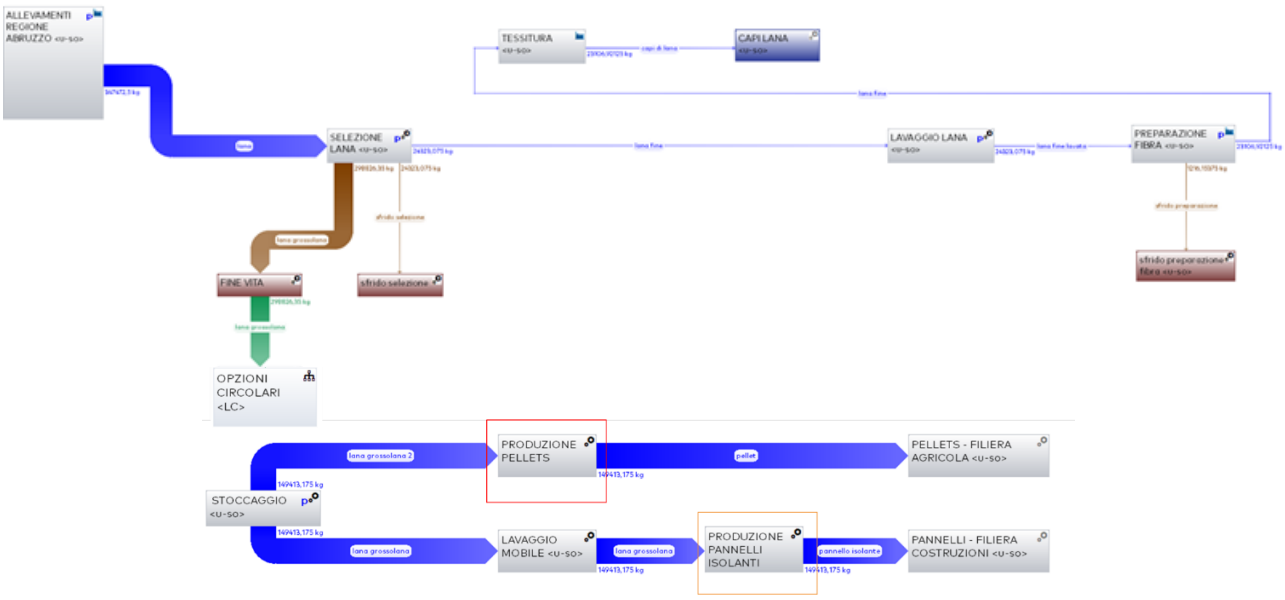


Figure A.6. *MFA with LCA For Experts software*



Actors Pellets

Tecnolpall srl	Teramo
L.e.a. srl	Teramo
Sirolli srl	Chieti

Actors Insulation panels (Italy)

Brebey tech S.r.l.	Sardegna (Cagliari)
Isolana System Srl	Toscana (Prato)
Nordtex	Trentino Alto Adige (Bolzano)
Hackustica	Puglia (Bari)
Case in legno De Prà	Veneto (Treviso)

Figure A.7. *Modeling CE solutions with LCA FE software*

- During the modeling phase, a CLD (*Figure A.8*) was also developed using **Vensim** software with the aim of representing the causal relationships between key variables and supporting the identification of the main dynamic mechanisms underlying the observed behaviors. This type of representation made it possible to highlight the feedback loops (positive and negative) that influence the evolution of the system over time, and to set the conceptual basis for any subsequent dynamic simulations. Vensim proved to be an effective tool for constructing the diagram, offering a good logical structure and useful features for defining dependencies between variables. A particularly positive aspect is the possibility of creating modules or subsystems, which makes it possible to divide the model into manageable parts, improving readability and facilitating the management of complexity in cases where the system is structured across multiple levels. However, some operational limitations have also emerged, particularly related to the visualization of large models. As the diagram grows in terms of the number of variables and connections, the overall visualization becomes difficult to read, and when printing or exporting to static formats, the clarity of the design is lost, making it difficult to follow the links between variables. Furthermore, although Vensim makes it possible to move, group, and customize graphic elements, it does not offer advanced automatic layout or interactive export functions, which can limit the communicative effectiveness of the diagram in sharing or presentation. A further limitation concerns collaboration possibilities, in fact the software does not provide specific features for teamwork or simultaneous model sharing among multiple users, making it necessary to resort to sequential working methods (e.g., sharing .mdl files via email or cloud), which slow down comparisons and increase the risk of misaligned versions. This aspect is particularly critical in multidisciplinary projects, where dynamic modeling requires input and validation from multiple parties. Overall, the use of Vensim represented an important shift toward formalizing dynamic links within the analyzed system, but it also highlighted the need for complementary tools or alternative graphical solutions when the goal is to communicate complex models or work collaboratively and iteratively.

