GREEN DEAL, CIRCULAR ECONOMY AND INDUSTRIAL ECOLOGY

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Introduction

In December 2019, the European Commission presented "The European Green Deal" roadmap, aimed at making the European Union's economy more sustainable, turning climate and environmental challenges into opportunities and making the transition fair and inclusive for all. The European Green Deal has specified the types of actions to be implemented, focusing on four challenges: (i) boosting resource efficiency, (ii) tackling global warming by limiting greenhouse gas emissions and the use of fossil fuels, (iii) reversing the collapse of biodiversity, (iv) reducing chemical pollution (especially fine particles and aerosols) and waste. The Green Deal also describes the investments required and the financing tools available.

The European Green Deal covers all sectors of the economy, including transport, energy, agriculture, buildings and industries such as steel, cement, ICT, materials, textiles and chemicals. Within the EU's monitoring framework for the circular economy, 5 thematic areas receive particular attention: (1) production and consumption patterns, (2) waste management, (3) secondary raw materials, (4) competitiveness and innovation, 5) global sustainability and resilience. Numerous indicators are now used to assess the material footprint, resource productivity, total waste production per capita, municipal waste production, share of plastic in packaging waste, waste recycling rates, contribution of recycled materials to the demand for raw materials, end-of-life recycling rates for raw materials, private investment and employment in circular economy sectors, patents relating to waste management and recycling, dependence on imported materials and EU self-sufficiency in raw materials.

Figure 1 : Green Deal, transforming the EU's economy for a sustainable future

Source : European Commission, 2019

Since 2021, the European Commission has focused on two important pillars of the circular economy: eco-design and packaging reduction. Ecodesign (SsbD : Safe and sustainable by-design) is at the heart of goods production, aiming for sustainable product design with an emphasis on improving repairability, reuse and recycling, reducing the presence of hazardous substances, strengthening consumer information or even banning programmed obsolescence. The packaging issue can be summed up in a few figures: 180 kg of packaging waste is produced by each European citizen per year, and almost 40% plastic and 50% paper are used in packaging production in Europe. The aim is not only to introduce sustainability requirements for packaging and labeling standards, but also to impose restrictions on the use of plastic bags (target consumption of 40 plastic bags per person per year by December 31, 2025).

In February 2023, the European commission presented a *Green Deal Industrial plan* to enhance the competitiveness of Europe's net zero industry and support the fast transition to climate neutrality. The starting point for the Plan[1] is "*the need to massively increase the technological development, manufacturing production and installation of net-zero products and energy supply in the next decade, and the value added of an EU-wide approach to meet this challenge together*" (EC, 2023). This is made more difficult by the global competition for raw materials and skilled personnel. The Plan aims to address this dichotomy by focusing on the areas where Europe can make the biggest difference. It also seeks to avert the risk of replacing our reliance on Russian fossil fuels with other strategic dependencies that could impede our access to key technologies and inputs for the green transition, through a mix of diversification and own development and production. The Plan will complement ongoing efforts to transform industry under the European Green Deal and the EU Industrial strategy, in particular the Circular Economy Action Plan. Modernising and decarbonising energy-intensive industries also remains a top priority, as does ensuring job transitions and quality job creation through training and education. The Green Deal Industrial Plan is based on four pillars: (i) a predictable and simplified regulatory environment; (ii) faster access to sufficient funding; (iii) skills; and (iv) open trade for resilient supply chains.

2024 has improved regulations and principles for the EU industrial Carbon Management Strategy. The Commission presented recommendations for 2040 emissions reduction target (february 2024) to set the path to climate neutrality in 2050, adopted the Net-Zero industry (may 2024) to reduce methane emissions in the energy sector, published the right to repair directive (may 2024) and finally approved the nature restoration law[2] (June to August 2024).

This book entitled *Green Deal, Circular Economy and Industrial ecology* aims to look at research, experimentation and evaluation of circular economy projects and industrial ecology case studies related to the EU Green Deal. All the contributions have been presented to the symposium Green Deal, Circular Economy and Industrial ecology organized in December 2024 at Clermont Ferrand. **This publication is one deliverable of the different activities of the *Jean Monnet Chair 'Europe, Circular Economy and Industrial Ecology'* (JC3E)[3].**

Many challenges have been introduced in this publication : (1°) feedback on experiences and results from Horizon Europe Projects, focusing on the circular economy and in particular on the development of innovations (low tech vs. high tech) in line with the 10R model (Reject, Rethink, Reduce, Reuse, Repair, Renovate, Remanufacture, Recycle, Recover) or metrics; (2) paradigm shifts triggered by the emergence of new economic models; (3) reflections on industrial policies and strategies implementing the circular economy. The field of industrial ecology - in particular work on industrial symbioses and eco-industrial parks - is mobilized from different case studies applied to sectors (construction, agriculture, energy, waste, plastics, etc.); (4) research on metrics

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023DC0062

[2] This law aims to put measures in place to restore at least 20% of the EU's land and sea areas by 2030, and all ecosystems in need of restoration by 2050. https://www.consilium.europa.eu/en/press/press-releases/2024/06/17/nature-restoration-law-council-gives-final-green-light/

[3] https://erasme.uca.fr/version-francaise/chaire-jean-monnet-ecei

and indicators for the circular economy, seeking to develop new methodologies (life-cycle analysis, flow-stock models, social acceptability approach) or defining different levels of analysis (micro, meso or macro); (5) business models relating to the circular economy and in particular the integration of circularity principles and other related features like efficiency, resilience and/or cooperation. As well as the development of supply chain management models for supply chains, hub logistics where lifespan estimation models increase our understanding of the industrial ecosystems like the manufacturing, textiles, plastics, etc. In this context, digital platforms and other digital tools such as the Digital Product Passport facilitate the exchange of information between the different actors in a supply or logistics chain.

The book has been divided into two parts.

The first part presents theoretical and methodological challenges of the Green Deal. *Jenneth Parker (Schumacher Institute)* uses systems thinking approaches to address European Security and Circular Economy and looks at international challenges to the EU and internal political upheaval in Europe. Consideration of Critical Raw Materials (CRMs) can illuminate security issues and help situate wider sustainability concerns and strategies in the bigger geo-political picture. The new Trump regime in the US is dramatising the question with threats of land-grabs and blackmail of Ukraine, showing the importance of these resources, but also some crucial differences in approach to the EU. CRMs are found only in some places on the globe, but are considered essential for the functioning of modern economies including the digital and energy transitions. Some implications and potential solutions and strategies are identified, together with the prioritisation of research and action these might involve. One of the key challenges for the sustainability movement is to keep the agenda moving in the light of the increased security concerns of Europe. A complex systems approach can help to capture and communicate the synergies across the security and sustainability agendas. Conclusions include further engagement and advocacy with civil society in Europe around resilience and sufficiency approaches. Gaining further civil support and engagement could be key to the continuation of effective forms of environmental governance and defence of democracy in the EU. *Veronica Casolani, Raffaella Taddeo, Valentino Tascione and Alberto Simboli* (G. d'Annunzio of Chieti-Pescara University) consider that many of the principles and tools underlying Circular Economy (CE) are shared with the research field of Industrial Ecology (IE). To investigate the interrelationships between the two fields, they produce a cross-bibliometric analysis and a subsequent content analysis of the scientific literature, considering several parameters such as authors, countries, keywords and typical research methods and tools. Results provide insights on the origin, current state and future development of the two fields. *Ayhan Demirci (Toros University)* highlights the importance of circular economy practices in sustainable development, focusing on waste reduction, resource optimization, and recycling. These practices are essential for achieving European Green Deal goals like carbon neutrality and decoupling economic growth from resource use. By ranking 27 EU member countries based on circular economy practices, his chapter analyzes their impact on social and economic indicators such as welfare, education, employment, and health. Using the Entropy-based WASPAS method and Spearman Rank Correlation analysis, the author identifies a strong link between circular economy performance and economic/social development. The findings underscore the need for EU countries to integrate social and economic dimensions into circular economy strategies. This provides policymakers with actionable insights to reduce disparities and enhance sustainable development policies. Viktoriya Onegina (Clermont School of Business) considers that the European Green Deal (EGD) gave a start to the new growth strategy, accelerating the green transition of Europe and changing technological and business processes. Her chapter aimed to reveal the impact of the EGD on the total entrepreneurial activity (TEA) in the EU countries and to define the entrepreneurs' awareness of EGD objectives and regulations. The research methodology of this study includes two steps: the first step is based on the quantitative analysis of secondary data on changes in TEA in the EU countries; for the

Jaroslaw Gorecki (Bydgoszcz University of Science and Technology, Poland), Valentin Molina Moreno (University of Granada, Spain) and Pedro Nunez-Cacho Utrilla (University of Jaén, Spain) argue that a transition of the construction industry towards Circular Economy (CE) represents a critical shift in achieving sustainability and resource efficiency. The chapter explores various strategies to enhance a contractor's maturity in embracing CE principles, emphasizing the importance of a structured transformation model. The proposed model serves as a tool to assess a company's readiness and inclination towards implementing CE concepts. It comprises multiple dimensions, each representing a pillar of evaluation that can guide the transformation process. These dimensions include performance of management in seven main areas: materials, energy, water, waste, emissions, 3R policies, and overall factors of transition to CE. By evaluating these scales, companies can identify gaps in their current practices and develop targeted strategies to enhance their maturity in CE practices. This approach mirrors similar methods used in other industries. The chapter also highlights the pivotal role of expert opinions in shaping and refining transformation scenarios. Experts can provide valuable insights that help contextualize the model to specific industry realities, making it more applicable and effective. Their perspectives are crucial in identifying potential challenges and opportunities, ensuring that the proposed strategies are both feasible and impactful. Different transformation scenarios, ranging from incremental changes to radical shifts, are examined to illustrate how companies can navigate the complex journey towards CE. The involvement of experts ensures that these scenarios are grounded in practicality and aligned with industry trends. Such a solution can provide a basis for further modelling extensions, including in the field of the smart city concept and artificial intelligence.

Ässia Boukhatmi suggests that Digital technologies (DTs) are key enablers of the Circular Economy transition, as they provide the necessary infrastructure for data collection, integration, and analysis to drive circular business models. The European photovoltaics (PV) industry presents a compelling case study to explore this intersection, given its rapid expansion, geopolitical competition, and the growing challenge of managing End-of-Life (EoL) PV waste streams. With projections estimating 33 million tons of decommissioned PV modules in Europe by 2050 (Czajkowski et al., 2023), integrating DT-driven circular strategies is not only necessary but urgent to master the CE transition. This chapter contextualizes DTs for data collection, integration, and analysis, followed by an exploration of their applicability across different VC stages. It also examines the role of digital platforms in uniting diverse DTs and industry stakeholders to collaboratively advance circularity, illustrated through a case study from the solar industry. Finally, it concludes with policy recommendations to support the adoption of DTs and platforms for circularity. The findings, while grounded in the PV sector, offer transferable insights to other industries striving for digitally-enabled circularity.

Tipawan Durand and Arnaud Diemer (University of Clermont Auvergne, France) present a new approach to strategic project management in the context of circular economy initiatives. The objective of the chapter is to define steps for selecting key indicators at the company level that impact the economy, environment and society by integrating Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis with the Cross-Impact Matrix (CIM). This combined methodology provides both qualitative and quantitative results, achieving a deeper understanding of potential future forecasts and help to define key indicators to follow up in each domain. A case study involving a recycled Polyethylene Terephthalate (rPET) for tire industry (WHITECYCLE project) uses this approach, incorporating brainstorming sessions with project stakeholders and analyzing 182 indicators from relevant frameworks, including Cost-Benefit Analysis (CBA), Life Cycle Sustainability Assessment (LCSA), Sustainable Development Goals (SDGs), circular economy and the company-specific performance indicators. This chapter emphasizes the broader application of the methodology, providing valuable insights for future research and strategic planning within circular economy initiatives. Finally, *Henri Sourgou and Arnaud Diemer (University of Clermont Auvergne, France)* evaluate the impacts of Polyethylene terephthalate (PET) recycling for the tire industry (WHITECYCLE project of the European Union Commision). The goal of this chapter is to analyze how System Dynamics (SD) modeling can help to minimize environmental, social and economic adverse impacts of PET recycling and to foster a circular economy of PET recycling (rPET) supply chain. The chapter uses System Dynamics method to describe the organization of actors, the flow of complex wastes from tires, hoses and multi-material clothing treated by each actor across the PET recycling chain. Also, it consists of identifying the inputs used in waste treatment such as energy, chemical, water, infrastructure, vehicles, … in order to assess the sources of impacts and how much these impacts are. Then, the SD analysis is in line with Life Cycle Assessment (LCA) analysis, taking into account the rPET products' life cycle stages in the impact assessment in terms of costs and advantages for the environment and also social and economic.

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Table

Part 1

Theoretical and Methodological Challenges of the Green Deal

Circular Economy & Critical Raw Materials: how the EU can link Security and Resilience for new times in Geopolitics[1]

Dr Jenneth PARKER
Schumacher Institute

<u>Abstract</u> : This chapter uses systems thinking approaches to address European Security and Circular Economy and looks at international challenges to the EU and internal political upheaval in Europe. Consideration of Critical Raw Materials (CRMs) can illuminate security issues and help situate wider sustainability concerns and strategies in the bigger geo-political picture. The new Trump regime in the US is dramatising the question with threats of land-grabs and blackmail of Ukraine, showing the importance of these resources, but also some crucial differences in approach to the EU. CRMs are found only in some places on the globe, but are considered essential for the functioning of modern economies including the digital and energy transitions. Some implications and potential solutions and strategies are identified, together with the prioritisation of research and action these might involve. One of the key challenges for the sustainability movement is to keep the agenda moving in the light of the increased security concerns of Europe. A complex systems approach can help to capture and communicate the synergies across the security and sustainability agendas. Conclusions include further engagement and advocacy with civil society in Europe around resilience and sufficiency approaches. Gaining further civil support and engagement could be key to the continuation of effective forms of environmental governance and defence of democracy in the EU.

The EU and how it works, and sometimes does not work so well, is a complex subject. Add the extra layer of the Green Deal, and Critical Raw Materials and geopolitical Security concerns, and we are dealing with overlapping complex issues. Systems thinking has been designed to help us cope with complexity, and can provide big picture analysis. Larger perspectives and overviews of these issues and how they connect, need to be developed, in order to create more informed strategies and to better engage with citizens in the current tough geopolitical context. This chapter aims to contribute to such overviews. The figure 1 gives some idea of the interactions of levels of policy and concern.

<u>Figure 1</u>: Policy Dependency and Interaction

Security issues are largely seen as located at the EU Geopolitical 'level' of policy (NATO/ Critical Resources Alliance). This chapter argues that the proposed solutions of Circular Economy depend upon the EU governance model and the extent to which citizens in Member

[1] This analysis is my responsibility, but many thanks to all at the *Symposium for Green Deal, Industrial ecology and Circular Economy*, Hugh Atkinson, Peter Schlyter & Arnaud Diemer.

States support the Green Deal. Neglecting citizens' views and Human Security aspects is not good security policy. This consideration makes the link to questions of resilience and wellbeing all the more important. This chapter begins with a review of developing links made between critical resources, circular economy and security in EU policy. An overview of the NATO workshop in Stockholm in 2024 is provided, showing the importance of the circular economy in the new security landscape. This approach is then presented in a Causal Loop Diagram (CLD) analysis, which gives a systems dynamics account, highlighting key connections and feedback, both reinforcing and balancing. Some assumptions of the approach of the NATO analysis are identified to be explored further in the next section. The next section looks at the EU Green Deal and the role of Just Transition with respect to resources governance, circularity and the green transition of production. A CLD analysis of the relationships underlying the approach is developed. This is broadly in agreement with the NATO Stockholm report, but includes more emphasis on the Just Transition approach. The next section uses CLD analysis to depict the wider geopolitical model of the EU, which can be seen as basically built on recognition of forms of partnership and negotiation, albeit with many power imbalances. Two major shocks to the EU system are then considered. Firstly, the internal shock of growing challenges from the Far Right in Europe, who are against the Green Deal. These parties are often (at least partly) funded by hostile external actors, but also exploit some of the real weaknesses of the EU governance model, including perceived democratic deficit and the linked failure to communicate visions and goals to citizens. Secondly, the pressure that the loss of cheap energy is putting on key sections of the EU economy and increased exposure to shortages of CRMs in Europe, due the Ukraine conflict.

The chapter concludes with some questions regarding current developments and the problems for environmental governance, in Europe and the world after the coming to power of Trump in the US. The MAGA geopolitical model is analysed particularly with respect to CRMs and the Frontier Approach (or imperial approach) to resources is placed in the context of a Winner-Takes-All model. This is then compared to the EU model to help gain an overview of some of the clashes in perspective and actions in the current geopolitical moment. The linked issues regarding NATO and security for Europe are discussed and an approach suggested which works from the CLD analyses to link resilience for Europe and engagement with citizens. The proposal takes note of the need for some kind of New Social Contract between State, Business and Civil Society for resilience in Europe, and to make a solid European contribution to more sustainable pathways globally. An interdisciplinary and systems perspective is used here, working with a social-science form of systems dynamics mapping with Causal Loop Diagrams (CLDs) to present analyses, propose solutions and generate further questions. These diagrams are dynamic representations of the logics of the approaches being taken, which can then be contrasted and compared more easily. The analytical overview also helps enable inquiry into some of the background assumptions of the logic and to identify what potentially important elements may be left out. These points are summarised as the chapter progresses and addressed together in the Conclusions.

Circular Economy, CRMs, Security and Green Deal Policy

The importance of CRMs is stated clearly by the NATO Civil Protection Group (2024): ***'Why are CRMs so important?*** *Other than the high-risk associated with their supply, Critical Raw Materials are so important because they are 'critical' for the EU's mega-sectors and for a wide range of commercial and governmental applications: green technology, telecommunications, space exploration, aerial imaging, aviation, medical devices, micro-electronics, transportation, defence, and other high-technology products and services. As a result, EU industry, the environment, and our quality and modern way of life is reliant on access and use of these Critical Raw Materials. This can be seen in the following sectors: Defense, Automotive, Metals, Medical Devices, Consumer Electronics, Green Technology'.*

Figure 2: The importance of Critical Raw Materials to society

The energy transition and so-called 'digital transition' are both reliant upon supplies of CRMs which are in limited supply and under threat. The UN Resources Panel forecasts resource use to increase by up to 60% by 2060 if no action is taken (UNEP, 2024). The rate of depletion of many CRMs is already high and 'peak resource' is likely to be already reached in some resources (Ragnarsdottir and Svedrup, 2014), meaning that resources become more difficult and energy intensive to extract and process. The EU is exposed to global shortages and competition over CRMs because it is a high user of resources (Grabbe & Moffat, 2024). However, the EU is also a leader in Circular Economy and there is some evidence that this is having an effect in decoupling resource use from GDP growth although use still remains high (op cit p. 6) : *'The next decades are likely to be characterized by supply bottlenecks as climate shocks proliferate, economies race to decarbonize and trade rivalries disrupt flows. But even in the very short term, resource efficiency can offer a buffer to protect the EU's economic security. For CRMs, supply deficits are already expected for 2024 (Stewart et al, 2023). In the medium term, there are forecasts of potential supply gaps for copper and lithium of up to 10% and 49% respectively in 2030 (ETC, 2023).'* (Grabbe & Moffat, 2024, p. 9)

EU policies on critical resources and security were already developing before the Ukrainian conflict dramatised the effects on security of resources dominance. For example, *'……the **EU Commission Communication Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability** is in essence an EU critical raw materials action plan, albeit non-legislative (and therefore not legally binding) and not containing quantified targets. It recognises that EU resource security requires diversified supply from primary and secondary material sources, reduced dependencies, and greater resource efficiency and circularity.*' (Watkins & Mesner, 2022, p. 33)

Policies have been more rapidly developing since then, with a high political awareness in the Bloc on resources & resilience: *'The Critical Raw Materials Communication explicitly mentions the term 'circular' in the context of recognising that enhanced circularity of resources has a role to play in the EU achieving resource security, resilience against future shocks and increased strategic autonomy, in particular with regards to critical raw materials.'* (Watkins & Mesner, 2022, p. 34). Policies also include initiatives to provide technical support, and makes links with resilience, as for example the Technical Support Instrument: Supporting the Resilience of Natural Resources (EU Reform Support, 2024). The policy space has enlarged rapidly, reaching into national press coverage, with the recent interventions of Trump (considered further below) providing a good opportunity to heighten citizens' awareness of the threats to EU security posed at this time.

Taking the definition from Petelin (2024), Circular Economy is about 'closing loops' in production, so that material is efficiently used, as opposed to linear systems which produce waste and pollution. In this, and other respects, Circular Economy is also seen as a necessary part of the transition of land-based sectors to help support the biodiversity foundational to life on Earth (European Environment Agency, 2023; Paleari, 2024), but in this chapter the emphasis is on the non-renewable resources identified as CRMs. Petelin identifies three types of Circular Economy with regard to Materials: Closing Loops; Slowing Loops and Narrowing Loops (op cit, p. 661).

Table 1: Types of Circular Economy strategies adapted from Petelin (2024)

Closing Loops	Slowing Loops	Narrowing Loops
Material Recycling By-product recovery and re-mining, Organic waste into bioplastics production	Product collaborative or shared consumption and re-use, Product repair, refurbishment and remanufacture Product repurposing	Loss reduction in extraction and production; Production system dematerialization Refusing products; Avoiding material consumption

Many of these initiatives require additional policy and financial support to help bring them into current systems and the Circular Economy is a key part of the EU Green Deal, comprising a complex set of instruments, financing and incentives, law and regulation. Circular Economy likely to become more emphasized in the EU Green New Deal as resources security awareness develops further. Moves towards reshoring to produce on home ground, (Fernández-Miguel et al, 2022) or 'friend-shoring' to source materials from aligned state actors or regions are increasing as a way to greater resilience. The shortening of supply chains and recycling vital materials through the Circular Economy are also highly prioritized. The complexity and overlapping concerns in EU Circular Economy policy is described in full in the Institute for European Environmental Policy (IEEP) landscape overview report (2022).

Advocates for moving to a more holistic model of economy may be concerned that there is not enough questioning of the levels of resource use that are needed for human flourishing and prosperity (see the section on 'Sufficiency' in the Conclusions). There is a high level of agreement on the need for circularity as a goal for changing our systems towards longer term sustainability and away from collapse due to over-use of critical resources. As Petelin points out, the whole area of CRMs is linked to Geopolitics of power, human development and forms of neocolonialism (op cit 2024, p665). With respect to the political agenda and CRMs, the EU has policies which aim to support the EU's 'Strategic Autonomy'.

The policy drive for EU Strategic Autonomy has been well illustrated by the example of titanium in a paper by Jakimów, M., Samokhalov, V. & Baldassarre, B. (2024). They state that the EU's CRM Act of 2024 '*aligns the concern for strategic autonomy with the European Green Deal priority of decarbonisation…..*' (p2). They clarify the way in which the Ukraine war has, '…*exposed the strategic dependency of Russian-supplied imports of titanium products, which account for half of European aviation companies' imports of aeronautical-grade titanium.'* (op cit p. 3).

Equally concerning, in the light of recent pronouncements from Trump, are the lock-ins of the EU to US supplies of processed titanium through buy-back agreements. These achieve circularity but '*the loop is transatlantic rather than domestic*' (op cit p8). This study provides an insightful overview of one iconic case of geopolitical resource dependency which the EU considers as a problem for strategic autonomy. The authors identify the need for considerable EU expenditure if titanium processing facilities were to be developed within the EU itself. This provides one example of the challenge of fulfilling the EU's CRM Act requirements to extract at least 10% and process 40% of the annual consumption of the strategic raw materials in the EU.

Recent NATO Security and Resources Agenda-Setting

There are many links between security discourses and other aspects of governance and one very useful summary is given by Petelin (2024), who points out that threats have to be identified by enough people, in order for them to **become** security issues: '*Thus the challenges to resource security might not become a public concern unless they are presented and perceived as a threat. Only the challenges perceived as threatening become security concerns.*'(op cit , p. 657). Questions of human and social perspectives are vital when it comes to gaining public support for policy measures in democracies. Petelin divides the areas of focus in Circular Economy and Security into four: Ecological Security, Military Security, International Security and Human Security as shown below.

Table 2 : Four Security discourses on Circular Economy adapted from Petelin (2024)

Security Discourse on Circularity	**Concerns**	**Expected Outcomes**
National or Regional Security	Growing demand for resources, dependence on import, high prices, supply risks	Mitigating supply risks, enhanced self-sufficiency, avoiding resource conflicts
International Security	Competition for resources, shifts in global material flows, unequal power relationships between Low & Middle-Income countries (LMICs)	Increased interconnectivity, transparency, & economic, social & environmental conditionalities on LMICs
Human Security	Lack of food, energy, potable water, sanitation & basic material needs, social costs of extraction, processing & use, people feel abandoned	Food, energy, water & material sufficiency of local communities, increased well-being & community resilience- feeling supported in agency
Ecological Security	Eutrophication, acidification, eco-toxicity, soft erosion, biodiversity loss, climate change. Decline of biocapacity of Earth, age of extinction of species.	Elimination of hazardous waste, phasing out polluting practices, ecosystem regeneration, mitigation of greenhouse emissions.

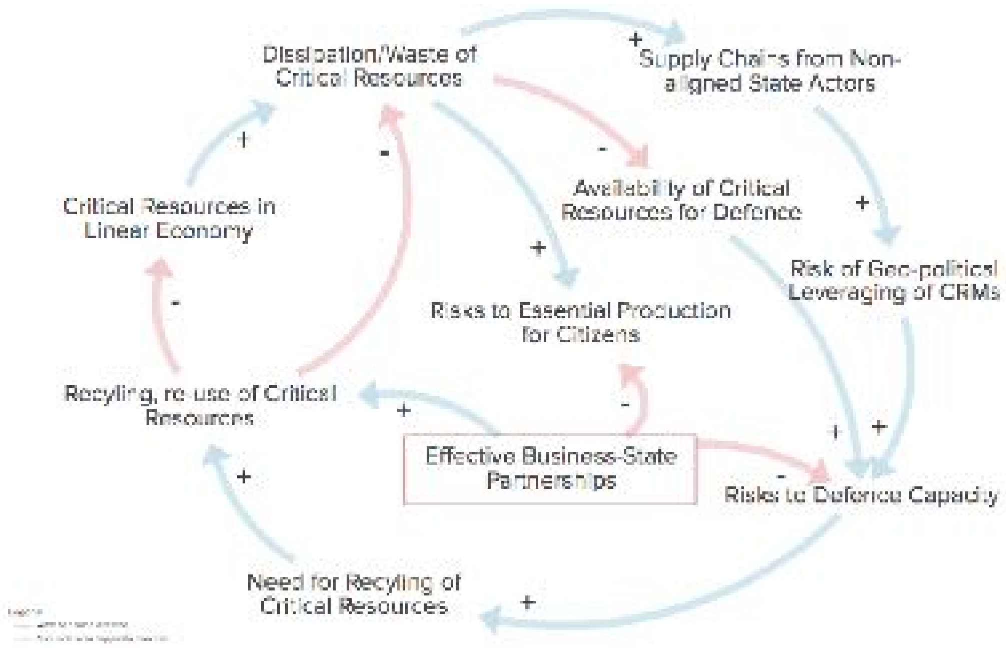
All these various discourses appear in different mixes in the policy areas mentioned in Figure 1 and will be identified throughout the chapter. However, it should also be noted that the **wider political concerns that are also identified affect the viability of policies and action on these areas**. The relationships go both ways. This simplified table leaves out the complexity of the various responses to the concerns identified in Petelin, most of which would require expert attention to plan and implement. However, it is worthy of note, that although the concerns may not be completely understood by the wider public, it is not difficult to communicate the hoped-for outcomes of security agendas and responses in the Outcomes column. In this way we can see that **it is possible for the EU and other areas to make a much better job of explaining the vision and aims of actions for security than is being done at present**. Communication and engagement is vital in democracies and this topic is picked up again further below. Working from the theme of Regional Security identified above, The Civil Protection Group seminar in Stockholm in March 2024 when 320 participants from 28 Allied nations and two partner nations attended the seminar. Approximately one third of participants came from the private sector, others were from security and research organisations. The aims of the meeting were to:

- *Engage private sector representatives on NATO's public-private cooperation policy priorities.*
- *Identify best practices, models, and frameworks on public-private cooperation in securing critical flows/security of supply.*
- *Identify areas where NATO's Baseline Requirements for National Resilience can contribute to improving interoperability between the public and private sectors.*
- *Provide recommendations to further improve public-private cooperation in support of NATO's resilience policies and non-binding guidance.*
- *Support national authorities to further develop national practices and networks.*

The idea of military-industrial cooperation is proposed as necessary at this point for European social democracy to survive in the current context, (van Rij, 2025). Space precludes full discussion of this issue, but the CRM Alliance report is interesting precisely because it appeals to a partnership model and approach, that has a rather different orientation to the classic accounts of a military-industrial complex (Newlove-Eriksson & Eriksson, 2023) and could include a much greater role for citizen participation, engagement and direction. This aspect is not really represented in this particular workshop, but that does mean that it is necessarily inconsistent with its conclusions.

The diagram below represents the logic of the NATO 2024 report and analysis of CRMs with regard to circularity. This provides a simplified summary in terms of issues, but also the dynamics of the proposed Circular Economy strategies. Issues of the nature of the 'partnerships' and what this might mean are considered further below.

<u>Figure 3</u> : NATO view from the 2024 Civil Protection Group Report



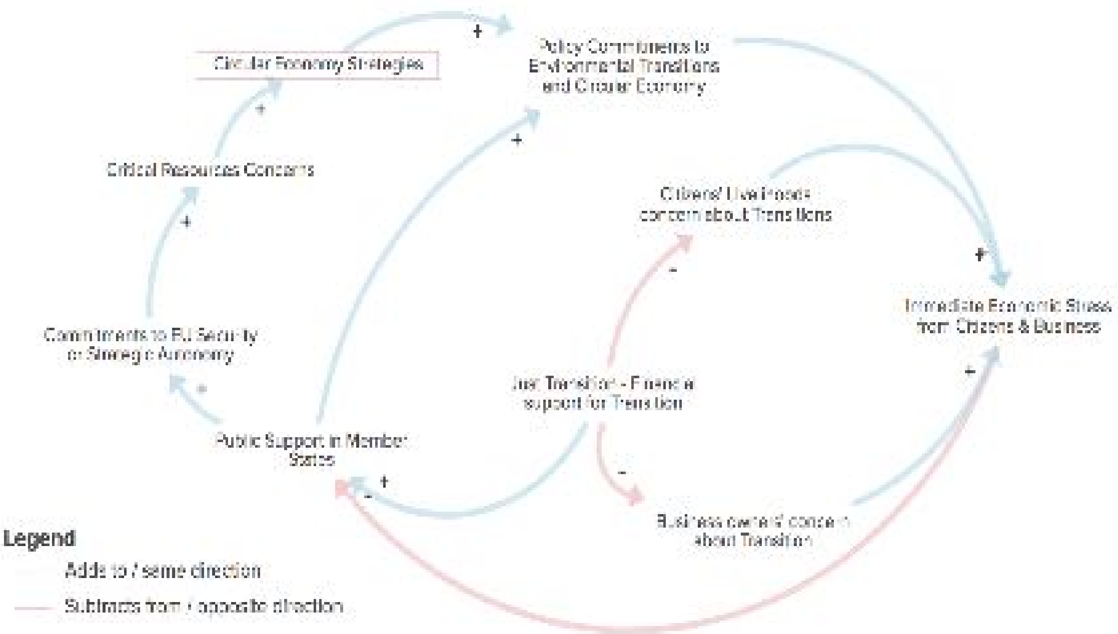
In this diagram the Critical Raw Materials in Linear Economy are seen as leading to Dissipation and Waste of CRMs which in turn leads to the need for more Supply Chains from Non-aligned Actors. These bring the risk of Geopolitical leveraging and hence risk to Defence Capacity. The Dissipation of CRMs also leads to less availability of CRMs for Defence and risks to Defence Capacity. Dissipation of CRMs also leads to Risks for Essential Production but these risks can be reduced by Effective Business-State Partnerships. The Risks to Defence Capacity lead to a recognition of the Need for Recycling of CRMs which in turn leads to more Recycling which both reduces the use of CRMs in Linear Economy. Strengthening Business-State Partnerships is seen as a requirement for effective Recycling of CRMs.

The main purpose of this diagram is to illustrate the thinking behind the linking of CRMs and Security issues. Circular Economy is seen as part of the solution to CRM problems and links to EU aims to achieve ‘strategic autonomy’. The risks of geopolitical leveraging of CRMs, and the damage to strategic autonomy, have been highlighted in the situation of Germany’s dependence on cheap Russian gas which affected the speed of support for sanctions against Russia after the invasion of Ukraine.

Business-state partnerships are seen as crucial to any effective rapid action on these issues. More dictatorial state power can readily enforce the alignment of production to security concerns. As an avowed alliance of democracies, the NATO approach from 2024 attempts to work with partnerships and this requires some degree of compromise, including on the part of business. Whether this approach will survive in 2025 with the Trump regime, is open to question. All these considerations lead to support for Circular Economy within the basic Green Deal approach of the EU. Although links are made to other aspects of the resilience agenda, including maintenance of core services and provisioning for citizens, the concerns about the civilian population are not really elaborated in this report. As will be argued further below, citizen engagement is vital for resilience, the question is whether policy-makers recognise this. Human Security in the EU is perhaps something to take more seriously as an essential ground of localised resilience, for this a more developed strategy for multi-level partnerships between civil society, states and EU levels will be needed. This also links to issues of Ecological Security as a relatively stable and thriving natural world is essential for all our livelihoods and wellbeing.

The CE strategy of the EU relies upon the Green Deal policy set. The diagram below illustrates this and the central role of Just Transition approaches, which are seen as sustaining public support and engagement, or mitigating opposition.

Fig 4. EU Green Deal, Just Transition and Circular Economy Approach 2024



In this diagram Policy Commitments are **considered to be** supported by the Public in Member States. Environmental Transitions are known to cause Economic Stress to Citizens and Business. This stress can lead to less support for Environmental Transitions. Just Transition provisions help to meet these concerns and thus mitigate loss of support. The commitment to EU Strategic Autonomy is likewise **considered to be** supported by the Public in Member States and Strategic Autonomy Commitments lead to Concerns about CRMs. These concerns lead to Support for Circular Economy Strategies, which further supports the overall Policy Commitments to Transition and Circular Economy. The phrase 'considered to be' is used here to indicate the rather tenuous nature of public support for these measures. This is not just a problem for EU environmental governance, but has been a problem for other areas such as the UK. The presumption seems to be that in the EU, citizens voted for their governments, and their governments have signed up to the Green Deal and therefore democracy is satisfied. Although polls show support for climate action, **the nature of those actions** is not discussed with citizens, but is left up to policy communities. The viability of this approach is questionable, as these policy communities do not engage fully with the range of stakeholders affected by policies, let alone consider co-production approaches (van de Molen, 2016).

The EU model of the Green Deal shown above is based around forms of partnership with citizens and business, where EU funding is leveraged to help front-load transition costs for infrastructure and human resources. This aims to support these partners through transition upheavals, leading to increased capacity for the EU in new industrial production, but also a basis for moving internationally influential trading standards further towards sustainability goals. There could be further Green Deal leverages on companies. For example, companies could be required to cooperate with a more securitized agenda in order to obtain subsidies for transition to a circular economy (Damsté et al, 2024).

The model of Circular economy used by both the EU Green Deal and the NATO Stockholm report shares a common set of assumptions about geopolitical approaches. **Circular Economy as a solution to CRMs implies the abandonment of imperialist land and resources grabs as a solution to domestic resources crises.** While the circular economy cannot reduce all resource imports, the presumption is that such imports would be negotiated with the suppliers, even under conditions of stress. The benefits of forward thinking and foresight of a highly developed policy machine would no doubt help in such negotiations. Blunt force would not be considered an option. These points about wider geopolitical assumptions lead to an analysis of the wider model of EU environmental governance in the global context.

Intermediate Conclusions for this section:

a) The CRM Alliance/NATO report implies a closer form of regulation of business autonomy and a further enmeshing of business in trying to develop a more secure world for citizens.

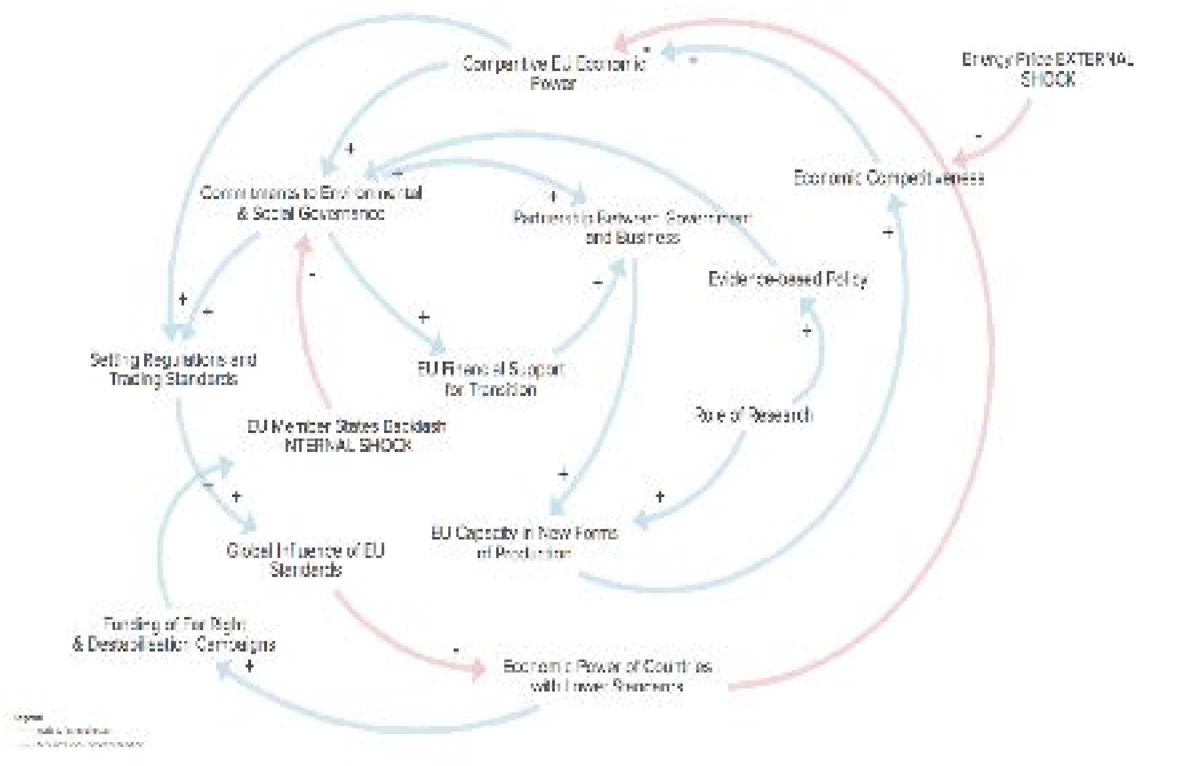
b) Something that is not fully identified in the NATO approach is that partnerships between State, Business **and Civil Society** for resilience are also essential in times of stress, a point that will be explored further below in the solutions section.

The European Geopolitical Model of Environmental Governance & Economy

The EU model of governance is complex and subtle, as negotiation on a partnership model has to be. This model can still operate within a difficult competitive global marketplace, but has done so by setting broadly progressive standards enabled by the size (450 million people) and (relative) stability of the EU economy (EU, 2025a). The EU supports standards of business and production which claim to support the wellbeing of citizens and the common good through global agreements. Although the EU does not always succeed in following these precepts, the EU model is basically a partnership model, not a Winner-Takes-All model. There are questions about which citizens are 'in the club', whether all in the club are treated equally, and who is considered outside of the club (Pelle et al, 2019) and these will need to be further addressed (see Conclusions). However, the partnership and relational approach is likely to endure as it is based upon the reality of the huge networked complexity of economic interdependencies across the world.

Internally, the EU has often seemed to be uncomfortably poised between a political project and a more technically-managed market aspect, more identified with the EU Commission. There is a strong sense that the Commission does not really want democracy interfering with its 'efficiency' (Plottka, 2020). There is some awareness in the EU policy communities that the success of the overall model does depend upon sufficient support from citizens in Member States. However, it seems that **the importance of citizen support has been severely underestimated**. Without citizen support policies cannot be carried through at the local community or regional level. In EU communications the main emphasis seems to be on presenting a set of competent and technical financial commitments, rather than in communicating with citizens, or the members elected to the European Parliament. The figure 5 provides a dynamic analysis of the EU model.

Figure 5: EU Standard-Setting and Support for Transition and Shocks



In this diagram the Comparative Economic Power of the EU helps in Setting Regulations and Trading Standards. The Global Influence of EU standards reduces the comparative Economic Power of Countries with Lower Standards. This then supports the Comparative Power of the EU. The Economic Power of the EU enables Commitments to Social and Environmental Governance which then contribute to Setting Regulations and Trading Standards. The Commitments to Environmental and Social Governance are supported by Evidence-Based Policy derived from the Role of Research. This Research also supports the further development of EU Capacity in New Forms of Production which is enabled by EU Financial Support for Transition. This helps support Partnership between Government and Business which also contributes to the development of EU Capacity in New Forms of Production. This capacity builds Economic Competitiveness, particularly in the context of the standards that the EU has promoted, increasing EU Comparative Power.

The diagram also shows interventions from some powerful Countries with Lower Standards to Fund the Far Right in Europe and to create an Internal Shock to this model, which can undermine the Commitments to Social and Environmental Governance. External shocks to Competitiveness come from the price of oil and power. Something conspicuously lacking from this model is a Partnership between EU Governance and Citizens, this is felt in various forms of democratic deficit, which is partly how attempts to destabilise the Green Deal find fertile ground. This is discussed further in the Conclusions.

Although still focussed on forms of growth and competitiveness, this model is a **slow-burn transition model** due to the developing commitments to Social and Environmental Governance and the transition away from harmful technologies to fulfil climate and other commitments. This also puts pressure on other countries. For example, the Carbon Border Adjustment Mechanism (CBNM), due to come into effect in 2026, has been designed to **penalise free-riders on the climate efforts of others** by charging their goods an extra tax (EU, 2025b). Whilst sustainability advocates might want this model to speed up, and change faster, under current global economic conditions, Competitiveness is still a major consideration, referred to as 'regulatory mercantilism' by Farrand et al (2024) in their analysis of the geopolitics of cyber-security. Although still in the market-economy frame, it has to be understood that even this limited common-good model is anathema to both undemocratic countries and to countries with an aggressive 'free-market' model. The global influence of EU standards is a continual irritant to those global areas that have lower standards. What is more, it is economically successful: *'……the EU's global leadership in setting environmental legislation and standards has been a cornerstone of its competitiveness and international influence for the last two decades. By setting stringent environmental standards and regulations, the EU has not only driven innovation within its borders but also shaped global norms and practices, compelling other regions to follow suit. Recent research (Fabrizi et al) show that Green Deal regulation has positively impacted innovation and European competitiveness internationally.'* (Schröder, 2024).

Setting standards has economic aspects as identified above, but is also a form of cultural power, which can be overlooked by those who seek to leverage more direct forms of power. This may be a growing consideration for the US under Trump, with risks of growing cultural and political isolation, considered further below.

The situation with regard to CRMs and Europe is informed by this slow-burn-transition model. Whilst Europe has a strategic interest in Ukraine's CRMs, the pathway envisaged is one of negotiated mutual benefit. Even though one could argue that the EU would hold a lot of the bargaining power, direct coercion to gain these resources is not expected. By way of contrast, Trump's America has no such qualms in using withdrawal of military support to Ukraine as a direct bargaining chip for control of their CRMs (Evans-Pritchard, 2025). Such considerations highlight the origins of the EU as founding a model for peace across Europe. One major ongoing question is whether this model can be adapted to strengthen Europe's security and resilience whilst strengthening its democratic mandate.

Most importantly for sustainability concerns, the **research capacity** of the EU is not only directed towards innovation for business, but is also supporting a broad set of commitments to evidence-based-policy (European Commission, 2025c). Evidence of climate change and biodiversity loss is fed into policy (Paleari, 2024). Whether measures taken are considered sufficient at this point of global environmental crisis is another matter. However, to abandon the good for the sake of the perfect is usually a bad strategy. Overall, the EU represents a globally influential form of workable economic life. Latterly, this model has been under stresses which need to be addressed as a matter of urgency to make the model more robust and resilient. Some of the issues to do with the external shocks and the EU democratic deficit will be addressed further below.

The two major shocks identified in the diagram reveal some of the weaknesses of the EU. Some of these weaknesses seem to be more in process than in overall approach, and process can always be improved to achieve greater internal stability and consensus. Other external shocks originating from the Ukraine war are likely to continue and be joined by some aggressive trade and political disruption from the new US regime (Koenig & Schütte, 2025).

Internal Political Shocks

It is well known that both Russia and the Far-Right in the US have been conducting long-term campaigns through social media to try to destabilise EU society and create divisions, plus supporting Far Right leadership figures in the EU.

Box 1. Examples of evidence of Russian and US Far-Right intervention in European Politics

The Social Design Agency acts under the orders of Russian President Vladimir Putin's deputy chief of staff Sergey Kiriyenko, according to the FBI court affidavit.The Russian document says the goal of the campaign is to "evoke in the audience rational (such as, 'really, why do WE need to help Ukraine?') and emotional (such as, 'Americans are such scumbags!') reactions." The psy-ops also relied on so-called doppelgänger domains to spread fake articles and content made to look like they came from Western media outlets.The domains included fakes of Reuters, Der Spiegel, Bild, Le Monde, Le Parisien, Welt, FAZ, Süddeutsche Zeitung, Delfi and others, and were paid for with cryptocurrencies such as bitcoin, according to the FBI affidavit. (Vela, 2024). A recent *openDemocracy* investigation found that America's Christian right spent at least $50 million of "dark money" to fund campaigns and advocacy in Europe over the past decade. (By the measures of US political financing, this may not seem like a vast sum, but by European standards it's formidable. The total spend on the 2014 European elections, for example, by all of Ireland's political parties combined was just $3 million.) (Fitzgerald & Provost, 2024).

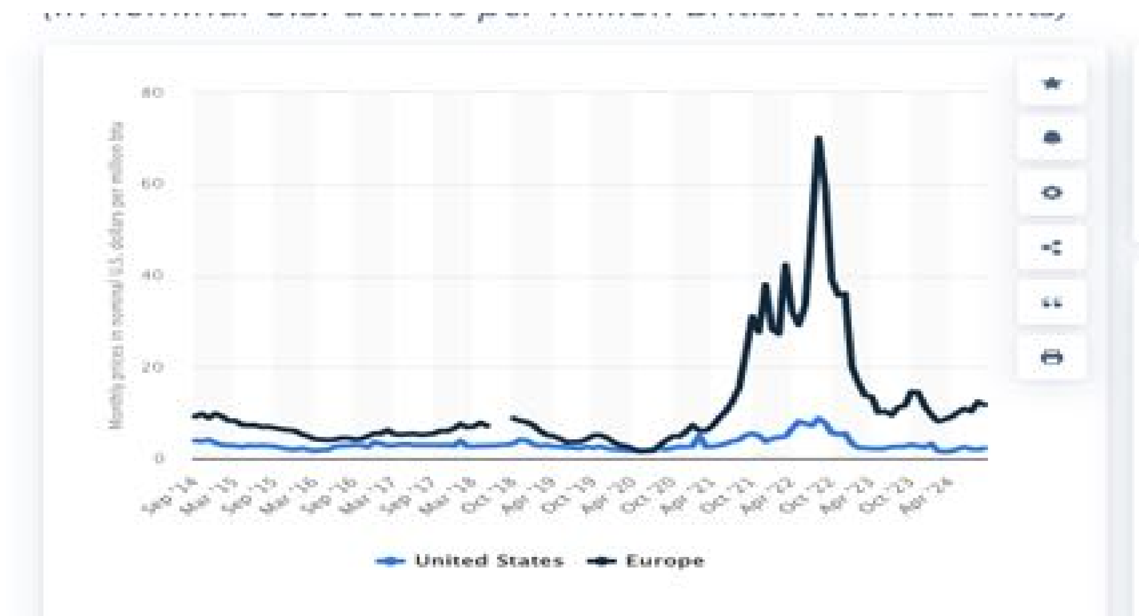
Some of the external political interventions could be more closely guarded against with rules about funding of parties, for example and a more robust security response from Europe (Consilium, 2024). The main point to be considered here is the way that support for the far right is helping to fuel internal opposition to the Green Deal in Member States: *'Tapping into a widespread sense of economic insecurity, both right-wing and centrist parties adopted this narrative and sparked a politicized debate that frames pro-green and pro-competitiveness policies as opposing forces. Italian co-leader of the hard-right European Conservatives and Reformists (ECR) group Nicola Procaccini called the Green Deal "crazy and sort of a religion," while Peter Liese of the center-right European People's Party (EPP) said the planned phase-out of the internal combustion engine—a central policy of the Green Deal's plan to decarbonize the transport sector—was a mistake. European policymakers now face the challenge of crafting a green industrial strategy that meets climate and sustainability targets and competes economically with the U.S. and China—but also addresses the concerns of disenfranchised voters who have turned to extremist parties, particularly regarding the cost-of-living crisis and the perception that green policies are out of touch. Ensuring a just transition for workers in declining industries will be essential for the strategy to be economically effective and politically feasible.'* (Schröder, 2024).

The argument presented further below is that linking resilience, CRMs and adaptation responses to climate change with the Green Deal is not only strategically necessary, but can also involve citizens in more of a developing partnership with the EU. This will involve some more budgetary allocation and leveraging of existing funds for local and regional forms of engagement. This will also involve establishing more direct feedback mechanisms and channels for those who feel aggrieved and unfairly targeted by the Green Deal. This would require the development of other additional forms of **responsive and adaptive governance,** more suited to developing agendas and volatile conditions. The importance of the political challenge is put very strongly by Politico, *The fate of Europe's historic climate mission and its political firewall against the far right are now intertwined.* (Mathiesen et al, 2025). Changing the culture of top-down EU governance is essential to keep updating and reinvigorate the EU as a unifying project in alliance with citizens.

Energy Shocks & Military Budgets

The energy shocks to Europe from the Ukraine war were partly due to the reliance of some EU countries on cheap Russian gas. Further consequences have been economic stress, particularly impacting Germany and considered to be contributing to the current political crisis. As reported in the Kyiv Post: '*When the war began, the economic impact on Europe's energy sector was staggering. The loss of Nordstream, sanctions and a host of other issues generated the perfect storm……. the price for natural gas jumped 500 percent across the EU……had the cost remained would have economically crushed the EU, perhaps something Putin expected…..'* (Fischer, 2024).

Figure 6: The rise in Energy Prices in Europe from 2014-2024



The law of unintended consequences in complex systems operates without prejudice. Far from benefiting from their leveraging of energy dominance in the EU, Russia has suffered from the EU responsive turn towards renewables, with China supplying the EU with over 90% of all solar systems. This means that the geopolitical power of the energy market is now heavily tilted towards China. This also highlights the international situation with regard to availability of CRMs and the fear of the US and EU of exposure to potential geopolitical leveraging of this dominance by China : *'China is the world's largest producer of lithium batteries for electric mobility and commands a 60 percent share of the global electric vehicle (EV) market. By strategically dominating the mining, metallurgy and material science sectors – often referred to as the "three Ms" – China dominates much of the world's clean-tech supply chains.'* (Umbach, 2024). The other economic shock from the Ukraine war comes from increasing military spending in a time of economic difficulty. Europe is under financial pressure to move from peacetime budgets to extending military support. For example, as a country on the border of Ukraine, Poland has increased its military spending, funded by the economic growth in Poland. There is also the stress of the Ukrainian refugee crisis. These are both serious strains on the EU model and are helping to fuel a combination of far-right discourses and appeasement of

Russia in some countries, which can be attractive to citizens who are struggling economically. The economic stress helps to fuel the backlash against the Green Deal, something which the enemies of environmental governance would like to see collapse.

This important set of considerations cannot be dealt with fully in this chapter, but some of the solutions below speak to the need for stronger geopolitical leadership by the EU with better communication of the vision for Europe in changing times to citizens. This is a part of the answer. From the sustainability perspective the main question is, 'how can we ensure the continuance and further development of European capacity for environmental governance and social improvement?' These issues are considered further below, together with some of the possibilities for the EU to **take back the initiative** on Democracy and the Green Deal, repel some of the advances of the Far Right and continue to support Circular Economy.

Some intermediate conclusions to this section are:

a) The EU model of environmental governance and prevention of 'race-to-the-bottom' is of global importance for sustainability – even more so given recent developments in the US.

b) Research outputs of the EU are of increasing global importance for sustainability transitions.

c) Need to bring the under-the-radar struggle between other geopolitical models and the EU social democratic model and vision into the light and advocate more strongly.

d) The EU needs to identify itself as post-imperial and working towards becoming more post-colonial to help global partnerships and understanding about sustainability transitions. The EU cannot hope to solve climate change by itself.

e) Energy shocks of EU need to continue to be addressed as strategic priority and explained to citizens as part of the overall situation of EU in the world

f) Exposure of the EU project to Far-Right undermining of the Green Deal means urgent attention to governance failures and perceived and actual democratic deficit.