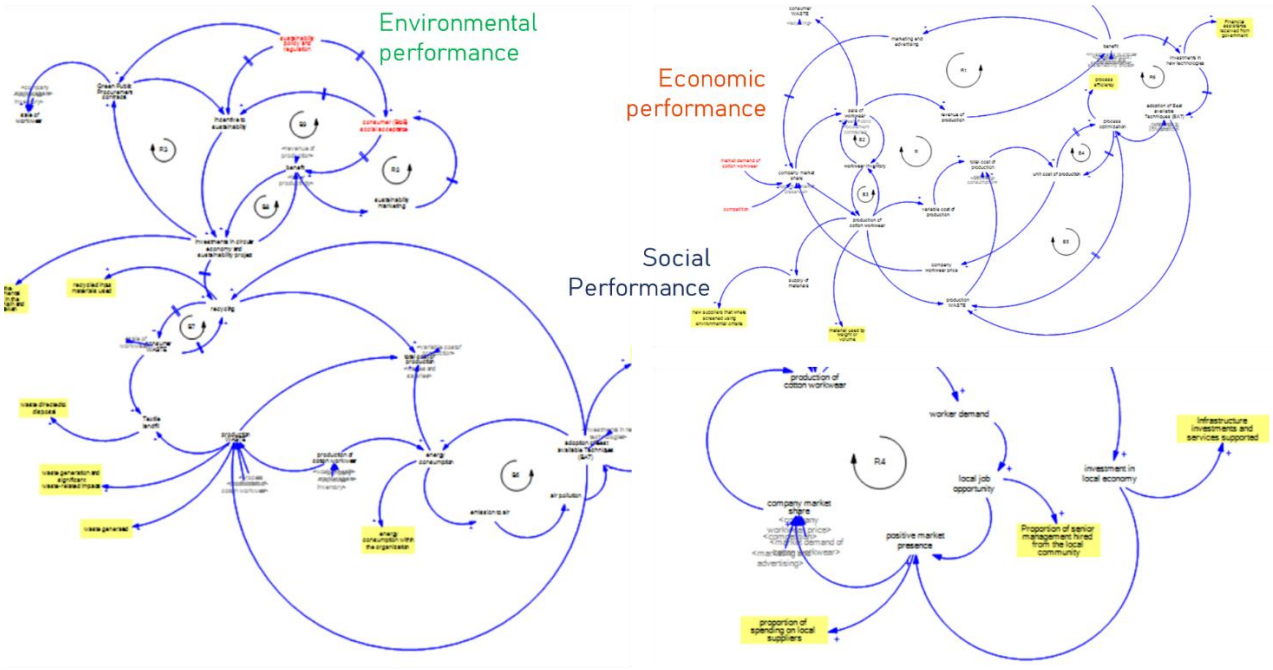


Figure A.8 *Causal loop Diagrams (CLDs) with Vensim software*

- Another CLD was developed using Stella Architect software (*Figure A.9*). The clear graphical interface facilitated the organization of variables and the reading of feedback loops that characterize the dynamic behavior of the system. However, when the model becomes extensive, the overall visualization becomes complicated, especially when printing or exporting, with a significant loss of readability. Furthermore, the model is developed on a single graphic area, which can make it difficult to manage complex models with many interconnected variables. Although the software supports the creation of modules, only the interface variables between the different modules are visible in the main interface, not the complete set of variables. Added to this is the fact that Stella Architect is proprietary, paid software. While its high license cost can limit accessibility, models can easily be shared for free with non-licensed users via 'isee Player' or by publishing interactive simulations on the 'isee Exchange'. However, there are no native features for real-time simultaneous collaborative modeling. A distinctive feature is the ability, during interactive visualization, to visually highlight causal loops in the system. For example, by hovering the mouse over a variable included in a feedback loop, it is possible to graphically highlight the entire loop, facilitating the identification of dynamic mechanisms even within complex models. In addition, the recent integration of Artificial Intelligence (AI) into the software shows promise in further facilitating the modeling phase. AI can automatically suggest causal relationships between variables, highlight logical inconsistencies, or propose recurring dynamic structures based on pre-existing models, reducing the time required for the initial construction of the model and supporting the user even in the absence of advanced experience in systemic modeling.