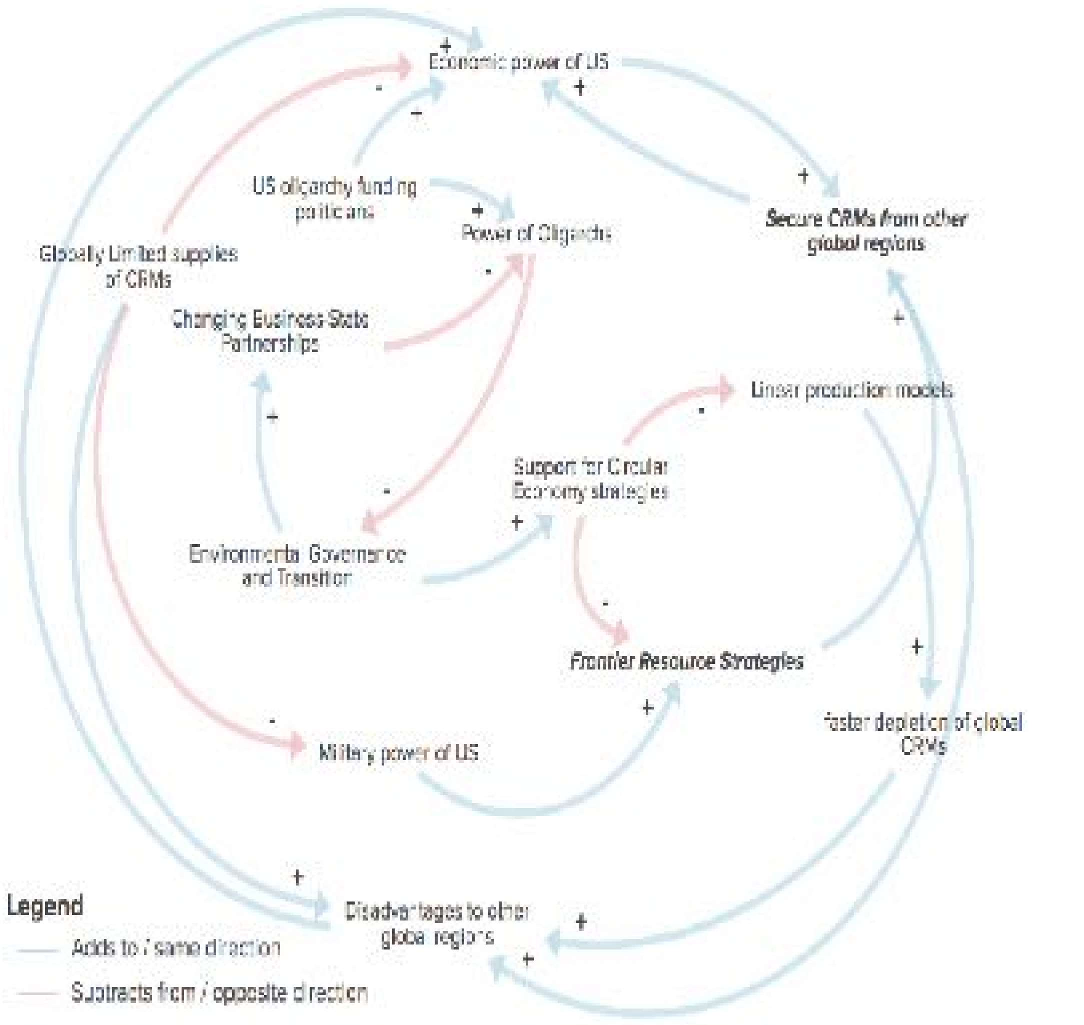
US Geopolitical Model and Approach to Critical Resources since Trump 2025

Recent events in the NATO alliance regarding Trump and Greenland have highlighted the growing importance and awareness of CRMs in a turbulent geo-political phase. The Trump phase began with a re-assertion of American exceptionalism and raw economic power, backed up with military threat. The major example of this with regard to Critical Resources is the threat to Greenland and its resources, now increasingly accessible due to melting permafrost. We have also seen opening salvoes in attempts to gain Canada's resources for the US (Coyne, 2025). **This approach fits with a return to a commitment to solving CRM problems through old imperial models.** With Trump we are dealing with a particular type of personality that influences behaviour and uses and abuses of power. However, we should not be blind to the underlying logics of these actions. They are rational within a particular limited and traditional world view and can readily be analysed as such.

The essential logic of the Trump approach is outlined by David Honig (2025): *'Distributive bargaining always has a winner and a loser. It happens when there is a fixed quantity of something and two sides are fighting over how it gets distributed. Think of it as a pie and you're fighting over who gets how many pieces. ……… The other type of bargaining is called integrative bargaining. In integrative bargaining the two sides don't have a complete conflict of interest, and it is possible to reach mutually beneficial agreements. Think of it, not a single pie to be divided by two hungry people, but as a baker and a caterer negotiating over how many pies will be* *baked at what prices, and the nature of their ongoing relationship after this one gig is over. The problem with Trump is that he sees only distributive bargaining in an international world that requires integrative bargaining.'*

The CLD model below suggests that the approach is actually worse than that, as it involves **seeking to reduce the power of other actors for future negotiations**, as also being part of the plan. This is referred to below as a Winner-Takes-All approach.

Figure 7: CRM Imperialism in the 'Winner-Takes-All' model



In this diagram globally limited supplies of CRMs could tend to reduce the Economic and Military Power of the US so steps have to be taken to secure a supply. The Economic Power of the US can be mobilised to secure CRMs from other global regions (by 'purchase' of those regions). Linear Production Models (favoured by established corporate interests who are either funding politicians or who ARE the politicians), result in faster depletion of Global CRMs, creating the need for more supplies. As Environmental Governance, and linked changes to Business, are rejected by the Oligarchs, this leads to no support for Circular Economy strategies. Lack of Circularity of CRMs creates more demand for Frontier Resources Strategies and attempting to secure CRMs from other global regions. The Military Power of the US can be deployed to underpin 'Frontier Resource Strategies' or land grabs and acts as a threat in any negotiations. This model of power-driven action and Winner-Takes-All, is shown in the increased disadvantages to other global regions which in turn increases the comparative power of the US. This is what Make America Great Again means to the Trump regime. This can be seen as a

Reinforcing Loop of Power, running round the outside of this diagram. In this reconstruction of the logics of the current Trump administration, circularity is ignored as a solution, going instead for a basically imperialist concept of gaining Critical Resources by coercion and/or military force. Clearly, these and other MAGA threats may not come to fruition, but the Greenland controversy helps to identify an illuminating central set of differences between this model and that of the EU considered further below.

Policies for Environmental Governance and Transition put in place during the Biden era, were quite similar to the EU Green Deal model in several key respects, including changing state-business relations to more of a partnership model. This was also supported by the leveraging of state funds to support transition and new Green jobs. In contrast, the MAGA model is hostile to anything that limits US oligarchic power. Democratic checks and balances, worked out to try to mitigate some of the worst outcomes of unconstrained capital, and to steer the economy more towards outcomes for wider society are now being shredded (Buncombe, 2025).

Any form of constructive environmental governance is now vilified as 'left-wing' in the US, and is currently being progressively eliminated in the current tsunami of unconstitutional actions (Euronews Green, 2025). The approach of MAGA is driven by the determination of the oligarchy to avoid all forms of environmental regulation, and anything else that is seen as interfering with their executive power. There will be no support for Circular Economy Transition – other than possibly to favoured companies. This is also highly unlikely to include any Just Transition elements for livelihoods of workers. The favoured 'solution' for the problem of CRMs and low availability and geopolitical risk is the imperial model of resources and land grab, leveraging American power, both economic and military. This is giving impetus for other countries to invest more strongly in Circular Economy (de Lange, 2025). The CRM issues are real and pressing, but are also just another geopolitical arena for the expression and performance of US power that is a feature of the MAGA project. The fact that this ignores any questions of cultural power and influence is instructive. Power gives the ability to ignore what others think of you and for some it appears that this is viewed as one of the perks. However, this could lead to serious consequences for the US in loss of global influence and trade. This is a point where the EU and social democratic project can continue to score highly in terms of global influence, as discussed further below (Sheriff, 2025).

The waste of CRMs in linear production, together with the plan for CRM dominance, is of concern to all of humanity including the citizens of the US (OECD, 2025). However, any conception of action for the wider common good has to be eliminated as this does not fit with the MAGA model, based on a view of greatness as accumulation of wealth and power. Climate change has to be denied as it absolutely requires collective action for the common good. This in turn leads to deliberate denial of facts, impacts and risks of sustainability crises and the destruction of the US machinery of environmental governance (NRDC, 2025). This means downgrading if not destruction of US research capacity in sustainability issues and policy recommendations flowing from that.

Comparison between the MAGA model and the EU model

"Trump's national capitalism likes to flaunt its strength, but it is actually fragile and at bay. Europe has the means to confront it, provided it regains confidence in itself, forges new alliances and calmly analyzes the strengths and limitations of this ideological framework."(Piketty, 2025, p. 1). Comparative systems analysis between the approach taken in the NATO report on Critical Resources (2024) and the EU Green Deal approach, with the linear approach of the current US administration, can help to clarify the underlying logics. This makes clear the severity of the strife, or potential breach in the NATO alliance. EU countries, whilst still benefiting from embedded forms of power and

advantage of their imperial histories (those that have them) are now basically post-imperial, if not yet post-colonial (Garton-Ash, 2023; Wolff, 2022). The assumptions about economy are broadly that negotiation and cooperation are possible and desirable, whilst the EU tries to maintain a competitive edge in the wider global economic system. Whilst Europe has a strategic interest in Ukraine's CRMs (Grabbe & Moffat, 2024) the pathway envisaged is one of negotiated mutual benefit. Even though one could argue that the EU would hold a lot of the bargaining power, direct coercion to gain these resources is not expected. For example, with regard to titanium, *'Some efforts to enmesh the EU and Ukrainian elements of the CRM value chains had already taken place before 2022, and they laid the foundations for nearshoring of the Tier-3 portion of the EU titanium value chain to Ukraine. In 2020/21 Volodymyr Zelensky's administration regained control over several major titanium facilities and established a ministry of strategic industries in the country, tasked with promoting the development of CRM production, mapping deposits and ensuring sustainable financing for their exploration. This change coincided with the EU's own attempts at diversifying its SVCs to include Ukraine, marked by the signing of the 2021 EU–Ukraine Strategic Partnership on raw materials and batteries, through which the EU invested €750,000 in technical support programmes; and by the 2022 memorandum of understanding aimed at modernizing geodata management in Ukraine, explicitly targeting Ukraine's potential for building resilient value chains for Europe's green and digital transition.'* (Jakimów, Samokhalov, & Baldassarre, 2024).

From the perspective of Trump, why should the US support NATO efforts to ensure that the EU benefits from Ukrainian CRMs when the US itself has a CRM problem that will not be solved by this? The recent demand from the US for CRMs in return for military support for Ukraine (Glebova & Nelson, 2025) is the existential blackmail of a predatory approach, not based on anything resembling partnership. Analysis of these two geopolitical models shows quite clearly that the EU model of influential standard-setting, along with European social democracy, can be seen as a threat. This has been made clear with recent political and economic attacks from the Trump regime. American exceptionalism demands the ability to freely drive down standards and will not join global agreements for the environment or human rights or the international rule of law. The EU is seen as a threat to the power oligarchy project in the US and other dictators around the world.

The mismatch between complex reality and simplistic WTA strategies does mean that MAGA threats and goals are likely to have to be moderated in the process of the sheer collision with reality. Another, worse kind of outcome is decline of trust into new wars, which can suit dictators and would-be dictators very well. On the face of it Trump has sold his programme domestically as one which will avoid war, but it remains to be seen what will happen if he fails to achieve his objectives through threat. However, we view these possibilities, the implications of the internal strife in NATO are profound, even though they may be manageable in the short term. With regard to NATO, Secretary General Mark Rutte is currently treading a finessed diplomatic path, suggesting that Trump was doing the west a favour by highlighting the security issues in the region: *'And on Greenland, what I think is very useful is that President Trump alerted us to the fact that when it comes to the high north, there is a geopolitical and strategic issue at stake. I would say that it's not only about Greenland. This has to do with Finland. It has to do with Sweden, Norway, Iceland. Yes, Greenland, and therefore Denmark. Also Canada and also the US. And clearly, collectively as an alliance, we will always look at the best way to make sure that we can tackle those challenges.'* Rutte, quoted in Sparrow (2025).

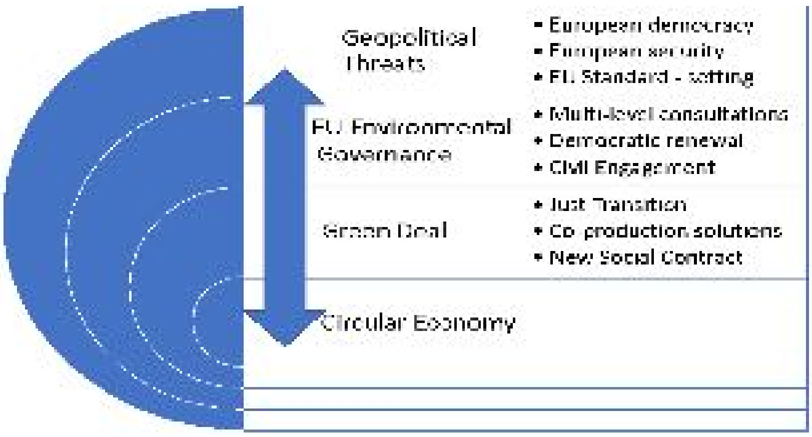
Although we may hope that the Trump phase will eventually pass, it would be unwise to presume that this will pass easily. Overall, the approach seems to be to try to manage it in public, whilst putting in place measures to defend and strengthen Europe : '…..*a brighter scenario would be one in which four more years of Mr Trump catalyse a pragmatic reset that is overdue. As Mr Macron has advocated, the EU has the chance to respond to a transformed global context by leveraging its own strengths as a market of 450 million people, and deepening strategic autonomy in areas such as defence, tech and AI, and the green transition.'* Guardian Editorial (2025).

Any reasonably positive scenario does depend upon the continuance of European capacity for environmental governance and social improvement and the survival of the EU model in the face of these difficulties.

Conclusions: Defending and Extending Democracy and Environmental Governance

There are two main themes in this section. The first is the internal issues of the EU and Green Deal, the second concerns the role and profile of the EU more globally. Comments towards solutions are interwoven with the problem statements which have been identified in this chapter. A short set of summative conclusions is provided at the end of the chapter.

Figure 8 : Linking democratic politics into technical aspects of Security and Circular Economy



This diagram reflects the progress of the argument in the chapter and the conclusions in this section. The main point is that, as with all sustainability concerns, an interdisciplinary approach has to be taken. If technical analysis forgets about the politics in European policy making, efforts for environmental governance, Circular Economy and Security will be undermined.

The EU Democratic Deficit & the Green Deal

As identified the EU works through multi-level governance and there are already multiple issues with how this works and the rather technical appearance of the 'top level' of governance, with the EU Commission as the Executive (Citizens' Information Ireland, 2025).

The stated model of good governance in the EU is partnership between Business, State and Civil Society. However, many commentators have noted that Civil Society is often the poor relation at the EU table, with corporate organisations paying large costs to maintain lobbying capacity at Brussels (Michalowitz, 2004; ALTER-EU, 2010). This increases the pressure against very active interventions on equality and social standards, as well as slowing down environmental legislation, and adding to the sense of democratic deficit (Terry, 2017). The ability of elected Members of the European Parliament to hold the EU Commission to account has been questioned, as the complexity of work done by the EU is high. Average voting figures in Member States for the European Parliamentary elections are only 50% (European Parliament, 2024). Both these latter points suggest that issues being dealt with at the EU Commission level are not readily explained to support the democratic engagement needed.

Mid-level communication and engagement is the bridge between political representation and constituencies. Further to that more two-way exchange of knowledge is needed. This becomes (at least) three-way exchange when local areas and stakeholder groups within Member States are considered. This means a renewal of Multi-level Governance around the mixed set of threats to Europe at this time. With regard to Circular Economy and Security, the IEEP report of 2020 provides a really good technical overview of interacting areas but does not consider the whole question of citizen engagement, livelihoods or forms of local knowledge. This has been added on later in a short briefing which is beginning to address some of the issues in European environmental governance (IEEP, 2024). This scrutiny only happened after a lot of citizens protested against various clumsy forms of environmental governance that do not appear to have considered their interests. Much more interdisciplinary working with sociologists and people working in politics is really needed and consideration of more forms of direct democracy such as co-production of policy. Governance of resources and economy will always be difficult but so many clear errors could be avoided by some foresight, such as bringing in cost measures which hit the poorest hardest and prevent smaller businesses from functioning (Wiese, 2024).

The Green Deal, Circular Economy and the EU agenda on transition is also a part of multi-level governance, but a relatively new part :*'When it was unveiled in December 2019 by Ursula von der Leyen, ……the European Green Deal appeared to be the largest and most ambitious integrated program of reform, investment and research ever conceived by the European Union.' (Enel Group, 2023).*

Multi-level governance already has stresses and strains in the relationships between state citizens, regional governance and member states and the EU levels (European Committee on Democracy and Governance, 2023). Governments at the national level often find it convenient to blame the EU for anything unpopular without explaining the purpose of legislation to their citizens. The Green Deal may seem to be making these worse by imposing changes on Member States, above and beyond the more accepted problems of economy. The EU overall seems not to grasp the need for a major publicity and engagement effort with citizens in order to gain support for Green Deal changes – citizens need to know WHY they are being asked to change, what this means for their lives, and how this can lead to a better future. This in turn implies more direct leadership at the EU level, but also ways to fund and enable engagement in Member States as a key part of the programme (IEEP, 2024). This requires a great deal more attention to how citizens can feel that this is their 'Green Deal'. Who was the 'deal' made with? The feeling is that citizens were not involved and so they do not support a deal made without them at the table.

There is no sense of the Green Deal as a political process of arriving at a 'deal' in the sense of social consensus with citizens. Moves towards protecting and extending aspects of democracy are already in place (European Commission, 2024), but this does not seem to consider the issues around internal democracy that affect the Green Deal. Communication issues have been researched (e.g. Deloitte, 2017), but commissioning an international consultancy should only be a starting point to inform a much more wide-ranging political effort. Something like an EU Social Forum would also be needed to start to gain innovative ideas from the many already active people in civil society, and to bring in others. Something similar was proposed by Julian Plottka (2020) for the 2020 conference on the Future of Europe. Something like this needs to be urgently revisited right now, considering the civil and Third Sector in Europe (Ever & Laville, 2004) : *'Participative democracy, defined as the participation of stakeholders, organised civil society, and individual citizens in EU-level decision-making, should complement and support rather than replace representative democracy. It strengthens input legitimacy, as participative democracy is an additional channel for inserting citizens' demands into decision-making and strengthens transnational opinion formation. By holding EU decision-makers accountable and forcing them to be more responsive, participative democracy helps to make electoral alternatives more visible. Finally, participative democracy contributes to further developing European public spheres.'*(Plottka, 2020, p. 1).

Many people identify the Green Deal as primarily ecological and this tends to leave out the question of Circular Economy, but also how the Green Deal links to Human Security and wellbeing. The rapidly rising profile of CRMs due to Trump gives an opportunity to change the Green Deal 'brand' to make CRM security and Circular Economy a bigger part of the strategy. The case for Circular Economy and the importance of CRMs needs to be communicated to citizens in order to gain more support for the strategy as a whole. Trump has also succeeded in dramatizing the security concerns of Europe with his recent undermining of Ukraine's position and side-lining of NATO allies, conducting direct talks with Putin. More links need to be made between these more traditional security agendas and the resilience of citizens to climate change, stressing European solidarity. This means gaining more involvement from citizens, finding new joint platforms for civil organisations to take part and shape policy, particularly at the local level (Korostoleva, & Flockhart 2020; IEEP, 2024)

Involving Civil Society and Extending Democracy to support Localised Resilience

The increasing need for European society to respond to some of the worst experiences of extreme climate incidents is becoming clearer every month. This needs to be understood and communicated as a key aspect of the Green Deal and emphasised as part of **European solidarity** across different European countries who are experiencing climate change and its multiple issues (FOE Europe, (2020-2021). The essential need for citizen action and support for building resilience needs to be a much more prominent aspect of the Green Deal (REGILIENCE, 2022). Public engagement could begin to translate this one-sided 'deal' into something more resembling a New Social Contract with Citizens.

One of the common presumptions of a security agenda is that this has to mean restrictions on citizens' freedom, as for example, in time of war. This fear is already being mobilised by the far right. A bold move is to pre-empt this fear by embarking on a clear mission to extend democratic engagement on ALL the aspects of security identified by Petelin, including Human Security and Ecological Security (Barroso, 2025). The complexity of the necessary changes for the Green Deal transition and adaptation, together with additional strains on civilian living standards, means that it is essential to have citizen agreement and support. Policy makers also need the input from extensive local and indigenous knowledge to assist with solutions suited to local conditions (van der Molen, 2016).

Figure 9 : Requirements for National Resilience (NATO, 2024)

The list of resilience factors identified above in the NATO approach does speak to a range of civilian needs and requirements. However, something that is not fully identified in the NATO approach is that partnerships between State, Business **and Civil Society** for resilience are also essential. This is particularly the case under conditions of stress.

The need for Civil Society to be centrally involved and enabled for resilience to climate impacts and supported adaptation is still not fully recognised in EU policy, for example in the Critical Entities Resilience Directive (EU, 2025d) : *'Critical entities must have a comprehensive understanding of the relevant risks to which they are exposed, and a duty to analyse those risks. To that end, they must carry out risk assessments in view of their particular circumstances and the evolution of those risks and, in any event, every four years, in order to assess all relevant risks that could disrupt the provision of their essential services* ***('critical entity risk assessment')****'.* This 'instrument' is actually about Human Security and citizen support and highlights that communications would really be helped if all such policy instruments could be branded in ways that actually made sense to citizens. Opaque technical language simply reinforces views about EU elites and these impressions matter to how citizens feel about supporting policies.

Assessments for Human Security need to be conducted in tandem with more localised input and discussion. Unless local people are involved, and their knowledge contributed and validated, we will not have a realistic assessment of issues, nor will we have access to the well of community creativity and commitment that can actually translate into success on the ground. Funding that was put in place during the pandemic (EU Commission, 2025e) attempted to make a solidarity response, but as the frameworks for engagement with the Third Sector were not in place this still lacked the missing citizen engagement dimension, as discussed above.

One key theme in solutions is relationships of resilience and sustainability, seen as key bridging factors across these first two accounts and draws out further the role of Circular Economy in this bridging. The rising profile of CRMs gives a great opportunity to make citizens and communities more aware of the common interests between States, Citizens and Business in finding new pathways. This could include **awareness of local exposure to CRM risks and local opportunities for Circular Economy business development, some of which is likely to be social business**, contributing to more 'sufficiency perspectives. Including civil society brings a possibility that the vision of the EU can be enlivened and taken forward in a revived form of Social Contract with citizens, that can also be of wider global benefit. **This means convening platforms in different Member States which also discuss some of the successes and failures of environmental governance and gains lessons learnt that may be transferable to other areas**.

Leveraging other existing funds in the EU toolbox could support such developments, also involving the ability of the Arts to shift and deepen cultural understandings. Beyond more elite pan-European approaches such as the European Bauhaus, what are the plans for more localised and regional cultural and artistic engagements with the Green Deal (Culture EU, 2021-2027)?

Links between common standards, the security and continued prosperity of the EU need to be more widely understood, as this model is rightly complex, it is not being communicated well in traditional formats. This means the benefits are in danger of being taken for granted, sometimes by those who can benefit most. Systems diagrams lend themselves to infographic forms of communication that can be 'warm' and accessible, including pictorial elements. Explanation of the EU model, the Green Deal and Security need to be made more available throughout the EU with civics education and learning being made available (EU Education, 2025).

Sufficiency Approaches and Civil Society: A Missing Piece of the Strategy

The further element that is not being visited properly in Circular Economy research and policy so far is our ability as societies to scale down consumer demand and move to a different set of economic goals rather than increasing GDP. The discussions about this are already underway in many areas and cannot be fully addressed here (EU Science Hub, 2025). However, the current situation with CRMs is a good opportunity to really dramatize the issues and to gain civil support and engagement for a lower-resource-intensive future. This is the third arm of the strategy that needs a great deal more thought and research. Some organisations are already active: *'……so far, the EU has sought to address this (crisis) agenda without seriously considering a critical lever at its disposal: managing Europe's resource use. Faced with surges in cost of living, growing inequality of wealth and income, and unprecedented consequences of climate change, the EU must take advantage of all levers available – including resource-wise demand-side policy – to ensure its economy is fit to deliver well-being and protection for all.'* (SHIFT, 2024, p. 2).

Figure 10 : Organisations supporting the SHIFT report 'A Resilient and Resource-Wise Europe: Sufficiency at the Heart of the EU's Future

Aspects of the Green Deal should include much more consideration of how to engage citizens and communities in building something like Wellbeing Economy linked to strong local resilience. This is a necessary part of the transition aspect of the EU model, but one that is in tension with the global competitiveness aspects. However, global competition over resources as dramatised by Trump, may be looking fairly unattractive right now. The SHIFT document references supporting data from citizen engagement including on the future of Europe, where citizens supported sufficiency approaches (op cit p2). With regard to CRMs, this also makes sense : '*By reducing demand and using resources wisely domestically, Europe can be less dependent on critical imports, less* vulnerable *to shortages, and more resilient to shocks. Sufficiency can thus provide the EU with more freedom of choice in trading partners and goods as well as greater resilience to global risks.'* (op cit p. 4). This will not directly help with current defence concerns, but none of the options will work alone, they need to work together and not be opposed to one another. However, developing cultural approaches to sufficiency and re-use could be a vital factor in supporting European resilience in challenging times. The ugly alternatives can be seen as increasing conflict over resources and a decline in human solidarity which many citizens understand is the basis of social life.

International levels

The EU needs to clearly identify and promote its transitional model and the benefits to both Member States and citizens as something positive in the wider global landscape. This means highlighting much more clearly the perils of the 'race-to-the-bottom' of which some other actors espouse. This can be done with some concepts from New Economy thinking, for example, 'Failure Demand' adapted by the Wellbeing Economy Alliance (WEAll, 2021). **Failure Demand' points out that social and environmental harms create demand for remedial measures**, which either cost a lot of money to 'fix' or, left untreated, cause widespread social ills. These can be estimated and illustrated through comparisons which can be made to countries' experiences with the race-to-the-bottom and what that does to citizen wellbeing. For example, the EU commitment to criminalise forms of environmental damage can help communities who are trying to protect their health and local ecologies (Green Intelligence, 2025).

The EU model of environmental governance and prevention of 'race-to-the-bottom' is of global importance for sustainability – even more so given recent developments in the US. This gives the EU a golden opportunity to spread the basics of the EU model more widely in communications, but this will also mean improving the model with regard to partnership and transparency. An approach could be put in place with the assistance of research organisations and funds to ramp up the audibility of a wider range of voices from different global regions about the relations with the EU and the effects of policies. There is a need for more EU engagement with a range of work that is pointing to the negative effects of some forms of trade and impacts on other countries' societies and ecologies that seem to be enabled by the EU (Greenpeace, 2024). This also includes work on the effects of the Carbon Border Adjustment Mechanism on countries in the Global South (African Climate Foundation & LSE, 2023).

Research outputs of the EU are also of increasing global importance for sustainability transitions, and it is of great concern that these be made widely available. However, these are often not directly transferable to the needs and concerns of other global areas. International aid for the development of home-grown forms of sustainability needs to continue, including how to protect existing forms of sustainable livelihoods that are under threat from extractive western development models. Wider debates need to take place with other global regions who want to engage in dialogue about sustainability transitions. Some of the more established and well recognised progressive overseas aid organisations in the EU could assist here, for example the Dag Hammarskjold Foundation and the International School of Social Studies in the Hague, to mention just two such institutions.