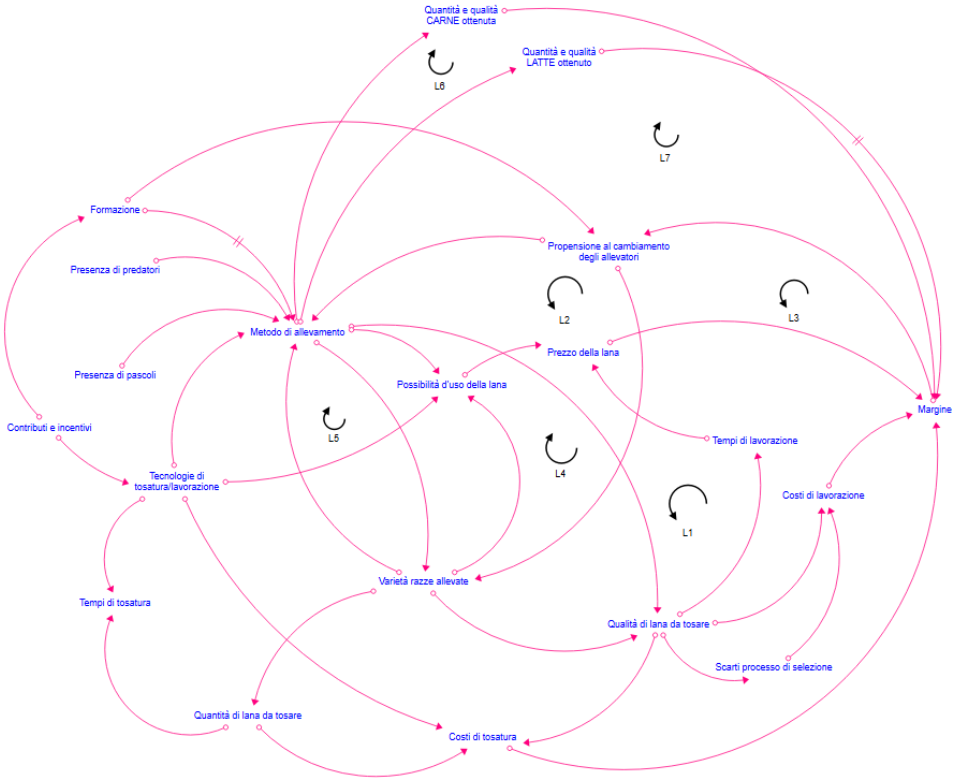


Figure A.9 *Causal loop Diagrams (CLDs) with Stella Architect software*

4. CIRCULAR SCENARIO SIMULATION

The circular scenario simulation phase involved exploring the behavior of the system under conditions that differ from the current state (linear system - baseline). Starting from the model reworked in the previous phase, the simulation begins with the baseline linear scenario, which represents the current configuration of the system. On this basis, the different CE solutions are gradually introduced in order to evaluate the effects generated by each intervention in a controlled and comparative manner. Different scenario configurations were constructed to analyze how structural or operational changes could influence the overall performance of the system.

- Simile and Stella Architect software were used to simulate a model (Figures A.10, A.11). Both tools can create graphic models to represent dynamic systems. Despite these shared capabilities, significant differences emerge in terms of usability and features. First, Simile supports only the development of SFDs, making it necessary to use additional software to create CLDs. In contrast, Stella Architect supports both SFDs and CLDs, making it possible to carry out the entire modeling process within a single integrated environment. Simile has a relatively outdated and unintuitive user interface,

especially when compared to Stella Architect, which offers a more modern and intuitive environment. As a result, the user experience in Simile is often fragmented and requires more effort to understand and use the software. In terms of model visualization, Simile offers limited flexibility in model management, connections between elements and the layout of objects on the workspace are not easily modifiable which often results in reduced visual clarity in more complex models. In contrast, Stella Architect provides a more flexible and intuitive graphical organization, facilitating the development and interpretation of complex system structures. Other differences concern the visualization and customization of results. Simile offers only basic, non-interactive graphical outputs and does not include tools for creating more sophisticated dashboards for interacting with results. Stella Architect, on the other hand, offers advanced visualization capabilities, including interactive dashboards and more customizable outputs, which enhance both the analysis and communication of results. Collaboration is another significant limitation of Simile. The software does not support shared model development or cloud-based access, restricting file management to local environments. In contrast, Stella Architect offers more advanced collaboration options with 'isee Exchange', which allows users to host and run models online. This makes Stella Architect better suited for group projects.

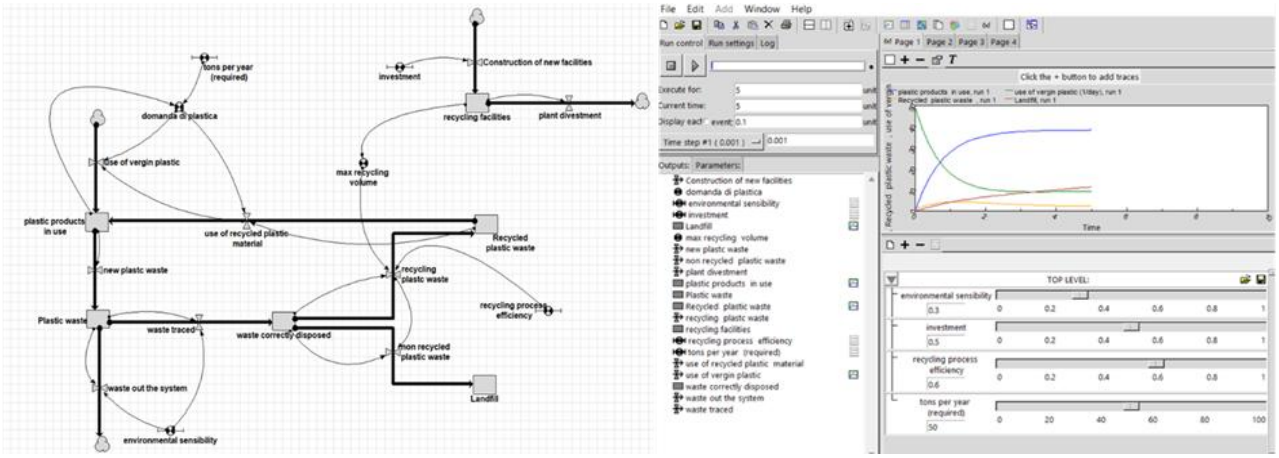


Figure A.10 *Simulation phase: Stock and Flow Diagram and simulation with Simile Software*

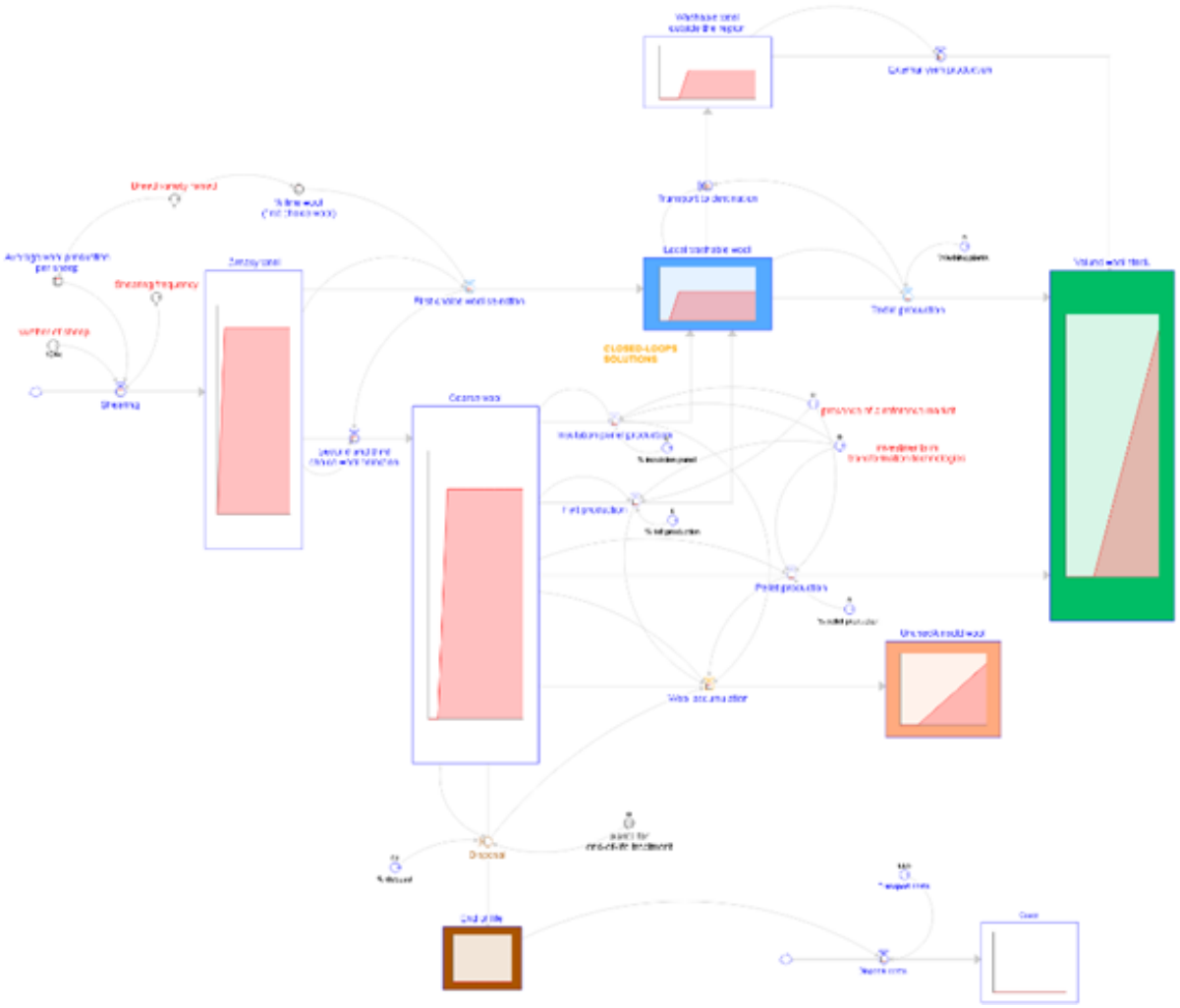


Figure A.11 *Simulation phase: Stock and Flow Diagram and simulation with Stella Architect Software*

The recently introduced functionality in Stella Architect was tested (*Figure A.12*), which enables the generation of dynamic models with integrated AI support. The objective was to verify the tool's ability to automatically construct a model structure starting from descriptive textual inputs. AI proved promising in the exploratory phase, managing to translate a qualitative description of the system into an initial SFD, including key variables and some basic causal relationships. This feature accelerated the initial construction of the model and provided a useful starting point for further development. An additional advantage is the ability to enter background information that AI can process to better respond to modeling needs. Nevertheless, human supervision remains essential to ensure conceptual coherence, verify causal assumptions, and guide the appropriate refinement of the model. The experiment showed that the AI was able to recognize the fundamental quantitative variables from text

prompts and populate the model with consistent values, at least at an approximate level (*Figure A.13*). This enabled the rapid generation of a dynamic, simulated scenario, complete with units of measurement and related variables. Moreover, the simulation mode proved to be more effective and user-friendly compared with older System Dynamics software, offering faster execution, clearer visual feedback, and more intuitive interaction during model testing and refinement. However, the quantities entered were plausible but generic, not calibrated to real data or specific territorial contexts. The logic of the flows, although formally correct, was simplified and lacked complex mechanisms. Furthermore, it was not always clear what rationale had guided the AI's choices, making it difficult to validate the model from a methodological point of view. Finally, the absence of explanations of the underlying assumptions (e.g., formulas, variables, constants) limits the transparency and traceability of the generated model. Despite this, the integration of AI has shown strong potential as a rapid prototyping tool, particularly useful in the early stages of exploration or for educational purposes, provided that the user maintains an active and critical role in the final review and validation of the model.