CRMs and International Cooperation

Even if the Circular Economy approach is fully adopted, this will take some time to come to maturity, although some efforts could be quicker than others. Not all the requirements for the EU will be met through CE and imports and agreements will still be needed. The partnership approach is necessary here, *'Rather than become inward-looking, Europe will need to increase its international cooperation with trading partners, especially low- and middle-income countries. The COVID-19 pandemic highlighted the issues arising from concentrated semiconductor supply, emphasizing the need for diversification in the supply of critical goods like semiconductors and raw materials. Since then the EU has initiated critical raw material partnerships with several resource-rich countries, including Namibia, Kazakhstan, the Democratic Republic of Congo, Zambia and Uzbekistan. These partnerships are crucial for European competitiveness (ensuring access to materials needed for the twin digital and green transitions), but must also support industrialization and value-added industries in partner countries beyond mere extraction to achieve mutually beneficial outcomes.'* (Schroder, 2024)

A strongly linked set of concerns are that the EU needs to identify itself as post-imperial (Garton-Ash, 2025) and work towards becoming more post-colonial to help global partnerships and understanding about sustainability transitions (Woolf, 2022). The EU cannot hope to solve climate change by itself. Strategies for CRMs are often seen as being in tension with environmental goals, as raw materials need to be extracted and these have been a disaster in imperial and post-imperial phases. Extraction has been linked to heavy pollution, and oppression of indigenous and local populations. Corruption has also been strongly linked to extraction industries, with histories of slavery and abuse of human rights. (Ragnarsdottir, 2020). Working more closely with the UN on extraction industry standards would help here.

During its presidency of the EU, Sweden took the theme of democracy and produced analyses which linked internal action and narratives about democracy with the approach of the EU on the international stage (IDEA, 2023). These themes should be urgently revisited and fully considered, both from the internal and external face of democracy in the EU, with additional special emphasis on issues and problems of environmental governance.

Summary Conclusion

This chapter has outlined a range of problems currently faced by European environmental governance, through the lens of Critical Raw Materials and commitments to Circular Economy. The recent accession of Trump and the MAGA regime in the US is raising doubt about the ability of NATO to take a joint view on these matters. Wider implications concern the threatened viability of the EU geopolitical approach and the strife between two very different economic models at the heart of NATO. The European model is under attack at the present time from a number of directions and its innovations in environmental governance are at risk. Overall, this chapter makes the case that the continuance of the EU Green Deal and measures for Circular Economy are essential for the future of sustainability and wellbeing of citizens both in the EU and at the global level. The lens on Circularity, Security and CRMs can help suggest some ways to grow more widespread support for the Green Deal among citizens in Member States, and develop more strategic use of foresight techniques for resilience. More emphasis on sufficiency aspects in culture and local economic resilience would also be an important aspect to develop. A stronger social contract with citizens in Europe needs to be part of any deal that calls for more collective action for security and defence of European social democracy. Consideration of the geopolitics of CRMs and how this links into current security issues highlights the risks to the wider European project on a regional and global level. If we want to protect our ability as citizens to contribute to effective environmental governance and Circular Economy for our planetary future, we need to defend and extend EU social democracy. This chapter has argued that this means much more attention to the politics involved. Exposure of the EU to Far-Right undermining of the Green Deal means urgent attention to governance failures and perceived and actual democratic deficit. Constructive criticism and innovative solutions need to be urgently convened, with the aim of extending democracy in numerous ways. We can draw on the histories of good examples of resources governance in some Member States. For example, the existence of really effective Intermediate Institutions that mediate between local actors and governance of natural and other resources. In order to really explain the need for the Green Deal and Circular Economy, the leaders of Europe need to communicate directly to citizens that we are in a form of civilisational crisis and that Europe has a plan that is consistent with European values. This would mean **finding a much stronger immediate form of leadership for the European project,** which currently relies upon a few particular advocates. This needs to be much more organised and thought through using the latest understandings of human psychology in messaging, but also using more direct communication channels. To rely on technical efficiency alone is to court political disaster when the times require a stronger sense of common identity and purpose. Resilience can be considered as the missing linking section between transition for climate change with citizens' wellbeing. This can link increasing the resilience of the EU to threats and problems from hostile actors and improving resilience to climate disasters and loss of livelihoods. Looking forward, further action by governments will be needed to deliver essential services and supplies to the civilian population through the continuing upheaval of dangerous climate change in the foreseeable future. Writing from the UK at this point in time the contrast between the EU and the US geopolitical models is rather on our minds. This analysis provides very good reasons for closer UK alignment with the EU model for future resilience and sustainability. From a sustainability perspective, all societies developed under conditions of extractive capitalism are experiencing chronic symptoms of deep systemic problems caused by this model. **Some societies are at least listening to the signals from the present and the future, and beginning to take action to transition. We cannot allow those who are seeking to go backwards to set the global agenda.** The systemic problems of sustainability will not go away, and denial could hasten the worst outcomes for our societies. The lock-in to the extractive economy that the MAGA project seeks is profoundly undemocratic in its attempt to shut down alternatives. The answer would seem to be a robust response, strengthening and deepening the beginnings of sustainability transitions in Europe, with extensions to European democracy, together with stronger commitments to more equal global partnerships. There is a need to be bold at this point in time and extend democracy in the EU to gain real citizenship ownership of these agendas. The current geopolitical moment should be seen as an opportunity to do this, with visible threats to Europe opening up new political spaces. This chapter proposes that one way forward could be developing the Resilience agenda alongside Green Deal and Just Transition measures to give a guarantee to support citizens through difficult times. This agenda needs to be one that is increasingly co-created with citizens and develops through extended democratic feedback systems and adaptive governance. Such moves could constitute a New Social Contract with citizens that is not seen as imposed from Brussels.

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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.

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 drawn.

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.

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.

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. IE, in contrast, 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.

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 in two levels: a general overview on the overall scientific production and an in-depth analysis.

Research design

For both bibliometric and content analysis, the data for the study were obtained from the Scopus database. 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 (Elsevier, 2023).

For bibliometric analysis, the search performed consists of two data extraction steps (Figure 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 & 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 & 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 shown 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;

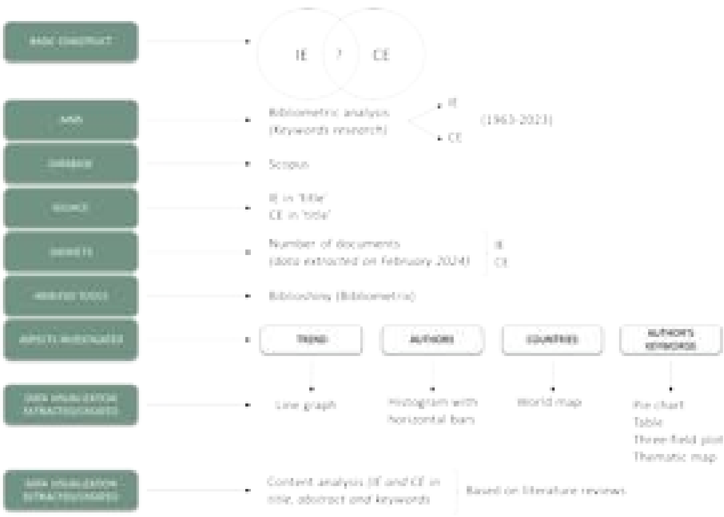
- *author's keywords* (most relevant keywords). Author's keywords are the keywords given by the authors. Data are extracted from Biblioshiny based on the keywords used by the authors and their frequencies. This data is processed to create a summary table that highlights the top 20 IE and CE keywords 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: Research design. Source: authors' elaboration



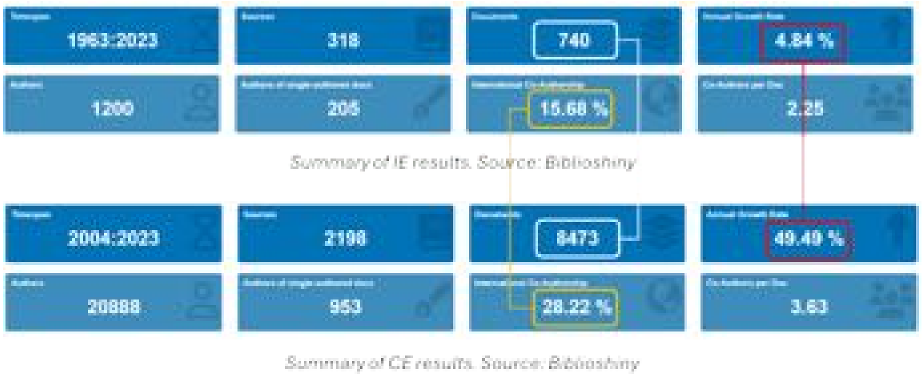
For the content analysis, the literature reviews identified through the following search criteria on Scopus were selected: "industrial ecology" AND "circular economy" in the title, abstract and keyword domains. The search was limited to the period 2004-2023, with 2004 representing the year of the first 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 us 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 the literature addresses and structures these topics, highlighting connections between the two fields of research, 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.

Results

Premise

Figures 2 A and 2 B 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.

Figure 2 : Summary of IE and CE results.



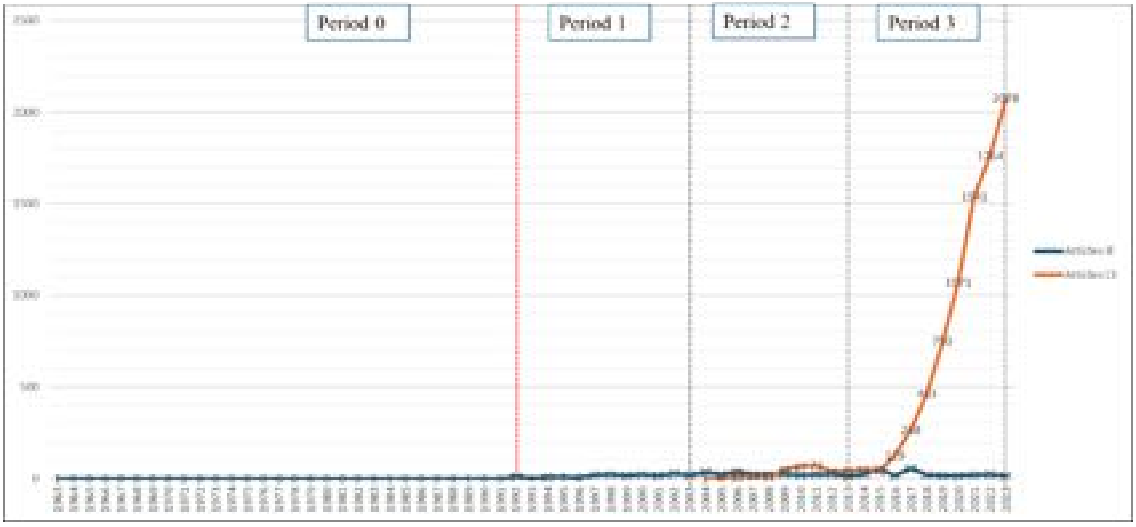
Source : Biblioshiny

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 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 3 : Line graph - historical evolution of IE and CE.

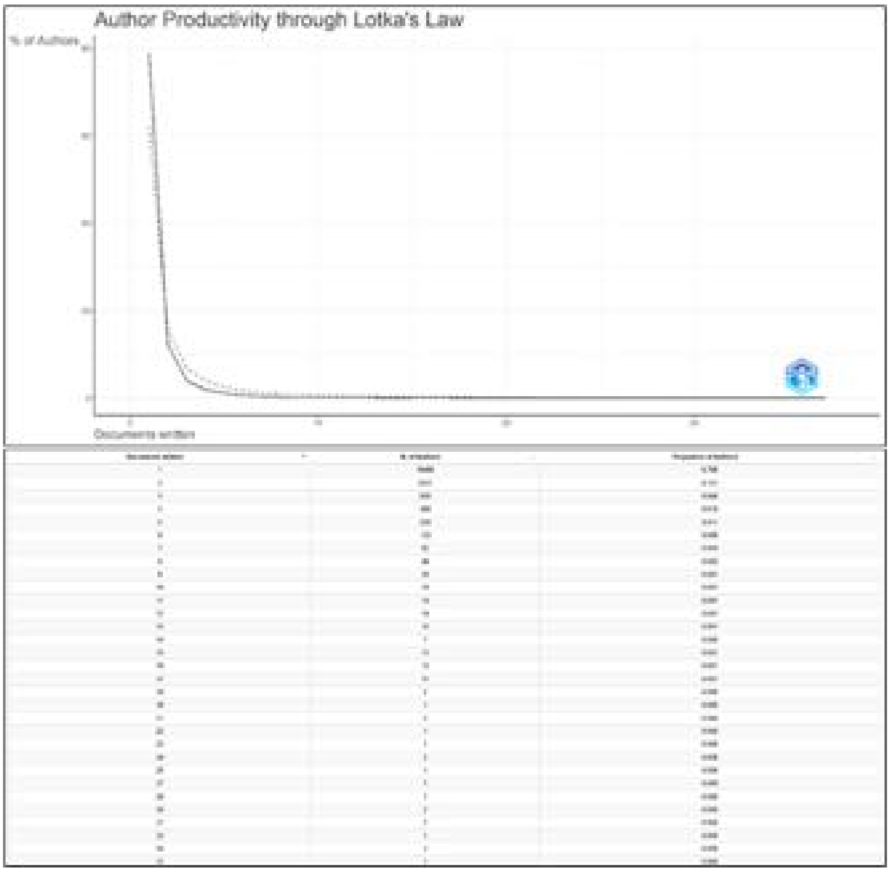


Source: authors' elaboration

Authors

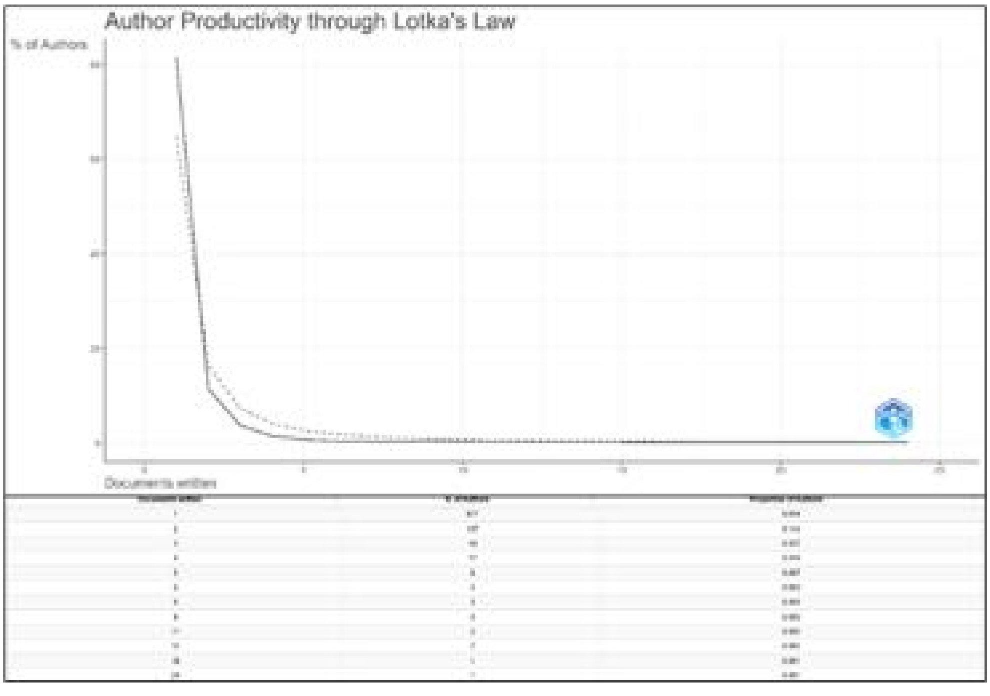
In the case of CE (Figure 4), the continuous line (observed distribution of data) shows a higher percentage of occasional authors (1-2 documents), with a rapid decrease in productivity for authors with more than 5 articles. This suggests that CE is a relatively new or interdisciplinary field, characterized 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 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 4 : Circular Economy. Author Productivity through Lotka's Law.



Source: Biblioshiny

Figure 5 : Industrial Ecology. Author Productivity through Lotka's Law.

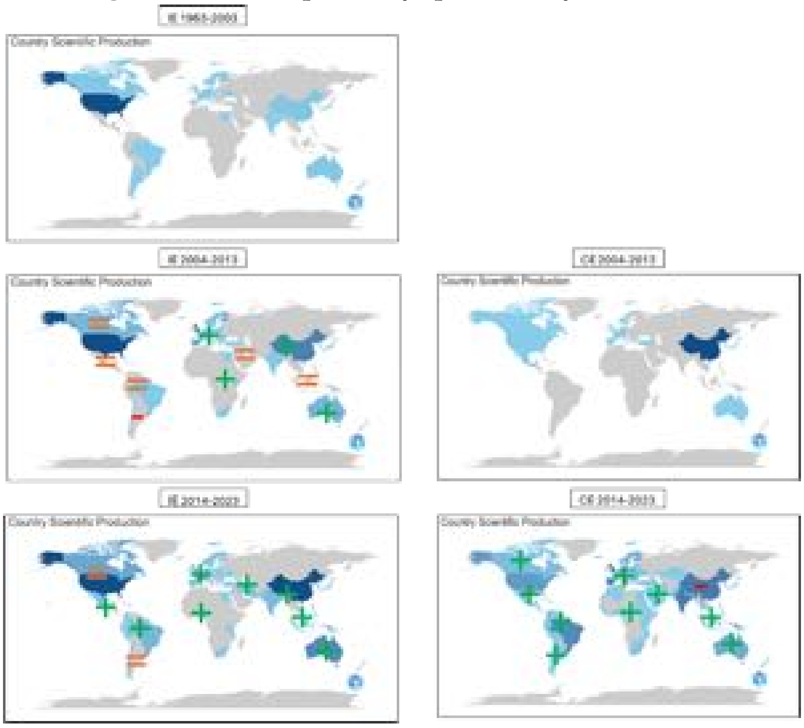


Source: Biblioshiny

Countries

Figure 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 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 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).

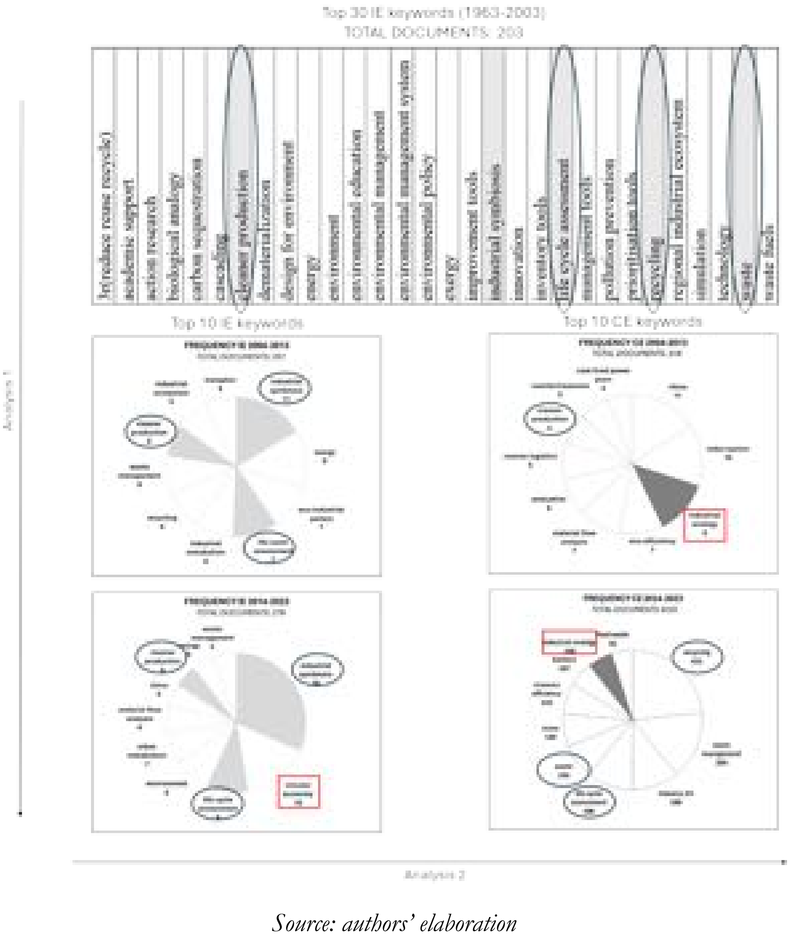
Figure 7 : Summary Table (IE and CE) - all period

	anaerobic digestion	barriers	bioeconomy	biological analogy	business model	china	circular economy	cleaner production	complexity	dematerialization	eco-industrial park(s)	emergy	**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**

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 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 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 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.

<u>Figure 8</u> : Pie chart - 3 periods of IE and CE.

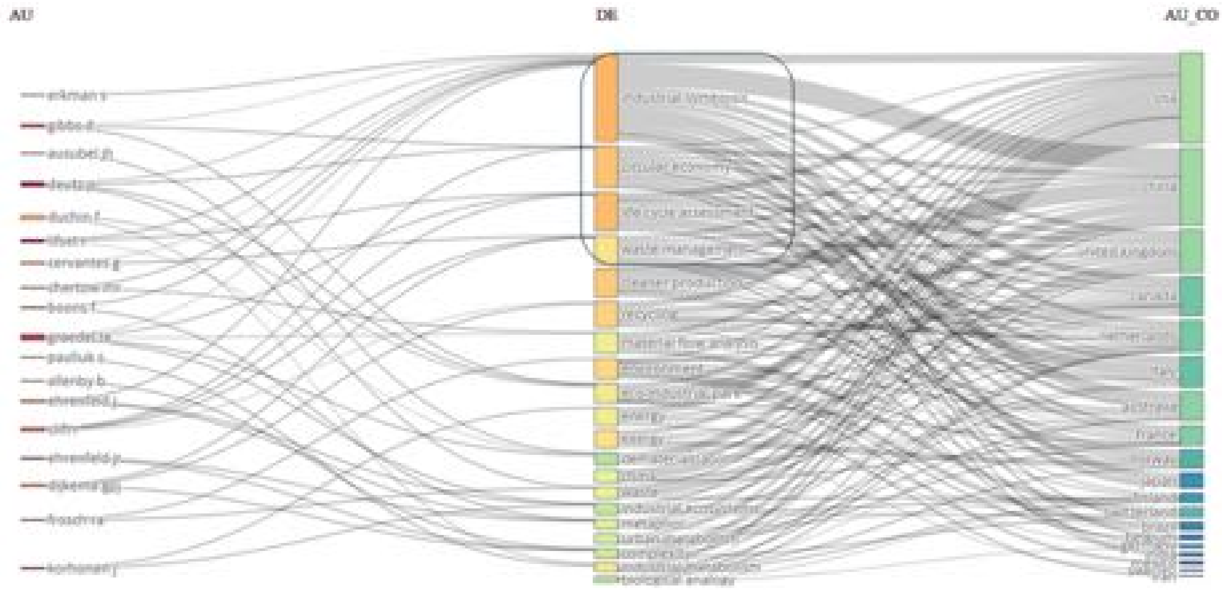


Source: authors' elaboration

Cross-analysis

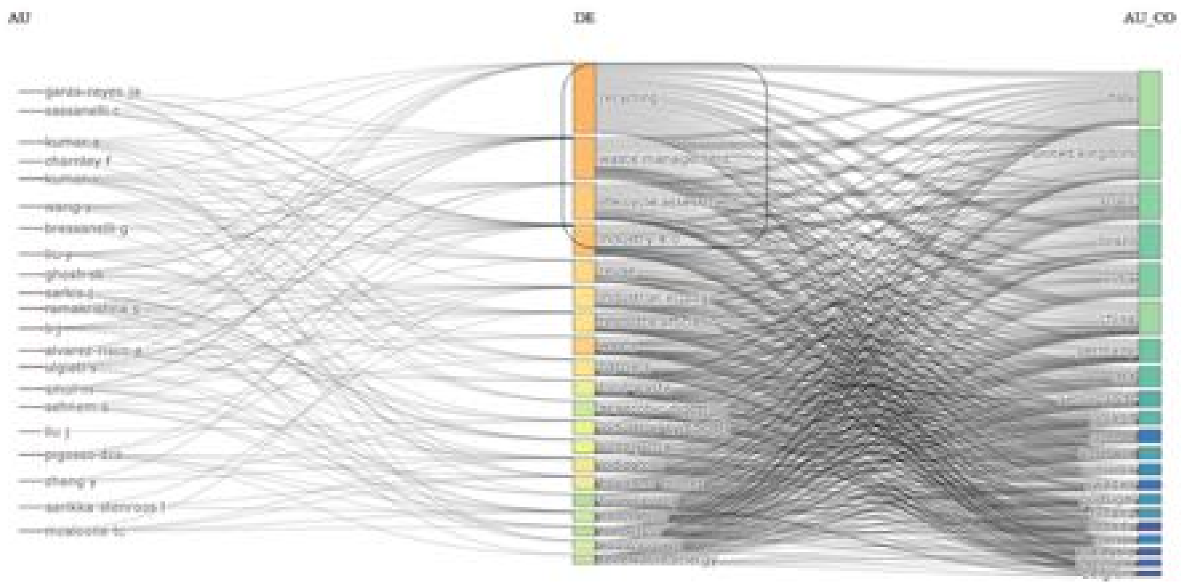
In a cross-analysis of the previous results, and with reference to the entire period of scientific production for the two fields of research considered, a three-field diagram was used to investigate which authors in the two fields are concerned with which topics of study and where they come from. The purpose was to map both the current distribution of dominant research interests and their geographical location. Figures 9 and 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 9 : Three-field plot – IE (1963-2023)



Source: Biblioshiny

Figure 10 : Three-field plot – CE (2004-2023).