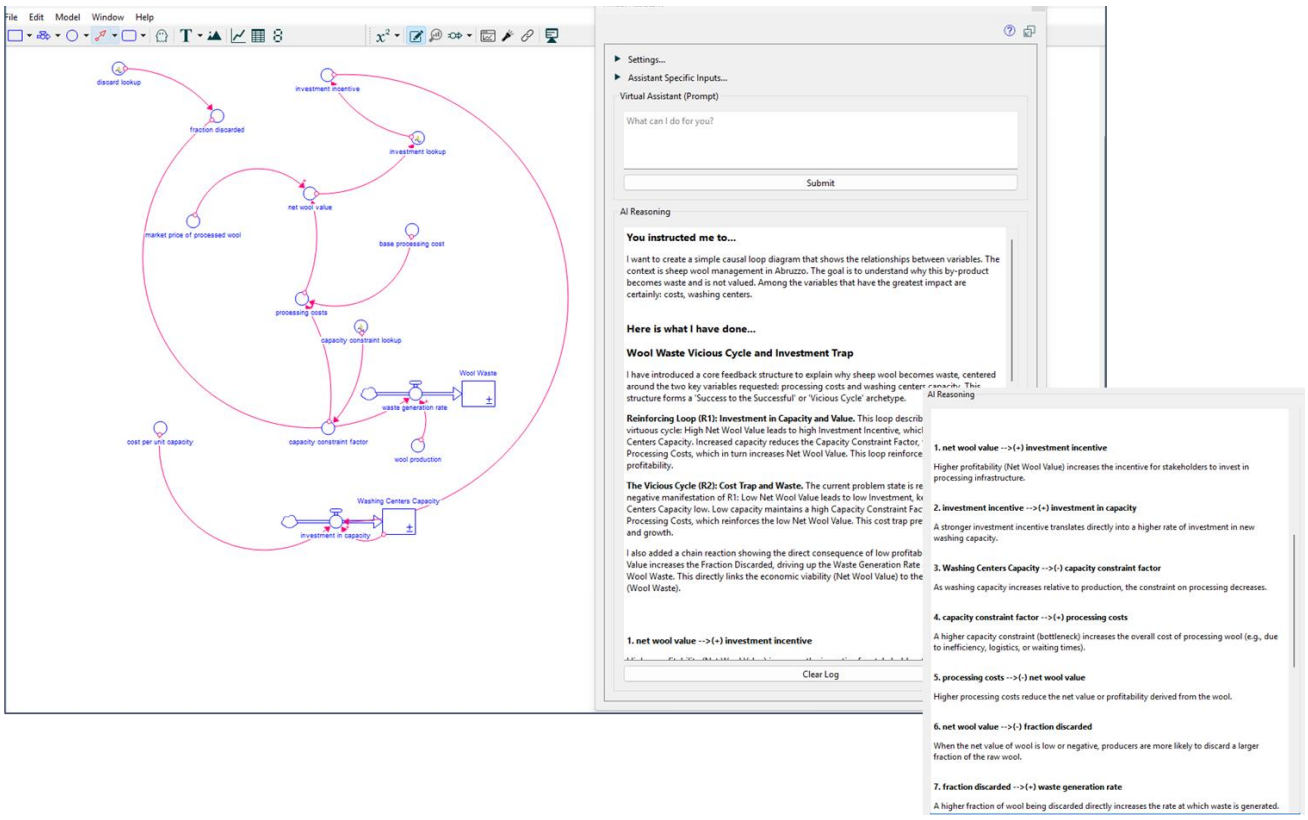


Figure A.12 *Simulation phase: AI tool in Stella Architect Software*

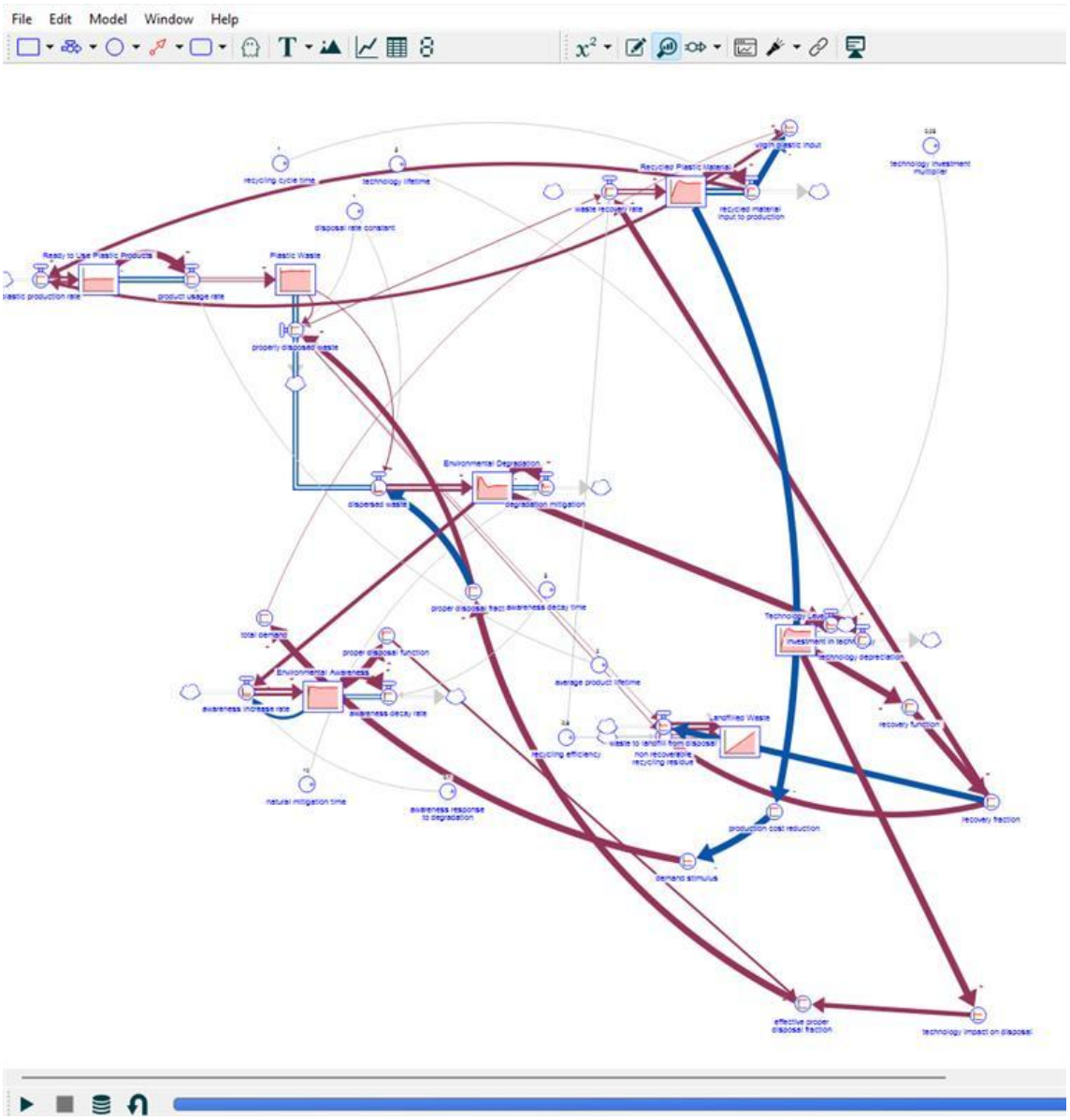


Figure A.13 *Simulation phase: AI tool in Stella Architect Software for simulation*

5. IMPACT ASSESSMENT

The impact assessment phase described in this section does not yet present a quantification of impacts, as the processing of results requires additional data that is not yet available. The objective of this part of the work is then to show how the model for the impact assessment was constructed for the Environmental Impact Assessment (*Figures A.14, A.15, A.16*). The **LCA For Expert** software was used for this purpose. Although designed for conducting LCA studies, it was adapted to represent the system and prepare the structure needed for future impact analysis (useful for the modeling phases). The software made it possible to define processes, links between flows, and measurement points

throughout the entire life cycle under consideration. However, significant critical issues emerged related to modeling requirements, which are not naturally provided for in software designed exclusively for LCA. LCA For Expert has a rigid structure that is not well suited to representing dynamic behaviors or conditional logic typical of systemic modeling. There is no possibility of managing feedback loops, temporal dependencies, or adaptive behaviors, and the possibilities for integration with external tools are very limited. A particularly relevant aspect is that, unlike the conceptual modeling phase, representing circular solutions can be relatively simple. In the LCA phase, however, it is necessary to completely rethink the logic of the model to make it compatible with the methodological requirements of LCA. In fact, the system structure defined in the initial modeling often conflicts with LCA rules, making it necessary to create a parallel model that complies with the definition of the functional unit and the reference flow, exclusion rules, the allocation logic, and the attribution of environmental impacts. This step introduces additional methodological issues, such as defining system boundaries, selecting significant processes and managing flows in accordance with LCA principles from the earliest stages of the analysis. Despite these complexities, the software offers some interesting features. For example, it is possible to enter parameters directly linked to flows, which enables efficient model scaling and the simulation of alternative variants. It is also possible to construct alternative scenarios and enter custom indicators, including those related to circularity, paving the way for comparative assessments between linear and circular configurations. To arrive at an effective calculation of impacts and avoid compromising the material balance, it is necessary to precisely set the reference flow and appropriately 'to fix' one or more key processes. In complex systems, especially on a meso or macro scale, the choice of functional unit, system boundaries, and reference flow is particularly complex and has a substantial impact on results. There are no single solutions, only modeling compromises that must be carefully justified. Another additional strength of LCA For Expert, compared to other LCA software more oriented towards tabular or abstract structures, is the ability to view the system through a process Flowchart. This graphical representation makes it possible to read the system in terms of flows, processes, and direct connections, improving the understanding of its overall functioning and facilitating the identification of hot-spots or levers for intervention. This visual potential represents added value in the construction and interpretation of impact models, especially when working in interdisciplinary contexts or when seeking to facilitate dialogue with non-technical external actors. However, as the software is proprietary, the files can only be opened and modified by users who have a license, effectively excluding any possibility of external collaboration. In the absence of open visualization tools, the only way to show the model is to take static screenshots, which are not an effective solution especially when the details of individual processes need to be explored.