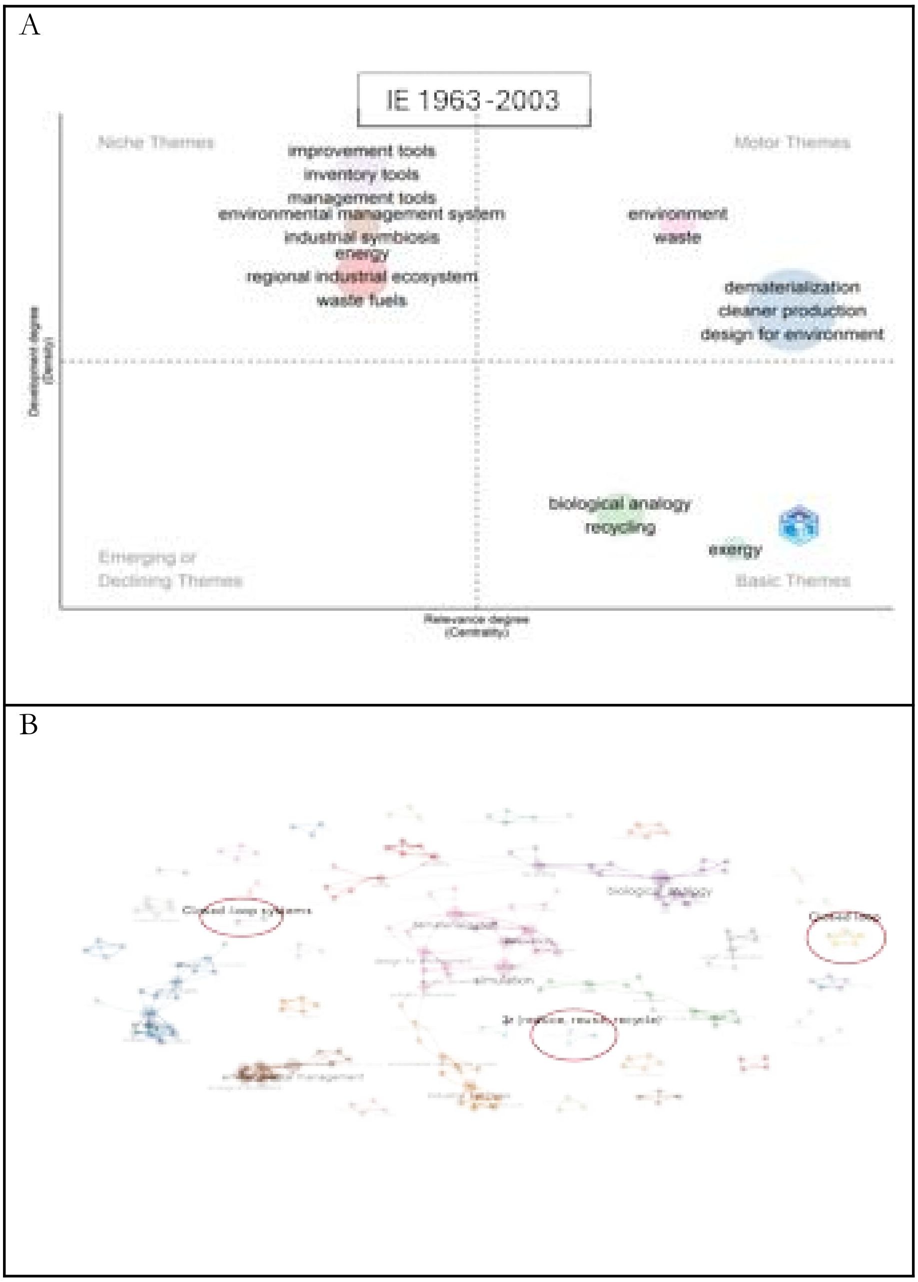


Source: Biblioshiny

Relevance and centrality of the themes

In a 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 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.

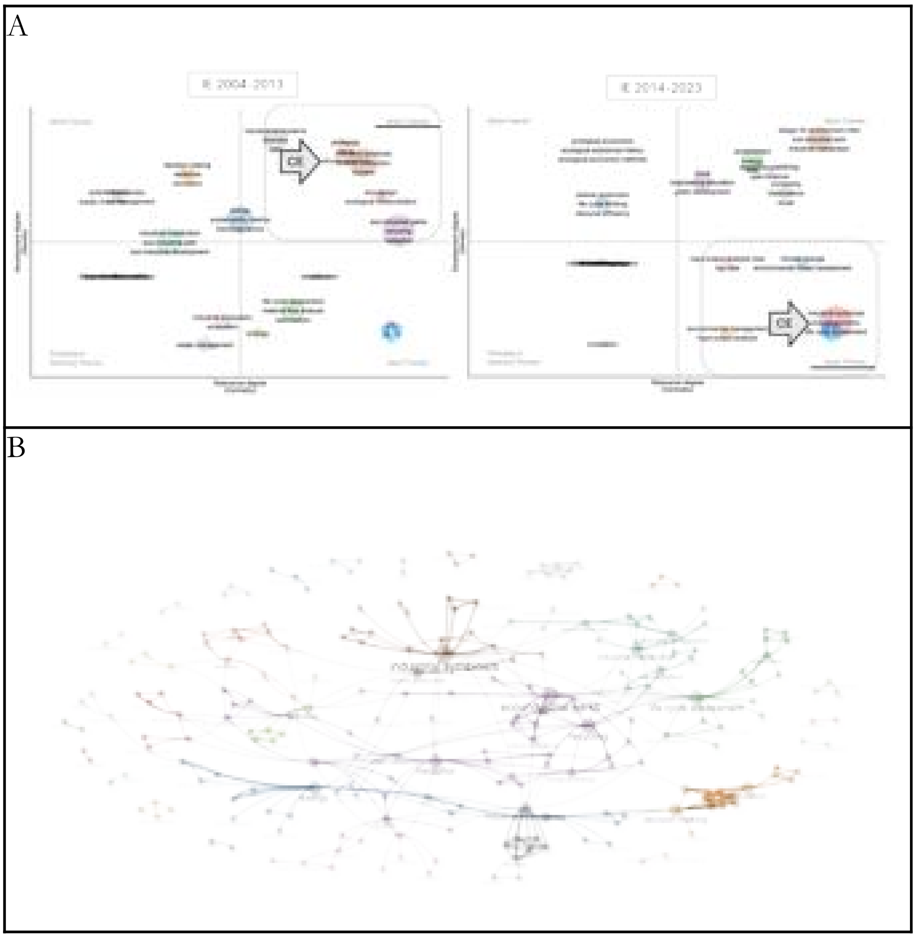
Figure 11 : Thematic map – IE (1963-2003)



Source: Biblioshiny

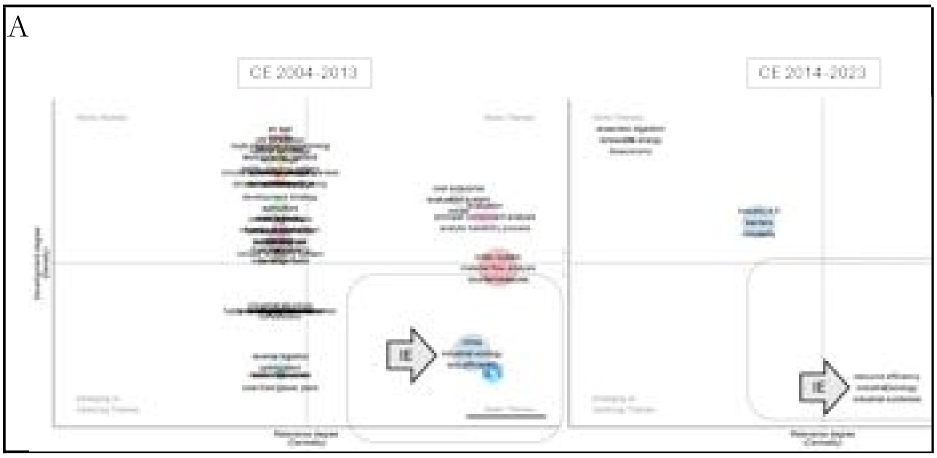
A cross-sectional comparison of the two fields in the subsequent decades (Figures 12 A and 13 A) reveals that the concept of CE was a "niche" topic for IE in 2004-2013, which then became "basic" in the next decade. The concept of IE in CE was considered "basic" in the first decade and then appears to have regressed into a state of decline. In addition to the thematic analysis, the associated network analysis (Figures 12 B and 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 12 : Thematic map – IE (2004-2023)

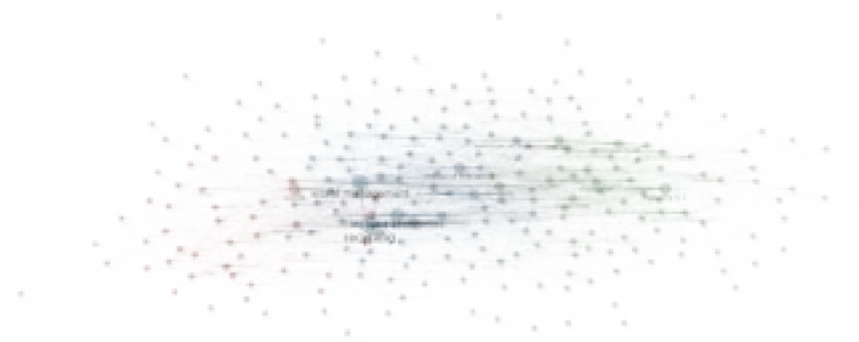


Source: Biblioshiny

Figure 13 : Thematic map – CE (2004-2023)



B



Source: Biblioshiny

Content Analysis

The results of the bibliometric analysis have led to a further step of the literature reviews in order to investigate the presence of any other relevant aspects. Table 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 the CE (see figure 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: 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

Discussion and conclusions

The outcomes of the comparative bibliometric analysis performed 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 the 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 at least three aspects: subjectivity in the selection of data and algorithms, parameters used, and 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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Analysis of European Union Countries in Terms of Circularity: Multi-Criteria Decision-Making Approach

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Abstract : The study highlights the importance of circular economy practices in sustainable development, focusing on waste reduction, resource optimization, and recycling. These practices are essential for achieving European Green Deal goals like carbon neutrality and decoupling economic growth from resource use. By ranking 27 EU member countries based on circular economy practices, the research analyzes their impact on social and economic indicators such as welfare, education, employment, and health. Using the Entropy-based WASPAS method and Spearman Rank Correlation analysis, the study identifies a strong link between circular economy performance and economic/social development. The findings underscore the need for EU countries to integrate social and economic dimensions into circular economy strategies. This provides policymakers with actionable insights to reduce disparities and enhance sustainable development policies.

Introduction

The 1972 UN Conference on the Human Environment stands as a landmark international convention for environmental protection. This conference highlighted the importance of a shared vision and unified principles to inspire and guide global efforts in preserving and improving the human environment. The Stockholm Declaration, a key outcome of the conference, outlines 26 principles that have since formed the foundation of international environmental law. Notably, the declaration emphasizes the importance of protecting both species and their habitats, particularly in Principle 2, which states: “the natural resources of the earth, including the air, water, land, flora and fauna and especially representative samples of natural ecosystems, must be safeguarded for the benefit of present and future generations through careful planning or management, as appropriate” (Nabiebu and Ijiomah, 2023). After several decades, the topic of circularity has been brought into discussion today with a similar approach.

As the EU determines a target of zero carbon emissions by the year 2050, at the same time the European Commission has declared a new concept as the circular economy. The circular economy paradigm promotes material efficiency by encouraging the rational and sustainable use of resources throughout all stages of the production cycle, while also minimizing waste generation. Its overarching objective is to move beyond the traditional take-make-dispose model, where materials are extracted, converted into products, and ultimately discarded as waste at the end of their lifecycle (Murray et al., 2017). Achieving this requires a transition to a restorative and regenerative economy, enabling the recycling and recovery of numerous materials rather than relying solely on primary extraction for their production.

With a focus on absolute resource input reduction and balancing sustainability dimensions, the circular economy (CE) strives to maintain products, components, and materials at their highest utility and value. This is achieved by extending product lifetimes through reuse, refurbishment, and remanufacturing, as well as closing resource cycles through recycling and related strategies (Bocken et al., 2017).

Adopting the circular economy approach could foster innovative solutions to the environmental challenges of industrial production, promoting a waste-free value system such as; eco-design of products (focusing on extending product durability by creating modular and decomposable components, facilitating effective downstream waste management), substitution of materials (replacing virgin raw materials with secondary raw materials and biomaterials to reduce environmental impact) and end-of-life product management (implementing control and management systems for the return flows of end-of-life products, ensuring a sustainable supply chain) (Agyemang et al., 2019).

A circular economy embodies a restorative and regenerative business model, aiming to keep products, components, and materials at their highest utility and value (Stahel, 2016). Despite its growing adoption in organizational and governmental policies, the circular economy remains an essentially contested concept, complicating its application as a managerial decision-making tool. Circularity assessment has yet to be systematically utilized as a decision-making framework, especially within the context of supply chain management (Korhonen et al., 2018).

Although the concept of the circular economy is being extensively explored across various contexts, there remains a lack of clearly defined tools, criteria, and analytical methods to evaluate the diverse aspects of circular systems and their degree of circularity. In this regard, the application of multi-criteria decision-making methods for assessing sustainability challenges has grown significantly, proving effective in addressing a wide range of environmental and management issues. Such assessments involve complex, multidimensional problems that require the integration of multiple indicators to develop composite indices (Wu and Wu, 2012).

Integrating decision-making into the circular economy (Balasbaneh and Sher, 2024) introduces unpredictability in certain criteria, such as market dynamics, variability in material flows, and diverse stakeholder preferences. Multi-criteria decision-making processes address these complexities by simultaneously considering multiple, often conflicting, criteria. Advanced multi-criteria decision-making methodologies employ tools such as interval numbers, fuzzy numbers, neutrosophic sets, or probabilistic linguistic set models, tailored at various scales, to manage imprecision and uncertainty. These tools enable the development of a robust decision-making framework for effective implementation of the circular economy.

In this context, the study is structured as follows: The first section, following the introduction, explores the concept of cyclicality, highlighting its positive and negative aspects. In the second section, information is provided about the studies conducted in this field according to the results of the literature research. The third section provides theoretical insights into the multi-criteria decision-making techniques utilized in the study. The fourth section presents the ranking of 27 European Union member countries based on selected cyclicality criteria, using entropy-based WASPAS techniques, and examines the correlation between the resulting rank values. Finally, the conclusion and evaluation section discuss the findings derived from the analysis.

Concept of Circularity

Since the Industrial Revolution, resource consumption has increased rapidly, creating significant challenges. This excessive resource use has not only posed a severe threat to nature but has also pushed vital natural resources -rightfully belonging to future generations- toward depletion. This issue extends beyond environmental concerns, as it also underpins economic imbalances and has profound social implications.

Sustainable development requires balancing three key dimensions: environmental, economic, and social. In contrast, circularity primarily focuses on two aspects of sustainable development -economic growth and environmental sustainability- guided by the principle that "everything is an input to another". The circular economy emphasizes extending the value of products and materials while minimizing waste generation and the use of virgin resources. Although distinct, sustainable development and circularity are closely aligned and play a critical role in shaping the future of our socio-economic systems (Nguyen et al., 2024).

The concept of the circular economy has garnered significant attention from scholars and practitioners. Circular economy is an economic system designed to minimize resource consumption and waste generation by maintaining materials within the production cycle for as long as possible. Adopting circular economy offers substantial benefits, including reducing waste volumes, lowering raw material inputs, and supporting sustainable economic growth (Kirchherr, 2017).

The primary goal of circular economy is to preserve the value of products, components, materials, and resources within the economy by implementing various circularity strategies. These strategies, which extend product lifespans and close resource loops, include reuse, repair, refurbishment, reconditioning, remanufacturing, repurposing, cannibalization, and recycling. The choice of circularity strategy depends on factors such as product characteristics, legislation, technology, and market dynamics (Bocken et al., 2017; Bakker et al., 2014).

Successful implementation of these strategies in businesses requires leveraging multiple circular economy building blocks, including product and service design, innovative business models, reverse supply chains, patterns of product and service use, end-of-life recovery systems, and supportive policies. Among these, reverse logistics plays a critical role in enabling strategies such as reuse, refurbishment, and remanufacturing, serving as a foundational component of circular economy and a key driver of sustainable production and consumption (Alamerew and Brissaud, 2020; Julianelli et al., 2020).

By promoting a shift in production and consumption behaviors, the implementation of circular economy principles and strategies can contribute to achieving several United Nations Sustainable Development Goals, thereby supporting a more sustainable global future (Korhonen et al., 2018; Brissaud and Zwolinski, 2017).

Circularity offers an alternative to the traditional linear model by enabling resources to be reused repeatedly, often for the same or similar purposes. A circular economy is guided by three core principles (McKinsey & Company, 2025);

a. Preserve and enhance natural capital: Safeguard the planet's finite resources while balancing the flow of renewable resources to sustain the world's stock of natural assets.

b. Optimize resource yields: Maximize the utility of products, components, and materials by keeping them in circulation at their highest value for as long as possible.

c. Increase system efficiency: Minimize unintended negative impacts, such as air and water pollution, to create a more effective and sustainable system.

Literature Review

In recent years, the use of multi-criteria decision-making techniques has significantly increased in studies aimed at determining circular economy and circularity efficiency. The ability of these techniques to consider numerous criteria of varying scales and weights has contributed to their widespread adoption. So the literature contains a wealth of studies on circularity, with some focusing on circular efficiency at sectoral, regional or global scales. Notable examples include studies that utilize multi-criteria decision-making techniques, such as the following:

Torkayesh et al. (2023) reviewed studies conducted on circularity and sustainability using the MABAC method, one of the multi-criteria decision-making techniques. A total of 117 studies were analyzed in their review. Of these, 19 were conducted under certainty conditions, while 98 were carried out in uncertainty environments using fuzzy methods. Additionally, 100 of these studies employed MABAC in combination with another multi-criteria decision-making technique as a hybrid approach.

In their systematic literature review, Lombardi and Todella (2023) examined studies conducted on product life cycles using multi-criteria decision-making techniques. These studies, carried out with 19 different techniques, highlighted the significance of agricultural waste and water among the criteria used.

Biswar et al. (2024) evaluated the variables of sustainability, resource management, product lifespan, collaboration and partnerships, and technology and innovation, which were obtained through expert opinions. In their study using DEMATEL, one of the multi-criteria decision-making techniques, they examined the impact of the identified criteria on circularity.

Kabirifar et al (2023), tried to determine the construction sector's circular economy efficiency at Tehran, by using a hybrid approach combining the fuzzy AHP and enhanced fuzzy Delphi methods. They used six factors and 19 associated sub-dimensions in their study.

In their study discussing the circular economy strategies of two companies in Sweden, Alamerev et al (2020) utilized the SMART method, one of the multi-criteria decision-making techniques. For the evaluation conducted based on the two companies, they employed variables such as environmental, economic, social, legislative, technical, and business factors.

Multi-Criteria Decision-Making Techniques

Multi-Criteria Decision-Making techniques are highly effective for addressing various decision-making challenges. These methods can be applied across diverse fields, including engineering, production, supply chain management, healthcare, logistics, and more. Many experts recognize these techniques as a powerful tool for analyzing complex problems involving multiple criteria. Multi-Criteria Decision-Making techniques focus on selecting the optimal option from a range of alternatives based on a defined set of attributes or criteria (Berberoğlu et al., 2023).

These techniques can produce results by considering numerous variables defined on different scales and assigned different weight values. For this reason, they have been frequently used in almost every field of literature in recent years. In this study, two of these techniques were utilized. The first is the Entropy method, used to determine the weight values of the criteria, and the second is the WASPAS method, applied to rank the 27 EU member countries in terms of circularity. Additionally, the study examined the correlation between the ranking values of countries concerning their circular efficiency. For this purpose, Spearman's rank correlations were calculated.

Entropy, originally introduced by Rudolph Clausius (1865) as part of the second law of thermodynamics, is fundamentally a measure of uncertainty and disorder within a system. It represents the degree of chaos or randomness present. The concept of entropy suggests that all systems, if left to natural conditions, will inevitably move toward increased disorganization, disorder, and deterioration over time. The concept of entropy, which has become prominent across nearly all branches of science and is widely applied in fields such as physics, mathematics, and engineering, was defined by Claude E. Shannon (1948) as a measure of uncertainty in information. Shannon adapted the concept to the framework of "information theory" (Manavgat and Demirci, 2022).

WASPAS (Weighted Aggregated Sum Product Assessment), proposed by Zavadskas et al. (2012), represents a multi-criteria decision-making methodology aimed at ranking alternatives based on their performance values and associated criterion weights. This technique is particularly noteworthy for its ability to provide a compromise solution by integrating the advantages of both the weighted sum and weighted product methods, thereby enhancing its applicability and robustness in decision-making processes (Demirci, 2021).

Spearman's rank correlation is a statistical measure used to assess the strength and direction of the association between two ranked variables. It evaluates the degree of monotonicity in the relationship between the variables, indicating how effectively the association can be described by a monotonic function. The framework of the study and the implementation phases of the techniques used in the study are outlined in Table 1.

Table 1: The implementation steps of the techniques

<table>
<tr><th>Phase 1
(Entropy Technique)</th><th>Phase 2
(WASPAS Technique)</th><th>Phase 3
(Spearman's Rank Correlation)</th></tr>
<tr><td colspan="2">Decision Matrix
$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$</td><td rowspan="6">$\rho = 1 - \frac{6\Sigma d_i^2}{n(n^2-1)}$
Here;
ϱ; refers to Spearman Rank Correlation Coefficient,
di; refers to the difference between the two ranks of each observation,
n; refers to the number of observations.</td></tr>
<tr><td>Normalization of Decision Matrix
$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}$</td><td>Normalization of Decision Matrix
Benefit Oriented Cost Oriented
$\bar{x}_{ij} = \frac{x_{ij}}{\max_i x_{ij}}$ $\bar{x}_{ij} = \frac{\min_i x_{ij}}{x_{ij}}$</td></tr>
<tr><td>Calculating the Entropy Value
$e_j = -k \sum_{i=1}^{m} r_{ij} \ln r_{ij}$
Here; $k = \frac{1}{\ln m}$</td><td>Weighted Sum Technique
$Q_i^{(1)} = \sum_{j=1}^{n} \bar{x}_{ij} * w_j$</td></tr>
<tr><td>Calculating the Differentiation Degree Value
$d_j = 1 - e_j$</td><td>Weighted Product Technique
Benefit Oriented Cost Oriented
$Q_i^{(2)} = \prod_{j=1}^{n} \bar{x}_{ij}^{w_j}$ $Q_i^{(2)} = \prod_{j=1}^{n} \bar{x}_{ij}^{-w_j}$</td></tr>
<tr><td>Calculating the Weights of Criteria
$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}$</td><td>Compromised Solution
$Q_i = \lambda * Q_i^{(1)} + (1-\lambda) * Q_i^{(2)}$
Here the λ value can be determined freely.</td></tr>
</table>

Data Set and Analysis

While sustainable development necessitates balancing three dimensions -environmental, economic, and social- circularity is more closely associated with the economic and environmental aspects. In this context, the two concepts, often regarded as inseparable and complementary in the literature, were not treated separately in this study. A more comprehensive approach was achieved by broadening the study to incorporate the social dimension, while considering its economic and environmental implications.

The selection of variables to be used in the study is of utmost importance. In this study, which aims to determine the circularity performance of countries, this aspect has been considered, and particular attention has been paid to ensuring that the selected variables can represent the dimensions of sustainability. As in the study, separate rankings were conducted based on the three dimensions of sustainability to determine the circularity performance of 27 European Union member countries, the latest data obtained from the official website of the World Bank and EuroStat were used, including 5 variables for the economic dimension, 5 variables for the social dimension, and 10 variables for the environmental dimension. These variables are defined as follows:

Eco.1. GNI per Capita, PPP: This indicator represents gross national income (GNI) per capita in current international dollars, adjusted using the purchasing power parity (PPP) conversion factor. GNI encompasses the total value added by all resident producers, along with any product taxes (excluding subsidies) not factored into output valuation, and the net income received from abroad, including compensation for employees and property income. The PPP conversion factor acts as a currency converter and spatial price deflator, removing the impact of price level differences across countries.

Eco.2. Inflation (Consumer Prices): Inflation, measured by the consumer price index, represents the annual percentage change in the cost incurred by an average consumer to purchase a basket of goods and services. This basket may remain constant or be adjusted at specified intervals, such as annually. Typically, the calculation is based on the Laspeyres formula.

Eco.3. Logistics Performance İndex: The overall score of the Logistics Performance Index reflects evaluations of a country's logistics performance, considering factors such as the efficiency of customs clearance, the quality of trade and transport infrastructure, the ease of organizing cost-effective shipments, the standard of logistics services, the ability to track and trace shipments, and the consistency of on-time delivery to consignees. Scores range from 1 to 5, with higher values indicating superior performance. The data are sourced from the Logistics Performance Index survey, conducted by the World Bank in collaboration with academic and international organizations, private companies, and professionals involved in global logistics.

Eco.4. Ease of Doing Business: The ease of doing business scores benchmark economies with respect to regulatory best practice, showing proximity to the best regulatory performance on each Doing Business indicator. An economy's score is indicated on a scale from 0 to 100, where 0 represents the worst regulatory performance and 100 the best regulatory performance.

Eco.5. Central Government Debt: Debt refers to the total amount of direct fixed-term financial obligations owed by the government to external parties as of a specific date. It encompasses both domestic and foreign liabilities, including currency and money deposits, securities (excluding shares), and loans. This represents the gross value of government liabilities, offset by any equity and financial derivatives held by the government. As debt is a stock variable rather than a flow, it is recorded on a specific date, typically the last day of the fiscal year.

Soc.1. GINI Index: The Gini index quantifies the degree of inequality in income (or occasionally consumption expenditure) distribution among individuals or households within an economy. It is derived from the Lorenz curve, which illustrates the cumulative share of total income earned by the cumulative percentage of the population, starting from the poorest. The Gini index calculates the area between the Lorenz curve and the line representing perfect equality, expressed as a percentage of the total area beneath the line. A Gini index of 0 indicates complete equality, whereas a value of 100 signifies absolute inequality.

Soc.2. Unemployment (Totaly): Unemployment represents the proportion of the labor force that is not currently employed but is actively seeking and available for work.

Soc.3. Life Expectancy at Birth: Life expectancy at birth reflects the average number of years a newborn is expected to live, if the current mortality rates at the time of birth remain constant throughout their lifetime.

Soc.4. Labor Force Participation Rate, Female: The labor force participation rate represents the percentage of the population aged 15 and above that is economically active, including all individuals providing labor to produce goods and services within a given time frame.

Soc.5. School enrollment tertiary: The gross enrollment ratio is the proportion of total enrollments, irrespective of age, compared to the population within the age group that officially corresponds to the specified level of education. Tertiary education, which may or may not include advanced research qualifications, typically requires the successful completion of secondary-level education as a minimum admission criterion.

Env.1. Waste treatment: Waste management by operation type and material includes processes such as disposal, incineration, recovery, backfilling, and recycling, measured in thousand tons per 1,000 people.

Env.2. Circular material use rate (%): Represents the percentage of materials reintroduced into the economy through recycling and other recovery processes, relative to the total material use in the economy. It reflects the extent to which secondary materials (recycled from waste) replace the need for primary raw materials.

Env.3. Material flows for circular economy (Import): Material flows for circular economy - Imports of waste for recovery - recycling Thousand tons (per 1000 capita).

Env.4. Material flows for circular economy (Export): Material flows for circular economy - Exports of waste for recovery – recycling thousand tons (per 1000 capita).

Env.5. Total environmental taxes in total tax revenue: Refers to the proportion of a country's total tax revenue generated from taxes aimed at addressing environmental issues. This metric highlights the extent to which environmental taxes contribute to a government's overall tax income.

Env.6. Persons employed in circular economy sectors in total employee: Refers to the share of workers employed in industries or activities directly contributing to the circular economy, relative to the total number of employed individuals in a country or region.

Env.7. Private investment related to circular economy sectors: Private investment related to circular economy sectors - Percentage of gross domestic product (GDP).

Env.8. Gross value added related to circular economy sectors: Gross value added related to circular economy sectors- Percentage of gross domestic product (GDP).

Env.9. Waste generation per capita kilogram: Refers to the average amount of waste produced by an individual within a specific population, expressed in kilograms over a defined period (typically a year). It is an indicator used to assess the efficiency of resource usage and waste management practices in a country or region.

Env.10. Greenhouse gases emissions from production activities: Greenhouse gases emissions from production activities- Total Kg per capita Greenhouse gases (CO_2, N_2O in CO_2 equivalent, CH_4 in CO_2 equivalent, HFC in CO_2 equivalent, PFC in CO_2 equivalent, SF_6 in CO_2 equivalent, NF_3 in CO_2 equivalent).