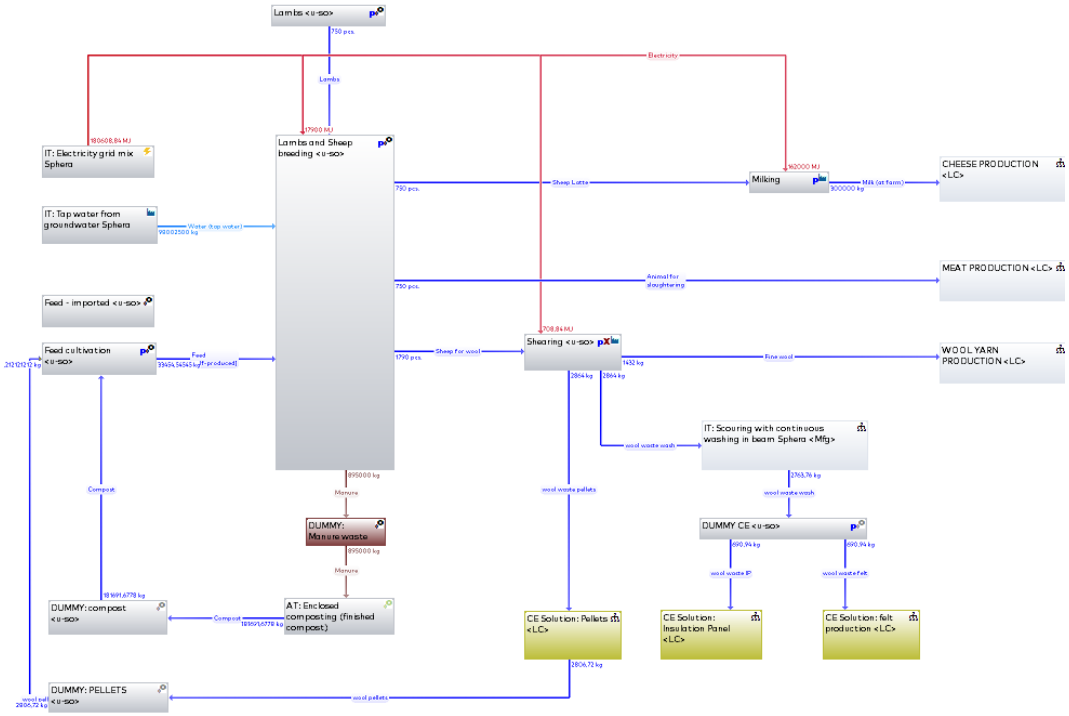


Figure A.14 *Model for Impact assessment with LCA FE software*

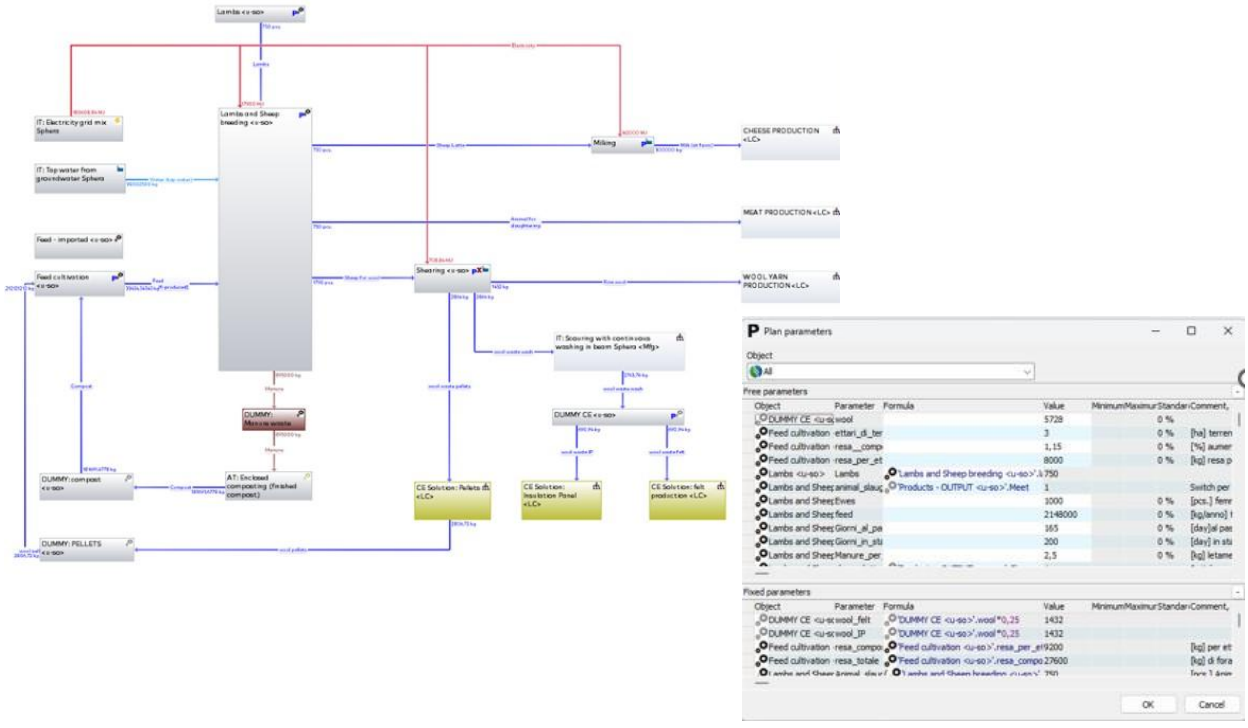