At the conclusion of the variable selection and data collection phase, the data and descriptive statistics for the economic dimension of sustainability, aimed at determining the circularity performance of 27 European Union member states, are presented in Table 2. The data and descriptive statistics for the social dimension are presented in Table 3, and the data and descriptive statistics for the environmental dimension are presented in Table 4. Here, data marked with a "+" are considered benefit-oriented, while data marked with a "-" are considered cost-oriented. In other words, benefit-oriented variables are positive variables, and higher values are desirable. In contrast, cost-oriented variables are negative variables, and lower values are expected.

Table 2: Data Set for the Economic Dimension of Sustainability

	Eco.1.	Eco.2.	Eco.3.	Eco.4.	Eco.5.
	+	-	+	+	-
Austria	73520	7.81	4.00	78.75	74.92
Belgium	71990	4.05	4.00	74.99	92.48
Bulgaria	37380	9.44	3.20	71.97	30.20
Cyprus	51330	3.54	3.20	73.35	91.67
Czechia	51370	10.66	3.30	76.34	14.00
Germany	72110	5.95	4.10	79.71	20.85
Denmark	79390	3.31	4.10	85.29	75.33
Spain	52420	3.53	3.90	77.94	109.22
Estonia	47350	9.16	3.60	80.62	24.90
Finland	64940	6.25	4.20	80.18	58.31
France	62130	4.88	3.90	76.81	98.05
Greece	40880	3.46	3.70	68.42	202.08
Croatia	45950	7.94	3.30	73.62	83.00
Hungary	44650	17.12	3.20	72.42	75.53
Ireland	98650	6.30	3.60	79.58	45.40
Italy	58650	5.62	3.70	72.85	77.28
Lithuania	50100	9.12	3.40	81.62	36.04
Luxembourg	98490	3.74	3.60	69.60	2.90
Latvia	41420	8.94	3.50	80.28	10.59
Malta	56880	5.09	3.30	66.14	69.81
Netherland	77750	3.84	4.10	76.10	54.21
Poland	47380	11.53	3.60	76.38	60.45
Portugal	47850	4.31	3.40	76.47	5.66
Romania	46620	10.40	3.20	73.33	50.89
Slovak Republic	43500	10.53	3.30	75.59	64.32
Slovenia	54130	7.45	3.30	76.52	16.24
Sweden	72990	8.55	4.00	81.99	36.91
Min. Value	**37380**	**3.31**	**3.20**	**66.14**	**2.90**
Max. Value	**98650**	**17.12**	**4.20**	**85.29**	**202.10**
Mean Value	**58882**	**7.13**	**3.62**	**76.22**	**58.56**
Std. Deviation	**16674**	**3.29**	**0.34**	**4.39**	**41.82**

<u>Table 3</u>: Data Set for the Social Dimension of Sustainability

	Soc.1.	Soc.2.	Soc.3.	Soc.4.	Soc.5.
	-	-	+	+	+
Austria	30.70	5.24	81.09	56.75	93.94
Belgium	26.60	5.51	81.70	50.55	82.69
Bulgaria	39.00	4.30	74.36	50.11	74.03
Cyprus	31.30	5.96	81.89	60.26	96.54
Czechia	26.20	2.59	79.03	51.92	69.11
Germany	31.70	3.05	80.71	56.45	75.67
Denmark	28.30	5.14	81.30	59.52	84.59
Spain	33.90	12.14	83.08	52.63	94.59
Estonia	31.80	6.35	77.94	61.14	71.43
Finland	27.70	7.16	81.19	57.72	104.94
France	31.50	7.32	82.23	52.78	70.79
Greece	32.90	11.00	80.64	45.19	150.20
Croatia	28.90	6.06	77.58	47.93	72.33
Hungary	29.20	4.13	76.02	53.98	56.52
Ireland	30.10	4.34	83.06	59.87	78.78
Italy	34.80	7.62	82.90	41.27	71.29
Lithuania	36.70	6.96	75.79	57.08	71.91
Luxembourg	32.70	5.19	83.05	57.82	20.73
Latvia	34.30	6.53	74.58	55.68	91.33
Malta	31.40	3.13	82.70	56.94	78.62
Netherland	25.70	3.56	81.71	61.72	88.95
Poland	28.50	2.91	77.30	51.58	73.98
Portugal	34.60	6.49	81.58	55.29	71.87
Romania	33.90	5.60	75.30	42.37	55.27
Slovak Republic	24.10	5.84	77.07	56.29	52.50
Slovenia	24.30	3.63	81.28	53.85	82.39
Sweden	29.80	7.59	83.11	63.38	83.90
Min. Value	**24.10**	**2.59**	**74.36**	**41.27**	**20.73**
Max. Value	**39.00**	**12.14**	**83.11**	**63.38**	**150.20**
Mean Value	**30.76**	**5.75**	**79.93**	**54.45**	**78.48**
Std. Deviation	**3.70**	**2.26**	**2.91**	**5.61**	**21.92**

Table 4: Data Set for the Environmental Dimension of Sustainability

	Env.1.	Env.2.	Env.3.	Env.4	Env.5.	Env.6.	Env.7.	Env.8.	Env.9.	Env.10.
	+	+	-	+	+	+	+	+	-	-
Austria	2.70	22.20	1.04	45.07	0.05	0.02	1.40	1.70	5899	6824.27
Belgium	14.36	4.80	0.14	71.81	0.15	0.03	0.60	1.50	16785	8238.92
Bulgaria	3.51	11.90	0.22	56.61	0.04	0.03	0.40	1.40	3598	8901.41
Cyprus	3.04	7.40	0.68	20.55	0.06	0.01	0.90	1.80	3453	12372.72
Czechia	4.03	13.00	0.25	14.01	0.04	0.03	0.90	2.20	4824	7391.81
Germany	14.71	16.00	0.18	54.05	0.07	0.04	0.70	1.90	12163	10226.90
Denmark	2.64	1.80	0.58	15.37	0.04	0.02	0.60	2.90	3248	11950.64
Spain	2.95	3.10	0.21	17.23	0.13	0.03	0.10	0.50	2651	7479.63
Estonia	1.53	7.10	0.25	8.98	0.04	0.05	0.50	1.90	2230	4927.18
Finland	3.69	19.30	0.15	11.35	0.04	0.03	0.80	1.60	4593	4853.92
France	1.09	5.80	0.46	45.97	0.09	0.05	0.70	2.20	1483	4606.96
Greece	2.29	18.70	0.19	5.50	0.05	0.06	0.70	2.50	2942	5425.47
Croatia	1.56	3.20	0.27	19.31	0.06	0.04	0.20	1.60	2491	7642.79
Hungary	0.76	5.40	0.59	95.66	0.07	0.04	0.70	1.50	1501	4943.36
Ireland	1.36	4.10	0.46	73.74	0.05	0.04	0.80	1.80	2396	6965.99
Italy	12.50	5.20	4.91	10.17	0.03	0.01	1.00	1.10	14618	12090.52
Lithuania	1.91	7.90	0.22	48.88	0.05	0.06	0.70	1.70	1759	5101.32
Luxembourg	6.10	15.10	0.03	17.46	0.06	0.03	1.10	2.90	6847	3705.70
Latvia	3.88	27.50	1.02	51.22	0.06	0.02	1.00	1.00	7175	8227.72
Malta	4.62	13.80	0.54	20.01	0.04	0.02	1.40	2.00	7728	6063.70
Netherland	3.89	8.40	0.18	27.70	0.08	0.06	0.70	1.80	4492	9587.31
Poland	0.94	2.60	0.22	16.50	0.05	0.03	0.80	1.50	1612	4882.37
Portugal	7.59	1.40	0.09	35.77	0.10	0.02	0.50	1.00	7338	4775.14
Romania	3.83	9.40	1.21	92.83	0.08	0.03	0.20	1.50	3576	5857.97
Slovak Republic	1.69	9.10	0.23	55.58	0.07	0.03	0.50	1.20	2340	5658.96
Slovenia	21.34	0.60	0.16	10.44	0.06	0.03	0.30	1.40	20993	7738.45
Sweden	13.50	6.10	0.19	13.80	0.05	0.02	0.40	1.40	14664	3979.03
Min. Value	**0.76**	**0.60**	**0.03**	**5.50**	**0.03**	**0.01**	**0.10**	**0.50**	**1483**	**3705.70**
Max. Value	**21.34**	**27.50**	**4.91**	**95.70**	**0.15**	**0.06**	**1.40**	**2.90**	**20993**	**12372.72**
Mean Value	**5.26**	**9.29**	**0.54**	**35.40**	**0.06**	**0.03**	**0.69**	**1.69**	**6052**	**7052.60**
Std. Deviation	**5.28**	**6.89**	**0.92**	**26.40**	**0.03**	**0.01**	**0.33**	**0.54**	**5255**	**2501.44**

After the variable selection and data collection phase of the study, the weight values of the criteria were determined using the Entropy method, one of the multi-criteria decision-making techniques. The criterion weight values calculated by using the application steps of the Entropy technique, presented in Table 1, are provided in Table 5.

Table 5: Criteria Weight Values

Economic Criteria	Eco.1.	Eco.2.	Eco.3.	Eco.4.	Eco.5.
Weight Value	0.0962	0.2564	0.0110	0.0042	0.6321

Social Criteria	Soc.1.	Soc.2.	Soc.3.	Soc.4.	Soc.5.
Weight Value	0.0575	0.5749	0.0053	0.0434	0.3189

Environmental Criteria	Env.1.	Env.2.	Env.3.	Env.4.	Env.5.	Env.6.	Env.7.	Env.8.	Env.9.	Env.10.
Weight Value	0.1713	0.1120	0.2974	0.1119	0.0356	0.0407	0.0503	0.0223	0.1333	0.0253

After determining the weight values of the variables in the study, the ranking of 27 European Union member countries in terms of circularity performance was separately determined for the economic, social, and environmental dimensions of sustainability using the WASPAS technique, one of the multi-criteria decision-making methods. The application steps of the WASPAS technique were carried out as specified in Table 1. The results are presented in Table 6. While applying the WASPAS technique, different λ values (0.00, 0.25, 0.50, 0.75, and 1.00) were used, and the total rank values of the countries were calculated by the geometric mean of these results.

Table 6: Rank Values of EU Countries by Means of Circularity Performance

	Economic Rank Value	Social Rank Value	Environmental Rank Value	Overall Rank Value
Austria	11	24	15	**19**
Belgium	5	21	26	**16**
Bulgaria	19	13	24	**23**
Cyprus	3	27	8	**9**
Czechia	24	2	20	**11**
Germany	27	4	27	**17**
Denmark	6	22	3	**8**
Spain	2	7	9	**3**
Estonia	23	20	7	**18**
Finland	14	26	23	**25**
France	4	14	6	**7**
Greece	1	12	12	**4**
Croatia	8	17	5	**10**
Hungary	10	6	4	**6**
Ireland	22	19	11	**20**
Italy	7	11	1	**1**
Lithuania	21	18	19	**24**
Luxembourg	16	1	13	**5**
Latvia	20	25	18	**26**
Malta	9	9	22	**14**
Netherland	13	15	25	**21**
Poland	15	3	2	**2**
Portugal	18	16	17	**22**
Romania	17	5	14	**12**

Slovak Republic	12	8	16	**13**
Slovenia	26	10	10	**15**
Sweden	25	23	21	**27**

In the final stage of the study, the correlation between the economic, social, and environmental performance rank values obtained by the countries in the previous analyses was examined. The procedure presented in Table 1 was followed for this analysis, which was conducted using Spearman's Rank Correlation analysis (Daniel, 1990; Oktay, 2008). For this purpose, three hypotheses were determined such as,

H_{01}: The economic and social rank values of EU countries are independent of each other.

H_{02}: The economic and environmental rank values of EU countries are independent of each other.

H_{03}: The social and environmental rank values of EU countries are independent of each other.

The results of the Spearman's Rank Correlation analysis between the performance rank values of the European Union countries are presented in Table 7. For this analysis, the test value of Spearman's Rank Correlation, which will be used for the evaluation of hypotheses by comparing it with the Spearman's Rank Correlation values, was calculated as 0.324 at the 5% significance level.

Table 7: Hypotheses Test Results of Spearman's Rank Correlation Analysis

	Spearman's Rank Correlation Value	Decision
Economic & Social	-0,177	Rejected
Economic & Environmental	0,377	Objected
Social & Environmental	0,092	Rejected

As a result of the Spearman's Rank Correlation test conducted to determine the relationship between the performance rank values obtained by the 27 European Union countries in terms of circularity, it was found that there is a significant relationship between the social dimension and both the economic dimension (-0.177<0,324) and the environmental dimension (0.092<0,324). However, the relationship between the economic dimension and the environmental dimension (0.377>0,324) was found to be not significant. This finding suggests that while social factors are closely intertwined with both economic and environmental aspects, the economic and environmental dimensions may operate more independently in this context.

Conclusion

The study aimed to rank EU countries based on their circularity efficiencies. To achieve this, data considered influential on the circularity performance of EU countries, the latest data obtained from the official website of the World Bank and EuroStat database. Recognizing the strong connection between circularity and sustainability, the research was designed to encompass the three dimensions of sustainability.

The most significant weakness of multi-criteria decision-making techniques is the selection of criteria to be used in the study. At this point, identifying data that is appropriate for the subject of analysis is of critical importance. In other words, variables should be chosen in a way that accurately represents the topic of analysis. This is because the study will be conducted solely based on the variables used in the analysis. In this context, variables representing the three dimensions of sustainability -economic, social, and environmental- were carefully selected and employed in the study.

The countries were ranked according to their performance in the economic, social, and environmental dimensions. The criteria for each dimension were weighted using the Entropy method, and these weights were applied in the WASPAS technique to establish the rankings. The significance of the rank values was assessed using the Spearman Rank Correlation coefficient. The analysis revealed that the economic, social, and environmental efficiencies of EU countries were interrelated.

Notably, criteria with higher weights significantly influenced the efficiency rankings of the countries. Based on these findings, it is suggested that other countries could improve their performance by focusing on these key criteria.

Accordingly, among the criteria used for the economic efficiency ranking of European Union member states, the criterion with the highest weight value is "Central Government Debt", with a weight of 0.6321. It can be considered a reasonable approach to suggest that reducing this cost-oriented criterion would lead to economic improvement for other countries as well. Similarly, the second most important criterion for economic efficiency is "Inflation (Consumer Prices)", with a weight of 0.2564. To climb higher in the efficiency rankings, it is expected that this cost-oriented criterion will also need to be reduced. When examining the data for these criteria, it is observed that both the range of variation and the standard deviation values are quite high, indicating significant differences between countries. The leading positions in economic rankings held by Greece, Spain, and Cyprus can be attributed to their relatively low "Inflation (Consumer Prices)" values despite having high "Central Government Debt". Conversely, for countries at the bottom of the list, such as Germany, Slovenia, and Sweden, the opposite situation applies. It is assessed that these countries should prioritize combating inflation as part of their efforts to achieve economic improvement.

As a result of the analysis conducted for the social efficiency ranking, the criteria with the highest weight values were identified as "Unemployment (Total)" with a weight of 0.5749 and "School Enrollment Tertiary" with a weight of 0.3189. Among the top-ranking countries in this area -Luxembourg, Czechia, and Poland- it is observed that they perform above the average for the benefit-oriented criterion "School Enrollment Tertiary" while remaining below the average for the cost-oriented criterion "Unemployment (Total)". On the other hand, countries at the lower end of the list, such as Cyprus, Finland, and Latvia, rank significantly lower, particularly with respect to the "Unemployment (Total)" criterion.

As a result of the analysis conducted for the environmental efficiency ranking, the criteria with the highest weight values were identified as "Material Flows for Circular Economy (Imports)" with a weight of 0.2974 and "Waste Treatment" with a weight of 0.1713. In the environmental efficiency rankings, Italy, Poland, and Denmark occupy the top positions, while Germany, Belgium, and the Netherlands are ranked at the bottom. It would be appropriate for countries to prioritize these high-weight criteria, particularly to achieve improvements in environmental efficiency.

According to the overall rank values determined by the geometric mean, the country's leading in circularity (actually sustainability) are Italy, Poland, and Spain. Conversely, countries ranked at the bottom, such as Sweden, Latvia, and Finland, need to take significant steps based on these criteria to improve their circularity performance.

Another significant finding obtained from the analyses is the relationship between the economic, social, and environmental rank values of the countries. Contrary to expectations, no significant relationship was identified between the economic and environmental rank values, indicating that these two dimensions are independent of each other. However, it was determined that the social dimension is significantly related to both the economic and environmental dimensions, suggesting a meaningful interdependence between them.

The primary limitation of the study is the concern that a few data points may be insufficient for evaluating a country at the macro level. Additionally, it is possible that some key data representing the dimensions of sustainability may have been overlooked. However, it should be noted that increasing the number of variables may result in very small weight values for the criteria (since the total weight must equal 1.00), which could lead to misleading outcomes when using multi-criteria decision-making techniques. Considering this issue in future studies is crucial to ensure the robustness of the results.

Moreover, it should not be overlooked that future research could employ different groups of countries/regions and/or alternative variables, as well as other multi-criteria decision-making techniques.

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European Green Deal and Entrepreneurial Activity

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Abstract : The European Green Deal (EGD) gave a start to the new growth strategy, accelerating the green transition of Europe and changing technological and business processes. This study aimed to reveal the impact of the EGD on the total entrepreneurial activity (TEA) in the EU countries and to define the entrepreneurs' awareness of EGD objectives and regulations. The research methodology of this study includes two steps: the first step is based on the quantitative analysis of secondary data on changes in TEA in the EU countries; for the second step the survey of entrepreneurs' awareness was carried out and subsequent quantitative data analysis was conducted. The main findings of the study are: the average level of TEA among the EU countries has not changed significantly since EGD adoption; the level of entrepreneurs' awareness of main objectives, actions, regulations, and the possible impact of EGD on business is not high five years after EGD announcement, that might slow down the further deep green transformations.

Introduction

The climate changes, the threats of global warming, and pollution of our planet have become the most serious challenges for life on Earth in the last decades. The European Union made possible necessary steps to respond to these challenges and reduce the negative influence of the European economy on the environment. Launching the European Green Deal (EGD) at the end of 2019 gave a start for the implementation of a new comprehensive environmental policy. According to the European Commission (2019), the European Green Deal is "a new growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy", and "also aims to protect, conserve and enhance the EU's natural capital, and protect the health and well-being of citizens from environment-related risks and impacts". This strategy was supported by numerous legislative proposals, budgetary instruments, and planned actions to make it vital and to transform Europe into a climate-neutral and healthy continent for future generations. The following priority objectives were set up for the course progression to make Europe the first climate-neutral continent:

- achieving the 2030 greenhouse gas emission reduction target (by at least 55% compared to 1990 level) and climate neutrality by 2050;
- enhancing adaptive capacity, strengthening resilience, and reducing vulnerability to climate change;
- advancing towards a regenerative growth model, decoupling economic growth from resource use and environmental degradation, and accelerating the transition to a circular economy;
- pursuing a zero-pollution ambition, including for air, water, soil, and protecting the health and well-being of Europeans;
- protecting, preserving, and restoring biodiversity, and enhancing natural capital (notably air, water, soil, forest, freshwater, wetland, and marine ecosystems);
- reducing environmental and climate pressures related to production and consumption (particularly in energy, industrial development, buildings and infrastructure, mobility, and the food system).

First of all, the EGD was announced and accepted as a green growth strategy, however, it includes a set of policy initiatives in all sectors of the EU economy. In 2020-2024 numerous Laws and Directives regarding the steps towards the EGD objectives were adopted.

The European Green Deal's initiatives create a new regulatory framework and certainly impact business operations and economic development, affect entrepreneurship through implementation of new requirements, transforming business processes, and raising new opportunities in new business areas. The achievements of the announced EGD purposes, progress, and resilience in green transformations will build up the European business and customers and consequently depend on whether the European entrepreneurs are aware and ready for Green the Deal transformations. Some strikes, the most remarkable of them were farmers' protests, in the European countries in 2023-2024, were related to the policy changes towards necessary steps for emissions reduction and might be considered as a sign of weak support of some green policy actions. The effects of hundreds of EGD laws implementations will influence entrepreneurial activity and simultaneously depend on their ability to implement changes.

This study aimed to reveal the impact of the EGD announcement on the total entrepreneurial activity level in the EU countries and to define the awareness of entrepreneurs concerned with EGD after 5 years of its launching, including clarification of how the entrepreneurs are familiar with EGD regulations and evaluate their possible effect on their business.

The research topic developments

The development and approval of the EGD were preceded by public discussions and scientific research on the necessity and relevance of this development strategy, possible political measures, proper technological transformations, and business processes. Before the EGD announcement, the scientists (Diemer et al, 2017) pointed out there are enough reasons from ecology, health problems, and social disasters to think and work and build intercultural European and international alliances for sustainable futures, to promote and implement the basic principles of sustainable development.

The achievement of ambition and outstanding objectives of the EGD requires comprehensive transformations of policies, strategies, technologies, processes, business models, and behavior of producers and consumers. These versatile transformations have become the focuses of numerous research. The different strategies and policies were offered by scholars to respond to the contemporary challenges. The actions for green transformations at companies and state levels were studied. The scientists stressed the importance of collective actions initiatives in the energy transition. Diemer et al (2017, 2020), Morales (2020), developed the theoretical and methodological basement for the deep understanding and analysis of the green and circular economies, and their role for sustainability; circular economy was offered as a new paradigm for Europe.

Last years' publications highlighted the new business models related to green transformations, including the circular business models (Diemer, 2023), technological improvements and progress, twin transition considering the coevolution between green and digital transitions (Mazzucato and Perez, 2022; Jindra and Leusin, 2024).

Vasilescu et al. (2022) investigated the challenges for green entrepreneurship in transformation time. Perez (2016, 2019), Mazzucato and Perez (2022) argue that green innovations for renewable energy, resource efficiency, environmentally-friendly materials are essential and in the center of green transformation but alone they are not sufficient for sustainable growth, there great capabilities of information communication technologies to shift the planet towards green growth. Jindra and Leusin (2024) outlines possible pathways for smart specialisation in digital sustainability technologies, including in renewable energies, transportation, and carbon capture storage. Smol et al (2021) studied the drivers and barriers to the circular economy on the base of the Polish case. Riccaboni et al. (2021) published their findings on the research and innovations for the transformation of the "farm to fork" value chain system. These studies confirm the importance and complexity of technological transformation that must be implemented by businesses towards EGD objectives.

The European Environment Agency (2023) develops reports on progress towards the 8th Environment Action Programme (EAP) objectives, including changes of greenhouse gas emissions, raw material consumption (material footprint), air pollution, nitrates in groundwater, biodiversity, energy consumption, and others. The experts of the Institute for European Environment Policy (2024) carry out surveys and publish the European Green Deal Barometers, which provide the general assessment of different aspects of the Green Deal progress. Its latest edition (2024) presented the results of the interview of 312 sustainability experts worldwide on the resilience of EDG. Most experts believe the EGD will be moderately resilient following the 2024 European elections. Almost all experts living outside the EU think that the EGD will have an impact on a global scale, almost 70% of experts evaluated the overall external impact as positive. This study focused on the EDG impact on macro and global levels.

Since the EGD was launched not so far, the number of scientific publications on the European Green Deal's impact on entrepreneurial activity is not huge, however, the collection of academic papers that investigated entrepreneurship under the EGD regulations is in the process of actively replenishing.

Bogoslov et al. (2022) noted that the EGD is "an important step that will improve the environment, but, at the same time, will pervert the competition and the entrepreneurial activities within the EU", which is caused by governmental intervention and regulations. The research results illustrate that the European Green Deal affects entrepreneurial activity through a prioritization of the environmental dimension, despite the free market. Aiming to achieve the stated goals, the EGD provides the context of governmental interventions and regulations, which will distort entrepreneurship and competition through fiscal and monetary policies and other instruments. Also, these authors mentioned some critical points regarding the EGD's impact on entrepreneurship, namely EGD does not provide a clear plan of actions for entrepreneurs, there is a lack in its strategy; the EGD causes the implementation of strong regulations and control procedures; the costs of EGD goals achievement are immense.

Lee & Suh (2021) developed an approach for modeling causality between Environment, Social, and Governance (ESG) conduct and financial performance, which might be used for the influence of EGD policy on the financial aspects of entrepreneurship. Arfaoui at al. (2024) reveals specific innovation strategies which are most impactful for the transition to the circular economy. Smol et al. (2021) highlighted the relationships between failure, bankruptcy, institutional context, and local characteristics on one hand and entrepreneurship on the other. Despite some focus on the regulatory framework impact on entrepreneurship, the EGD regulations were not in the special focus in this study. Agraway (2024) considered different types of barriers for successful entrepreneurs, including financial constraints, regulatory hurdles, high initial costs, however these constraints were not connected to the European Green Deal.

Our study was focused on the possible impact of the EGD on the entrepreneurial activity level, the awareness and expectations of entrepreneurs relating to the EGD transformations.

Methodology

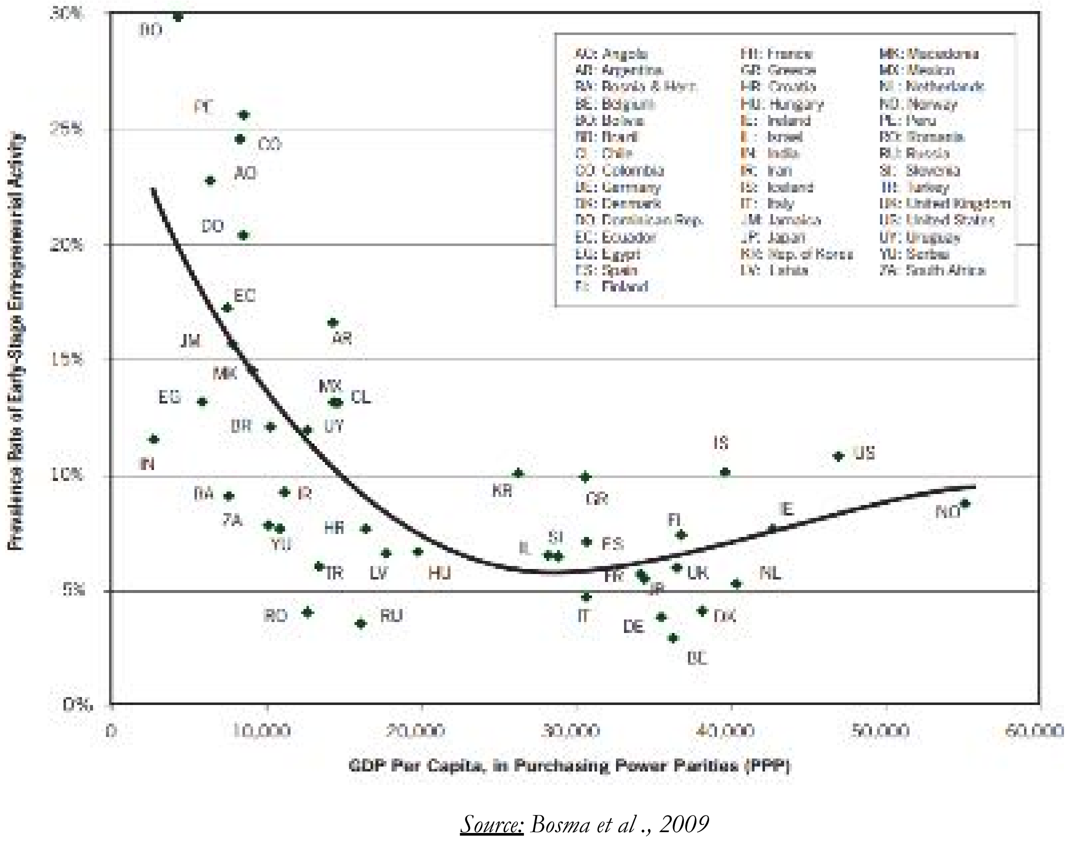
The research methodology of this study includes 2 steps. The first step is based on the analysis of secondary data on changes in the early-stage total entrepreneurial activity (TEA) that were obtained from Global Entrepreneurship Monitor (GEM) surveys. According to the GEM methodology (Global Entrepreneurship Monitor, 2023), the early-stage TEA represents the percentage of the 18-64 population who are either a nascent entrepreneur or owner-manager of a new business. The levels of TEA in the EU countries in the year before the Green Deal announcement (2018) and after, in 2020 and 2022, were analyzed. The Statistical Package for Social Sciences (SPSS) was utilized for data processing to find the differences between total entrepreneurial activity levels in the European Union countries before and after EGD adoption.