Figure A.15 *Parameters with LCA FE software*

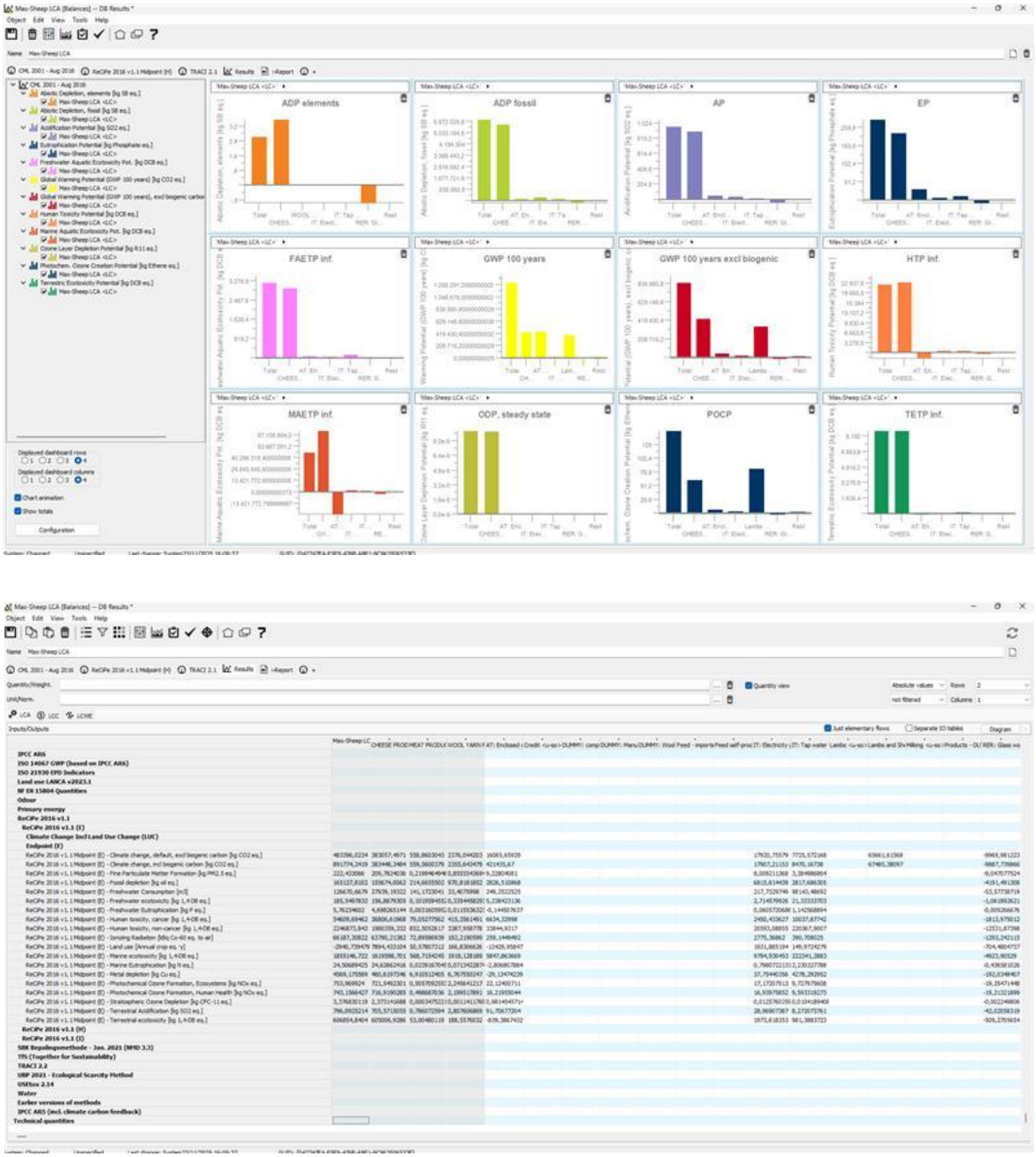


Figure A.16 *Environmental Impact Assessment with LCA FE Software*