The second step includes fieldwork to reveal the entrepreneurs' awareness and attitude to the EGD. To achieve the aim of the study the questionnaire (Appendix 1) was developed and shared among entrepreneurs, mainly from Clermont-Ferrand and the nearest settlements areas; the quantitative method was used, including data processing and descriptive analysis of their answers.

The EGD impact on total entrepreneurial activity: macroeconomic level study

The relationship between entrepreneurial activity and the level of a country's development evaluated by the GDP per capita has been in the focus of the research and a recurring theme in the reports of GEM over time. In 2009 the relationship between the TEA rate and GDP per capita was described by U-shaped curve (Figure 1), indicating that, as a country becomes more prosperous, entrepreneurial activity declines, but after the bottom (at around $30,000 GDP per capita) it increases (Bosma et al, 2009). A possible explanation for this fact is, that as a nation becomes more developed, there are more opportunities for employment, so entrepreneurship, especially its necessity-driven form, declines. After the bottom TEA increases again as there are more opportunities, particularly in service and knowledge-based industries, more resources, including educational and financial, are available, and a wider range of profitable new business opportunities.

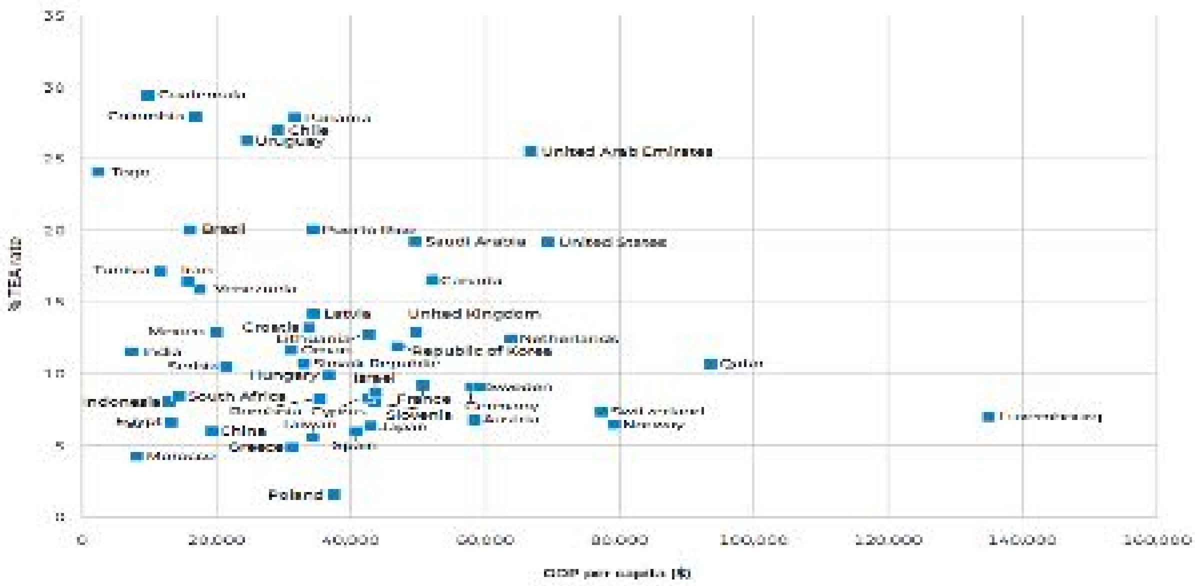
<u>Figure1:</u> The early-stage total entrepreneurial activity rate (TEA) and GDP per capita in 2007



<u>Source:</u> *Bosma et al ., 2009*

However, the surveys in 2020-th do not confirm the mentioned relationships between TEA and income per capita. In 2022, the TEA – GDP per capita correlation coefficient was equaled to −0.235 (Global Entrepreneurship Monitor, 2023, p.52). Figure 2, which shows GDP per capita against TEA for the 49 participating GEM economies in 2022, does not confirm the correspondence of the high level of the country's TEA to the high level of its GDP per capita, or that more developed countries continue to have a high TEA. It might be assumed that new regulations connected to the EGD, among other factors, influenced entrepreneurial activity in the European countries that belong to the group of developed countries with high levels of GDP per capita and disrupted the existing early dependence.

Figure 2: The early-stage total entrepreneurial activity rate (TEA) and GDP per capita in 2022



Source: Global Entrepreneurship Monitor (2023)

The results of the monitoring in 2024 is "there is a negative association between TEA and income, though with considerable variation within income groups" (GEM, 2024). The association of TEA with the alternative indicator Human Development Index (HDI), that includes more components of the development, was also tested. The relationship between HDI and national TEA was also weak and negative.

The analysis of countries' dimensions showed that TEA increased in some European countries after the EGD announcement (France), but in some countries – decreased (Austria, Poland). The percentage of adults (18-64 years old) who believe that in the next six months, there will be good opportunities to start a business in their area decreased in Poland, Greece, Spain, Slovak Republic, and Greece in 2022 in comparison with 2019, and slightly increased in Slovenia (GEM, 2023).

The association between TEA levels in the European Union countries in 2018 and 2020 and 2018 and 2022 were checked using paired samples tested in SPSS. The number of countries included in testing (23 for 2018 versus 2020 and 18 for 2018 versus 2022) is less than the total number of EU members, which is explained by the availability of data on TEA for 2018, 2020, and 2022. The test results are presented in Tables 1-4.

Table 1: Paired Samples Statistics of TEA in the European Union countries in 2018 and 2020

Paired Samples Statistics					
		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TEA 18	8.7913	23	3.52973	.73600
	TEA 20	8.7130	23	3.91388	.81610

Source: the author's survey

Table 2: Results of Paired Samples Test of TEA in the European Union countries in 2018 and 2020

Paired Samples Test									
		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	TEA 18 - TEA 20	.07826	2.23240	.46549	-.88710	1.04362	.168	22	.868

Source: the author's survey

Table 3: Paired Samples Statistics of TEA in the European Union countries in 2018 and 2022

Paired Samples Statistics					
		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TEA 18	8.6667	18	2.99077	.70493
	TEA 22	8.7778	18	3.17278	.74783

Source: the author's survey

Table 4: Results of Paired Samples Test of TEA in the European Union countries in 2018 and 2022

Paired Samples Test									
		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	TEA 18 - TEA 22	-.11111	2.78819	.65718	-1.49764	1.27542	-.169	17	.868

Source: the author's survey

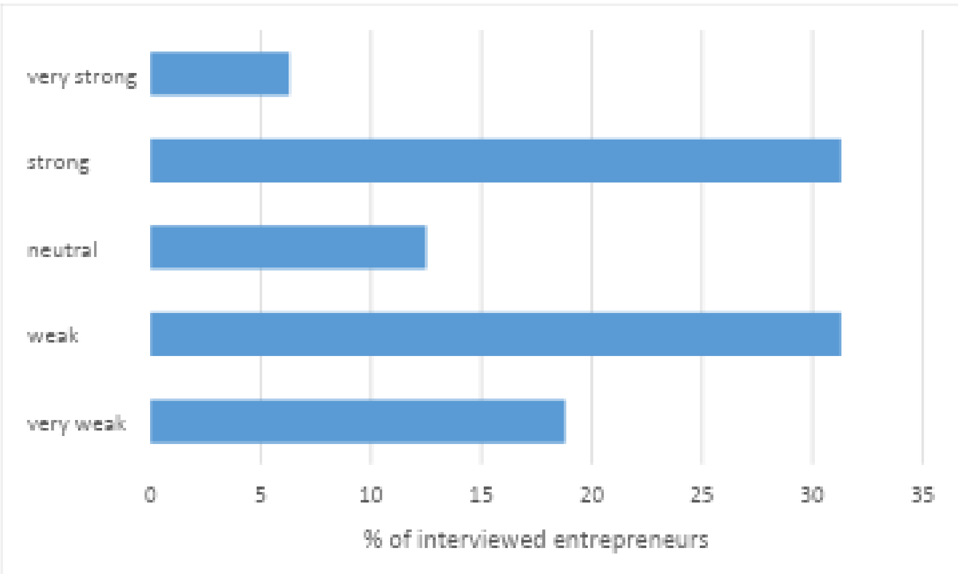
The results of paired samples T-Test show there are no significant differences in the average level of TEA before the EGD announcement and after. The meanings of means of TEA in 2018 and 2020, in 2018 and 2022 are close. The mean differences between TEA of 2018 and 2020, 2018 and 2022 are not statistically significant at $\alpha=0.05$, Sig (2-tailed) are bigger than 0.05. The null hypothesis, which states that there is no significant difference between samples, cannot be rejected. So, there is no strong evidence of the influence of implementing the EGD regulations on Total Entrepreneurship Activity in GEM surveys. The average levels of TEA among the EU countries have not changed significantly since EGD adoption. Also, there were many factors that affected entrepreneurship activity last year: Covid-19, and Russian aggression. The analysis of this macro-level data is not enough to give an answer to the question regarding the influence of the EGD on entrepreneurial activity in the EU countries.

Highlights of the survey on entrepreneurs' awareness of EGD and expectations

The survey of awareness and attitudes of entrepreneurs regarding the EGD objectives, actions, regulations changes, and expected consequences was undertaken in Clermont-Ferrand (France) in 2024. The profile of the interviewed entrepreneurs was the following: 63% of them have 2-4 years' experience of running a business, 31% started their business 5 years ago, and 6% - one year ago. Mainly, they represent small and middle-sized entrepreneurship. 63% of interviewees have their business in the sector of services, 19% - in trade, and 6% - in the agri-food sector. 25% of entrepreneurs run their business in Auvergne, 19% – in the Auvergne-Rhone-Alps region, and 56% – across different regions of France.

The results of our survey based on the questionnaire of French entrepreneurs are as follows.

Figure 3: The evaluation of the strength of EGD possible impact on business



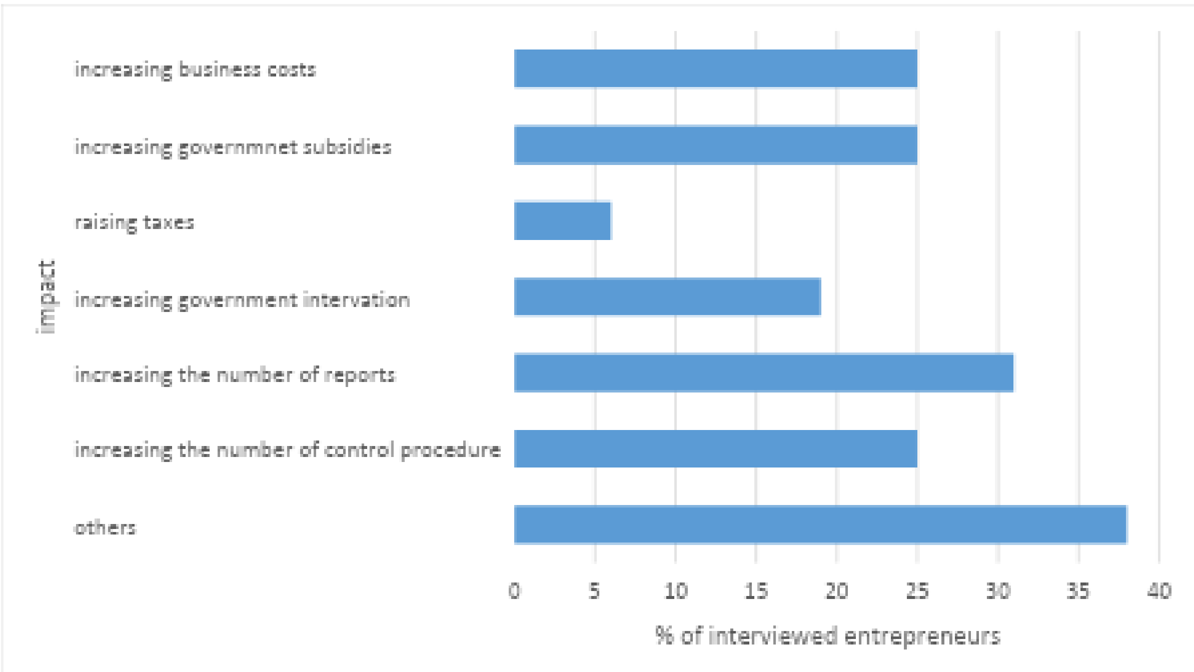
Source: the author's survey

Only 31% of entrepreneurs confirmed that they knew about the main objectives of EGD. According to their answers, the main objectives of EGD are the reduction of the carbon impact on the economy and achieving carbon neutrality by 2050 in compliance with the Paris Agreement "fit for 55", modernizing and making the economy and agriculture more resilient, with better consideration of the environment. Also, 31% of entrepreneurs gave a positive answer that they knew about the planned actions to guide the European environmental policy until 2030. The implementations of renewable energy technologies, new carbon and energy taxation, biodiversity plan, new agricultural policy "from farm to fork", end of diesel vehicles production, eco-certification of product, regulations concerning plastic, some actions in meat production, and new non-financial reporting were mentioned among main planned actions with connection to EGD. So, 69% of interviewed entrepreneurs did not confirm their awareness of the main objectives and planned actions on the EGD. The share of participants in the survey entrepreneurs, who think that European Green Deal actions will influence their business is 50%. The strength of the possible impact of the European Green Deal on business was evaluated as very weak by 18.8% of the respondents, weak – by 31.3%, neutral – by 12.5%, strong – by 31.3%, and very strong – by 6.3% (Figure 3).

Only 12% of interviewed entrepreneurs confirmed that they were aware of EGD regulations, which aim to facilitate the EU transition towards the European Green Deal goals, and 12% confirmed that they were aware of EGD regulations that would influence their business.

The main expectations regarding the influence of EGD regulations are increasing business costs (33.3% confirmed), number of control procedures (33.3%), and number of reports (25%). Most entrepreneurs are optimistic concerning the tax growth caused by EGD, only 8.3% of respondents expect it. Also, not many entrepreneurs (nearly 20%) expect increasing the government subsidies with EGD implementation (Figure 4).

Figure 4: The expected EGD impact on business



Source: the author's survey

56% of interviewed entrepreneurs confirm that the European Green Deal is an important step that will improve the environment, but, at the same time, will reduce the entrepreneurial activities within the EU.

The implementation of some practices regarding the European Green Deal in business was confirmed by 38% of interviewed entrepreneurs, and practices of Circular Economy confirmed by 50%. So, business is in the process of acceptance and implementation of EGD and circular economy principles. However, the difference in these answers might be explained as considering transformation forward circular economy and EGD practices as different by some entrepreneurs.

The need for more information about EGD regulations and business adjustments was confirmed by 94% of entrepreneurs, but only 31% answered positively about needs in professional consultations to adapt the business to the European Green Deal transformation. Taking into consideration too low a percentage of entrepreneurs who have a clear vision and understanding of the EGD agenda we assume that the personalized information support of business, especially with industries focused on EDG regulations and business transformations, will be worthy for the achievement of EDG goals and objectives.

Conclusions, limitations and perspectives

The European Green Deal has become an important step for the elimination of the urgent threats to sustainability and to build a prosperous and resilient society. This ambitious strategy implementation is based on a comprehensive plan of actions, that requires and involves the efforts of all economic agents, and the whole society.

The relationship between the EGD reforms and entrepreneurship is multifaceted. Progress in achieving EGD goals will depend on the awareness, and understanding of the EGD objectives by entrepreneurs, their willingness, and success in transforming their businesses in accordance with the EGD regulations. On the other hand, the EGD prioritization of environmental dimensions can significantly affect entrepreneurship through additional regulations and reduce entrepreneurial activity, which will negatively affect economic growth.

In this study, the changes in total entrepreneurial activity in the EU countries before and after the EDG announcement were studied, and the level of entrepreneurs' awareness and expectations was investigated.

A quantitative analysis of the early-stage total entrepreneurial activity rates was done. The application of statistical tests (Paired Samples Tests) confirmed that the average level of TEA among the EU countries has not changed significantly since EGD adoption, but the changes in some countries were relatively large (TEA increased by 4.1 percentage points (p.p.) in Germany, and decreased by 4.1 p.p. in Austria, by 3.7 p.p. in Poland in 2022 in comparison with 2018).

The survey of entrepreneurs was conducted in Clermont-Ferrand (France) revealed that the level of entrepreneurs' awareness of main objectives and possible regulatory impact of EGD on business is still relatively low even five years after EGD was announced. It might explain the revealed weak impact of EGD on the TEA changes. The low level of awareness and understanding of EGD objectives and regulations among entrepreneurs might cause difficulty in policy acceptance and slow speed of "green" transformation. The information support of business, especially with industries focused on EGD, is essential for the achievement of its goals.

The limitations of the analysis of TEA changes due to EGD coming into force deal with the choice of the years' situation for comparisons, and the availability of country's data. The survey of entrepreneurs' attitudes toward the EDG is in progress now, the sample is not big enough. It was conducted in one city, increasing the sample and broader geography of the survey might have influenced the obtained results.

The future study might reveal the relationship between the entrepreneurship experience, regional and industrial areas of business, and entrepreneurs' knowledge about the objectives and actions of EGD, the readiness of entrepreneurs for the implementation of EGD practices, the possible impact of EGD on startups, and business in different European countries.

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Appendix

Questionnaire

Hello! As you know the European Commission announced **The European Green Deal – a roadmap for making the EU's economy more environmentally friendly and sustainable**. Your insights are highly valuable for our research to clarify the possible influence of the European Green Deal on startups and entrepreneurship activity. Your responses will be anonymous.

1. When did you start your business?
    - This year
    - One year ago
    - 2-4 years ago
    - 5 and more years ago
2. What is the industrial area of your business?
    - Agri-food
    - Industry
    - Construction
    - Transportation
    - IT
    - Trade
    - Services
    - Other
3. What is the geographical area of your business?
    - Only Auvergne
    - Auvergne Rhône Alpes region
    - Other regions of France
    - Auvergne and other regions of France
    - Other than France country
    - International
4. Do you know the priority objectives of the European Green Deal?

- Yes
- No

5. Could you name any priority objectives of the European Green Deal?

6. Do you know the planned actions to guide the European environmental policy until 2030?

- Yes
- No

7. Could you name any actions to achieve objectives of the European Green Deal?
8. Do you think that European Green Deal actions will influence your business?

- Yes
- No

9. Could you evaluate the strength of the possible impact of the European Green Deal on your business?
    - Very weak
    - Weak
    - Neutral
    - Strong
    - Very strong
10. Do you know about implementation regulations, which aim to facilitate the EU transition towards the European Green Deal goals?

- Yes
- No

11. Do you know about regulations relating to the European Green Deal, which will impact your business?

- Yes
- No

12. What are your expectations regarding the influence of regulations relating to the European Green Deal on your business? These regulations will:
    - Increase your business costs
    - Increase number of reports
    - Increase number of control procedures
    - Increase government intervention
    - Increase taxes
    - Increase government subsidies for business
    - Other consequences (please, specify)

13. Do you agree with the following statement: "The European Green Deal is an important step that will improve the environment, but, at the same time, will reduce the entrepreneurial activities within the EU"?
    - strongly disagree
    - disagree

- neutral
- agree
- strongly agree

14. Have you already introduced some practices regarding the European Green Deal in your business?

- Yes
- No

15. Have you already introduced some practices of Circular Economy in your business?

- Yes
- No

16. Do you feel that you need more information about regulations relating to the European Green Deal to adjust your business to this transformation?

- Yes
- No

17. Do you feel that you need professional consultations to adjust your business to the European Green Deal transformation?

- Yes
- No

Part 2

Implementation of Green Deal, Circular Economy and Industrial Ecology Tools and Methods for different cases studies and supply chains

Industrial Symbiosis and Circularity: Transforming Europe's Textile Ecosystem for a Sustainable Future

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Abstract : New opportunities will emerge when textile companies rethink stock management and reduce overproduction, using collected and sorting materials in other value chains at the highest possible value. In Europe, a comprehensive set of new regulations associated with the EU strategy for sustainable and circular textiles is expected to be implemented in the coming years, fundamentally altering the way textiles are sorted, recycled, designed, manufactured, and handled at the end of their life cycle. Industrial symbiosis seeks to combine the product-driven approach, that will explore the sustainability benefits of the textile by-products reuse, with the technology driven analysis on the acceptability of this kind of technology at a commercial scale, across a wide range of cross-sectors like biotech fibers, water, agricultural or manufacturing (European Commission, 2023; Jia et al., 2020). Industrial symbiosis demonstrates clear benefits that synergies and interactions between companies, public authorities, business associations, research institutions, and civil society could bring to the entire circular textile ecosystem. Based on the concept of biophysical symbiotic exchanges of materials, energy, water, and by-products, industrial symbiosis engages distinct entities in a collective approach looking for competitive advantage (Desrochers, 2004; Morales et al., 2022; Shi & Li, 2019).

Industrial symbiosis opens a new economic era: competition and cooperation can get along

Today's environmental and climate challenges require collaborative strategies in which symbiotic win-win solutions could prevail. In this context, the concept of industrial symbiosis, known from the eco-industrial clusters, becomes more and more relevant. Authors claim that nowadays industrial symbiosis should be considered as social innovations (Durán-Romero et al., 2020; Gomes et al., 2018) in which sustainability and circular economy are two keywords. In modern times waste accumulation and pollution generated by technical progress and economic growth lead to mistrust of the development model of industrial economies. Therefore, in the past thirty years, the industrial economy concept has been structured around several fields of research, drawing inspiration from ecosystems (Committee of the Regions, 2016; Pietrulla, 2022) and biological species to rethink industrial relations within a spatial appropriation (France Clusters, 2018; Morales & Lhuillery, 2021).

Industrial symbioses demonstrate clear benefits that synergies and interactions between companies, public authorities, business associations, research institutions, and civil society could bring to the entire industrial ecosystem. Based on the concept of biophysical symbiotic exchanges, industrial symbiosis engages (Lovelady & El-Halwagi, 2009) distinct entities in a collective approach looking for competitive advantage involving the physical exchange of materials, energy, water, and by-products. In this chapter we claim that by working together, companies can offer a collective benefit greater than the sum of the individual ones expected from independent actions. Once undesirable residues of the production process, waste becomes economically viable products that can be reintegrated locally as resources in other production processes.

Minimizing the need for raw material

Industrial symbioses are a frequently underrated circular economy strategy aiming to close loops and add value to waste. The goal is for each industry to feed on the waste from its neighbors to minimize the need for raw materials and reduce the waste produced. Therefore, industrial symbiosis is not considered as an isolated environmental solution, but rather as part of a process of eco-efficiency improvement for individual companies and closing loop strategies for collective action (Desrochers, 2004; Yeo et al., 2019).

What is the recipe for success? A collaboration between partners who have different activities altogether with the importance of economically viable solutions? The geographical proximity between the participants? The desire to work together? Sharing values, and good communication between players? There is no conclusive answer. Symbiotic relationships emerged in each territory spontaneously and created different forms of coordination. Three possibilities for the exchange of resources are settled there: the reuse of products, infrastructure sharing, and the pool of services. The seminal industrial symbiosis study is the one explored in Kalundborg (Denmark) back in 1972. Moreover, many successful examples of industrial symbiosis, helping companies to save resources and reduce tons of CO2 emissions can be found in France, Belgium, China, Japan, Sweden, Australia, and many other countries.

However, it is not only a question of collective organization built on synergies for the sake of getting economic benefits, but industrial symbiosis also offers enormous possibilities in terms of energy efficiency and reduction in the consumption of raw materials. Industrial symbiosis appears to be at the heart of the circular economy transition, mobilizing renewable energies, reducing waste and greenhouse gas emissions, or even transforming waste into by-products.

Industrial symbiosis is an essential driver to imagine the industry of the future. Industrial symbiosis is part of a historical process of industrial change, which began in the 19th century with the mechanization and standardization of work and continued in the 20th century with the concept of industrial digitalization. The next step – and the societal challenge – is both to reinject people into industrial production, a challenge coined in the literature as Industry 5.0, and to lead industries towards a strong sustainability strategy, by using the circular economy (Cannas et al., 2025).

The transition from linear to circular paradigm makes it possible to consider industrial symbiosis as a form of social innovation that can respond to various challenges, like positioning industry at the heart of sustainability, defining the industrial ecosystem at the local level, reintroducing industry into the urban ecosystem, introducing agricultural activities into symbioses, developing bioeconomy projects by linking materials, energy and information, turning CO2 into products, and much more.

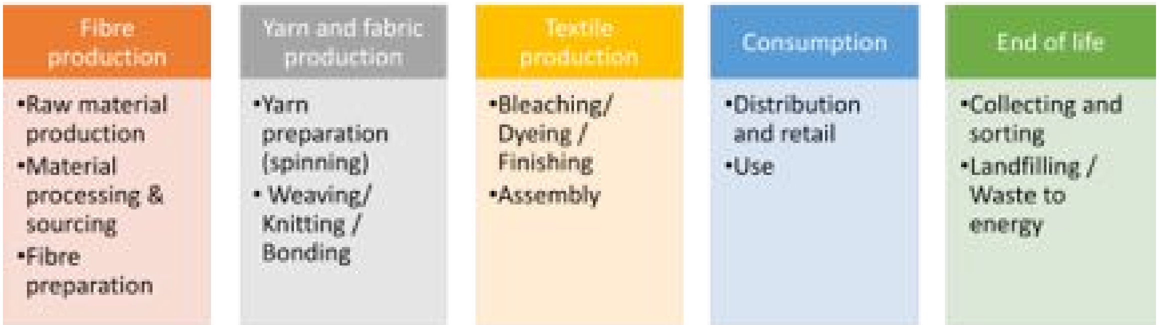
Circularity applied in the Textile European Ecosystem

The textile and clothing industry in Europe and around the world is undergoing a significant transformation, comparable to the shift that occurred during the mass production of synthetic fibers and large-scale manufacturing and distribution of textile-based consumer goods in the 1950s and 1960s. The supply of affordable and fashionable textiles and clothing to a growing consumer class, which became unsustainable due to the rise of cheap, fast, and disposable fashion, needs to be replaced with a more sustainable operational model that prioritizes quality, durability, efficiency, and circularity. Additionally, textile materials have the potential to contribute to the sustainable transformation of various sectors of the economy, including healthcare, construction, energy and transport, agriculture, defense and security, as well as leisure and sports (Philippa Notten, 2020).

The evolving trends in end markets are prompting significant transformations in products, production approaches, and business models. There is an anticipated rise in the demand for products that are sustainable, authentic, and/or locally sourced. As the costs associated with energy, raw materials, processing chemicals, and the utilization and disposal of process water continue to increase, there will be a preference for resource-efficient, waste-reducing, and circular technologies that can be employed as needed. To address the imperative of reducing and ultimately eliminating the use of fossil fuels, both for energy and raw materials, it becomes essential to place stronger emphasis on the utilization of bio-based or other renewable materials and chemicals (European Commission, 2023; Fontell & Heikkilä, 2017).

Currently only 12% of the textile materials used in Europe are recycled or recovered, and even when recovered they mostly downcycled to less valuable products. The textile circularity presents a huge limitation because suitable technologies for fiber purification, densification, and reuse have not been developed yet. And, since the transition towards circular solutions for the textile industry needs to integrate every process of the textile value chain, from innovative sorting, recycling, to design, the entire value chain is faced with interweaving forces influencing the sector (political, regulatory, socio-economic, technological, and end-market. In Europe, a comprehensive set of new regulations associated with the EU strategy for sustainable and circular textiles is expected to be implemented in the coming years, fundamentally altering the way textiles are sorted, recycled, designed, manufactured, and handled at the end of their life cycle. Since the transition towards systemic circular solutions for the textile industry needs to integrate every process of the textile value chain, industrial symbiosis appears as the ideal innovative organization where competition and cooperation (Wagner & Heinzel, 2020) can get along. Industrial symbiosis should be considered as a social innovation integrating sustainability and circularity (Desrochers, 2004; Morales et al., 2022; Shi & Li, 2019).

Figure 1: Stages of the textile value chain



Source: Authors own creation inspired by (Fontell & Heikkilä, 2017; Philippa Notten, 2020)

Discussion on Circularity transition roadmap in Europe

The objective of this book chapter is to identify and analyze the barriers posed by feedstock complexity through innovative sorting and mixed cellulosic fibers sorting technologies when applying the mechanical and bio-chemical (enzymatic and ionic liquids) recycling of textile fibers in the artificial man-made cellulosic fibers. The chapter seeks to analyze the value chain (Figure 1) and to map the network of industrial stakeholders, across a wide range of cross-sectors like biotech fibers, water, agricultural or manufacturing. The identification and analysis of barriers in the European textile value chain is essential to scale up the application of circular economy in sorting, enzymatic recycling, and disintegration technologies, able to ensure the consistent quality and safety of textiles loop closing and their suitability in the textile value chains of natural and plastic-based textile fibers.

This chapter seeks to analyze the current state of the art on the Circular economy field progress for the textile sector and be used as a cornerstone for the proposal of a project to be submitted in February 22nd to the Horizon RIA call on Circular solutions for textile value chains through innovative sorting, recycling, and design for recycling

(HORIZON-CL6-2024-CircBio-02-1-two-stage). Finally, we will use the insights coming from Life cycle analysis and Social acceptability of new secondary products by final consumers but also by intermediate industrial users interested in the implementation of innovative technologies will set the tone for the recommendation of ecosystem strategies enabling systems-based solutions like the Reverse logistics, tack-back and other innovation ecosystem strategies, facilitating the detection and removal additives in the secondary resources stream, and bio-based materials replacement. This chapter identifies the three main circular transition challenging areas in the textile sector: 1) Innovation in sorting, enzymatic recycling and disintegration technologies; 2) Innovation ecosystem strategies enabling chain-based solutions; and finally, 3) Systemic digital solutions that facilitate traceability and textile collection. The three of them are observed in Figure 2.

Figure 2: Circular transition challenges in the Textile sector

Sources: Authors creation inspired by the exchange of the ICO4TEX proposal to the Horizon RIA call on Circular solutions for textile value chains through innovative sorting, recycling, and design for recycling (HORIZON-CL6-2024-CircBio-02-1-two-stage)

The Innovative Circular Solutions for the Poly Cotton Textile Value Chain (ICO4TEX) project focuses on the upcycling of secondary resources that must lead to the same quality and diversity of products as those obtained when using primary resources. Mixed waste processing technologies have a strong relation with industrial symbiosis objectives. Enhancing the overall understanding of sustainable and circular textiles is essential, extending beyond industry advancements and technological integration. It is vital to continuously enhance the knowledge base among researchers, policy makers, and consumers regarding all aspects of these textiles. To facilitate this, expert networks and communities of practice like ECOSYSTEX play a crucial role. They contribute to accelerating the dissemination of knowledge within the European research community and ensure easier access to up-to-date scientific information and unbiased data for policy makers and consumer representatives (CSOs). Additionally, this Textile ecosystem and the network of actors out of the textile supply chain can serve as platforms to initiate, execute, and update comprehensive empirical data collection and analysis programs, ultimately leading to a better comprehension of industrial symbiosis potential in the textile sector.

European projects like *Circthreat, Whitecycle, MERLIN, T-REX Textile Recycling Excellence, GRETE, CISUTAC Circular & Sustainable Textiles & Clothing HEREWEAR, CIRCPASS CISUTAC, TExtended, Waste2BioComp, Sustrack and TRICK* seek to answer essential questions about the sustainability of the textile sector. Extended partnership among inter and intra-value chains stakeholders fosters connections of new production processes with revolutionary potential. The management and operational perspective of this new circular textile production process have to figure out the estimated commercial share of the market (volumes), and the final composition of the offered products (pure cellulosic fibers or mixed materials integrating other textile fibers, etc) as well as the targeted clients.

The intersection between the *Innovation ecosystem strategies enabling chain based solutions* and the *Systemic digital solutions that facilitate traceability and textile data collection* prove the technical, environmental and socio economic feasibility of the complex natural and artificial textile (Daddi et al., 2019) loops closing in the production, post production and post-consumer process. Circular transitions in the European context also seek to increase the use of secondary resources in the mainstream production processes, increasing significantly resource efficiency across the value chain and subsequent reduction of CO2 emissions; reduction of waste sent to landfill and overall positive environmental impact. The roadmap of the textile sector in Europe highlights a full circular loop potential (Molina-Sánchez et al., 2018) in comparison with other more simplistic visions abroad based on the recycling possibilities in an open loop mechanism. In order to move towards a circular loop transition in Europe the entire inter and intra-value chain (see Figure 3) involved stakeholders needs to implement the following activities:

- Sustainability analysis through the following processes and concepts: recyclability, bio-based, biodegradable, environmental footprint
- Study the potential user of a product and align with industrial infrastructures
- Roll-out of systemic solutions for textile sorting, using innovative digital technologies (such as digital product passports, water print marks, digital platforms and smart manufacturing)
- Roll-out of feasible solutions for facilitated disintegration to be incorporated in product design, as an enabler for recycling
- Increased uptake of enzymatic recycling solutions that deliver competitive alternatives using high-quality secondary materials in manufacturing and other sectors.

Figure 3 : Intra textile value chain stakeholders in a connected ecosystem

Source: Authors' creation

In figure 3 we can observe that macrosorting mechanical identification, spectroimaging/laser-induced breakdown spectroscopy, matrix separation, enzymatic depolymerization, chemical recycling, yarn production, trace and tracking technologies and digital platforms are the technologies that could contribute to the recycling matching while answering supply-versus-demand of feedstock at the level of quality constraints (removal of impurities or wrong matrices, concentration etc.).

The expected impacts of closed loop circular economy strategies in the textile industry are highly relevant, as they can reduce waste, conserve resources, and promote sustainable practices. Through industrial symbiosis, upcycling recycling, and better product design, the industry can minimize environmental footprint, enhance profitability, and meet the growing demand for ethical and eco-friendly products. The circular economy offers an opportunity to transform the textile industry into a more sustainable and responsible sector, benefiting both the environment and the economy. The project impacts can be defined through the following points:

- To demonstrate the uptake potential of chemical recycling solutions that deliver competitive alternatives using high-quality secondary materials in manufacturing, healthcare, construction, energy, transport, agriculture, defense and security, as well as leisure and sports.
- To optimize circularity through the limitation of pollution and consumption of water, energy in the circular value chain, carbon footprint, data digitization, etc.
- Evaluate the life-cycle economic and environmental KPIs of the complete circular solution. Ensuring that the indicators can adapt to new knowledge about impacts with enough flexibility
- Demonstrate the viability of project technologies with the industrial actors integrated in the consortium during the project to enable the rapid adoption in additional sectors.
- Prepare the future commercialization of developed technologies for broad-scale replication.
- Minimize adverse impacts on the environment and society through the safe and sustainable by design approach with demonstrable economic return, developed in closed cooperation between waste generators, waste collectors, waste converters, textile industries, users and technology providers.
- Document processes and procedures along the entire supply chain with the FAIR data implementation protocol (Kostakis & Tsagarakis, 2022).

Conclusions for a Circular transition roadmap

Successful circular transition in Europe relies on advanced monitoring and sensing in the process industries and value chains, and on an improved data completeness, accuracy and interoperability between the process, actively tracking and promoting the involvement of all the actors in the textile value chain from the waste generators to industrial waste converters, collectors, public authorities, and standardization actors.

The dominance of small and medium-sized enterprises (SMEs) in the textile industry, coupled with their limited internal resources for research and high-risk innovation, highlights the importance of public funding in collaborative programs involving research and academic institutions. External research providers have traditionally served as temporary outsourced research units for SMEs in the sector. They assist these companies throughout the entire innovation process, including idea generation, technology exploration, technical development, pilot testing and validation, scale-up, business development, and, when necessary, certification, training, and other consulting services. Additionally, collaboration with machines, tools, or chemistry providers is often necessary to transform a new product idea into a scalable and marketable solution.

The increasing number of applications for textiles and fiber-based materials adds complexity to the materials, processes, and end-market requirements that companies must manage. With long processing chains involving numerous specialized players, collaborative innovation approaches become more suitable and promising, as they facilitate alignment among these stakeholders. Circular operations, particularly in terms of reusability and recyclability, necessitate collaboration with new value chain partners such as collectors, sorters, recyclers, and re-processors of reclaimed materials, therefore claiming the urgency of industrial symbiosis emergence. Many of these partners are also SMEs with limited experience or resources to engage in collaborative research and innovation activities. Given that the potential for reusability and recyclability is often determined during the initial design, material selection, or processing stages, the importance of collaborative innovation programs becomes even more pronounced. Achieving greater use of natural or bio-based feedstock fibers will require strong collaboration with agricultural, forestry, or livestock producers to ensure scalable win-win solutions.

The roadmap for circular transition will need collaboration with existing projects and develop synergies with other relevant European, national, or regional initiatives, funding programs. International cooperation needs to be engaged especially on mixed complex fibers including all the previously mentioned project objectives. The proposals supported Horizon Europe calls may cover the industrial process in the following sectors: cellulose, cotton, plastic and composite fibers[1].

Circular transition roadmap in Europe requires new material and processing solutions engaged through multiple iterations to demonstrate their technical robustness and economic viability on a larger scale. Constructing and operating precommercial pilot scale units for these solutions is costly and challenging to fund through market-based financing, mainly because of the absence of cash flows. In the case of radically innovative technologies or product approaches, spin-offs or start-ups are often necessary, as they may contradict or compete with established operations. While private sector risk capital providers like venture capitalists favor digital or low-capital intensity start-ups, public funding providers should prioritize capital-intensive material and manufacturing start-ups.

The adoption of new technologies or business models across the industry is a gradual process that begins with pioneers and gradually reaches less innovative-driven companies or market segments. This process can be expedited through active dissemination among the innovation ecosystem, technology transfer, coaching, and training activities. Therefore, providing public support for these activities is a suitable and generally cost-effective way to accelerate innovation. If Europe aims to be at the forefront of sustainable and circular textiles, with the potential to successfully export or share European solutions worldwide, it is advisable to initiate international collaboration and research with European partners during the innovation stage. This collaboration would yield mutual benefits and facilitate the transfer of innovative ideas on a global scale.

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Proposal of Circular Economy Practices in the Agricultural sector in the Maule Region, Chile

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Abstract: The agroindustry in the Maule Region plays a pivotal role, contributing 15,44% of GDP and 26,2% of employment. However, it also accounts for 70% of water consumption, has a heavy influence on GHG emissions, and is also a major driver of biodiversity loss due to deforestation and land use changes. This study, aligned with industrial ecology and circular economy principles, proposes good agricultural practices to foster energy transition, manage organic waste, protect biodiversity, adapt to climate change, and measure progress towards sustainable development. Key results include a 64% increase in native forest areas by designating non-productive zones and a €11.377 NPV over 25 years from photovoltaic irrigation systems, avoiding 3,44 tons of CO_2 annually. Vineyard biomass energy prevents 246,39 kg CO_2/MWh, while wine waste utilization could cut 10.078 tons of CO_2 through anaerobic digestion. Industrial synergies were proposed to valorize common agricultural waste, and indicators were designed to assess the current performance of the agro-industrial sector and monitor sustainable development.

Introduction

The intensification of agroindustry, essential for the economic development of the Maule Region, poses significant environmental challenges due to the intensive use of natural resources and the generation of waste. In this region, where the fruit and wine sectors are predominant, an estimated 46% of solid waste consists of organic residues from agricultural, domestic, and forestry activities. Uncontrolled burning, a common practice due to its low cost, contributes to greenhouse gas emissions, with agriculture accounting for 21% of these emissions globally. This study, grounded in principles of sustainability, industrial ecology (IE) and circular economy (CE), proposes strategies to address these challenges, such as waste valorization, transitioning to renewable energy sources, and biodiversity protection. Through the characterization of the agricultural sector and the analysis of material, water, and energy flows, industrial synergies are identified, and indicators are developed to assess progress and sustainable development (SD) of the activity. These measures aim to reduce the sector's environmental impact, enhance regional resilience to climate change, and ensure balanced economic development that respects the planet's regenerative limits, benefiting both the local community and future generations.

The primary objective is to propose good agricultural practices (GAP) that promote closed material cycles and maximize resource efficiency, thus advancing a sustainable model for the Maule Region.

Theoretical Framework

Sustainable Development

The concept of SD, widely defined by the United Nations Brundtland Commission in 1987, emphasizes meeting the needs of the present without compromising the ability of future generations to meet their own needs. This study adopts the notion of "strong" sustainability, which rejects the substitution of natural capital for economic growth. Instead, it advocates for development that enhances living conditions by rationally utilizing non-renewable resources while ensuring that renewable resources are used at a pace aligned with their natural regeneration cycles (Cervantes, 2011). The framework promotes efficient resource management, renewable energy adoption, biodiversity conservation, economic diversification, and social equity by creating opportunities for education, local job growth, and social capital enhancement.

Good Agricultural Practices

GAPs are a set of principles designed to ensure food safety while considering economic, social, and environmental dimensions. These practices encompass land management, crop strategies, waste management, and food handling processes. The focus is on sustainable agriculture, aiming to minimize risks and promote long-term viability in food production systems (FAO, 2004). Central to GAPs is the responsible use of resources. This includes adopting alternative energy sources, recycling waste, reducing non-reusable materials, and enhancing soil quality through the reintegration of organic residues. Moreover, GAPs emphasize the conservation of habitats and biodiversity within agricultural settings, recognizing their importance as indicators of sound environmental management.

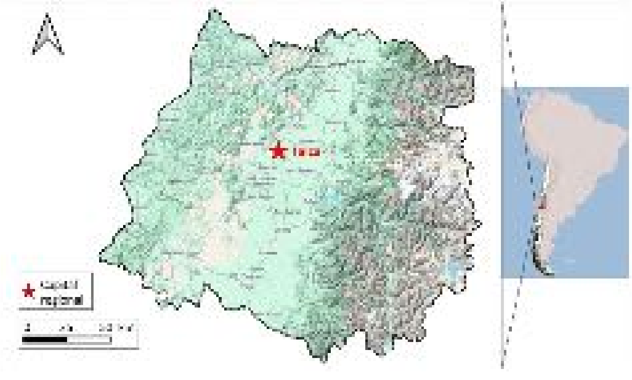
Industrial Ecology and Circular Economy

IE challenges the traditional linear model of production and consumption, proposing instead a circular approach inspired by natural ecosystems. This framework integrates industrial systems with societal and environmental contexts to reduce waste, optimize material use, and lower the environmental costs of industrial activity (Cervantes, 2021). A central view of IE is the closure of material cycles, where materials are reused, recycled, or recovered to remain within the industrial system for as long as possible. This is complemented by environmental design, which incorporates sustainability into every stage of a product's lifecycle, and technological innovation, which drives the development of sustainable practices and systems. An essential strategy within IE is Industrial Symbiosis (IS), which fosters collaboration between nearby businesses. This approach enables one company to use the byproducts or waste of another as raw materials, creating interconnected networks that mimic the resource flows found in natural ecosystems. CE, like IE, shares a systemic vision that takes nature as a model, aiming to close material cycles and optimize resource use. However, while IE has developed as a field of knowledge with a strong environmental focus, CE is structured as an economic model designed to put these principles into practice. For the purposes of this article, both disciplines can be addressed interchangeably, as their objectives are similar (Cervantes, 2013).

Regional Characterization

The Maule region is located in central Chile, with coordinates 35°25'36" S, 71°40'18" W. It is the seventh region of the country, covering an area of 30.296,10 km², which represents 4.0% of the national territory. Its regional capital is the city of Talca.

Figure 1: Topographic map of the Maule Region



Agro-industrial Characterization

Agriculture plays a vital role in Chile's economy, contributing 3,07% to the national GDP in 2022. It is particularly relevant in the Maule Region, with agroindustry accounting for 15,44% of its regional GDP, making it the third-largest economic activity after manufacturing and services.

The region benefits from favorable climatic conditions that support a wide range of crops, including fruit, vineyards, and vegetables. The Maule Region is also the leading wine-producing area in Chile, with 53.818 hectares dedicated to vineyards, representing 39,5% of the country's total vineyard area. The main grape varieties are Cabernet Sauvignon and Sauvignon Blanc.

The region also plays a significant role in fruit production, accounting for 22,3% of national fruit cultivation. Major fruits include cherries, apples, and hazelnuts. Additionally, the region is known for vegetable production, especially corn and watermelon, and has 86.580 hectares dedicated to annual crops like rice, wheat, and potatoes.

Forestry is another important industry in the region, with 384.690 hectares of plantations, primarily consisting of *Pinus radiata*, used for timber and paper production. In terms of livestock, the Maule Region is involved in beekeeping, pig farming, and horse breeding, contributing significantly to national figures.

The agricultural sector is also crucial for regional employment, generating 26,2% of the regional workforce from late 2018 to early 2019, well above the national average of 10,1% (ODEPA, 2019).

Socioeconomic Characterization

Demography

The 2017 Census conducted by the National Institute of Statistics reports a total population of 1.044.950 people in the Maule Region, representing 5,9% of the national population, making it the fifth most populated region in the country (Instituto Nacional de Estadísticas, 2021). Considering the regional area, this results in a population density of 34,47 people per km². The largest and most important cities include Talca, the regional capital with 220.000 inhabitants, as well as other cities like Curicó, Linares, and Constitución.

The average age is 36,5 years, with a trend of aging, and women make up 51% of the population. Of the total population, 5% report feeling connected to an indigenous community, the vast majority belonging to the Mapuche people (90,6%).

Economic Characterization

The Maule Region contributes 4,27% to Chile's national GDP, with a per capita GDP of 11.141 USD, ranking it 12th among the country's 16 regions. Its economy is diverse, with a strong focus on agriculture and agroindustry, which together account for 15,44% of regional GDP. The manufacturing sector, especially food processing, textiles, and wood products, leads with 16,8%, followed by services like tourism, education, and healthcare (15,8%). The region's economy has been stable, with significant growth in agroforestry and real estate services, while the electricity, gas, water, and waste management sectors have decreased. Agricultural worker salaries increased by 60,2% between 2001 and 2017, but they remain 37% below the national average, with corporate sector salaries being significantly higher.

Methodology

To achieve the stated objectives, various methodologies were employed, including literature review, geospatial analysis, economic analysis, process modeling, and impact assessment.

First, a background review was conducted through searches in academic databases and institutional repositories such as the FAO and the Chilean Ministry of Agriculture. Scientific articles and technical reports were analyzed to gain an overview of agricultural sustainability, CE, and natural resource management. This review was complemented by statistical data and geospatial analysis using QGIS to characterize the Maule Region.

Based on these findings, proposals were developed to promote sustainability and CE in agriculture, addressing sustainable practices, energy transition, and biodiversity. Methodologies such as influence diagrams were used to model decision-making in organic waste management. This graphical representation helps describe dependencies between variables and decisions, model decision-making processes, and identify key relationships and factors influencing the outcome. In these diagrams, nodes represent decisions, uncertain or deterministic events, and objectives or values. Additionally, arrows illustrate interactions between different nodes and can be classified as conditional, informational, or functional, according to the proposed graphical convention (Howard & Matheson, 2005).

Other methodologies included the calculation of key values related to emissions, biomass production, and energy generation obtained through different strategies. The economic viability of photovoltaic installation for agricultural irrigation was also evaluated through the calculation of relevant indicators.

Additionally, two synergy diagrams were created to visualize the flows of water, materials, and energy in the agroindustry, identifying opportunities for waste valorization. First, existing synergies in agro-industrial activity were identified, enabling the revalorization of common waste through collaboration with other industries. Then, additional synergies were incorporated into the diagram, considering current trends and opportunities to revalue mismanaged waste while involving other industries that can generate added value from these by-products. The symbology for the developed synergy diagrams can be seen in Figure 2.

Figure 2 : Color code for synergy diagrams

Description	Flow	Residual Flow	RGB code color			
			R	G	B	Color
Raw materials			0	176	80	
Products			204	0	255	
Energy			255	0	0	
Water			0	112	192	
Residues			127	96	0	
Proposed synergies			255	153	0	

R: red, G: green, B: blue

Source: Lule y Cervantes (2010)

In parallel, a system of SD indicators was developed, enabling the assessment of the agricultural sector's impact and its alignment with the sustainable development goals (SDGs). To develop these indicators, the following methodology was applied (Cervantes, 2017):

- System definition: The main function and boundaries of agricultural activity in the Maule Region were identified.
- Sustainability criteria: Key criteria were selected in three areas: environmental, economic, and social.
- Objectives and themes: Based on the criteria, sustainability objectives and their corresponding themes were defined.

- o Indicator development: Indicators were designed to measure progress toward the objectives, prioritizing those that relate variables in percentage form.
- o Indicator calculation: One indicator per area was selected and calculated using bibliographic sources and databases, enabling an assessment of the current state and the proposal of improvement measures.

Results

Through the application of the proposed methodology and the integration of the described concepts and strategies, this section presents a diagnosis of the Maule Region and highlights the main findings. Three key areas are analyzed: water and climate dependencies, energy transition, and biodiversity loss, all of which have a significant impact on the region's SD.

Diagnosis

Water and Climate Dependencies

The region heavily relies on water for agriculture (70% of local consumption) and electricity generation (84%). However, decreasing rainfall affects agricultural yields and increases competition for water resources, raising the risk of social and environmental conflicts. Climate vulnerability is high due to a combination of geographic, socioeconomic, and ecological factors.

Energy Transition

Reduced rainfall and increased solar radiation make renewable energy a viable option. Three main strategies are identified:

- Photovoltaic Energy: Greater future profitability due to rising solar radiation and increasing electricity costs.
- Biomass Fuel: Opportunity to utilize pruning residues, which are currently underutilized.
- Biogas: Potential in agricultural waste, particularly from the wine industry, though the lack of natural gas infrastructure limits its injection into networks.

Biodiversity Loss

Agricultural and forestry expansion has reduced regional biodiversity, replacing native forests with monoculture and *Pinus radiata* plantations. The area under official protection accounts for only 5% of the total surface occupied by *Pinus radiata* plantations. The adoption of GAPs could help mitigate these impacts and promote conservation.

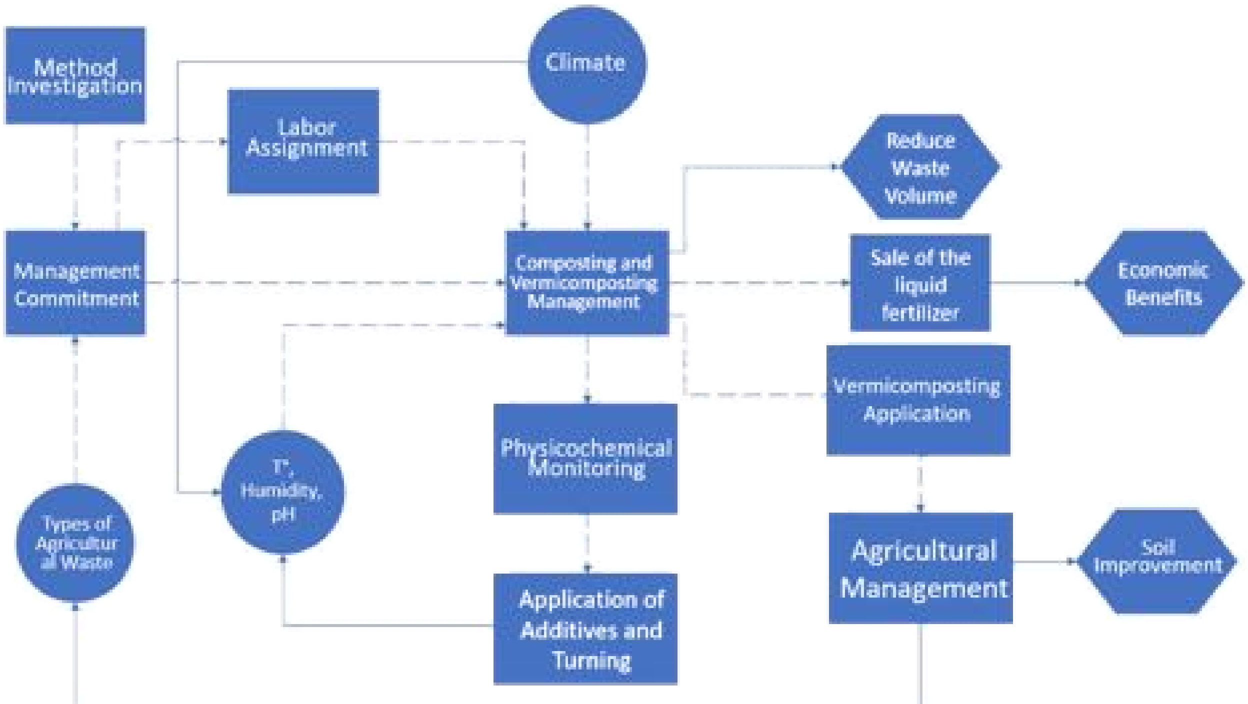
Biomass Valorization Plan through an Integrated Composting and Vermicomposting System

The main objective of composting is the proper disposal of organic waste generated in agricultural activities, which helps reduce its volume, promotes a closed-loop cycle of materials, and prevents its disposal in landfills or informal burning. This process not only improves waste management but also generates organic fertilizer, replacing synthetic fertilizers purchased from third parties, resulting in improved soil quality and economic benefits for producers.

The implementation of composting is aimed at obtaining mature compost, which can be further enhanced through vermicomposting. The integration of these techniques optimizes process efficiency and allows the production of higher-value products. Among the products generated, vermicompost stands out for its excellent properties in improving soil quality and crop yields. Additionally, leachate is produced, a liquid fertilizer rich in nutrients and beneficial microorganisms, which can be marketed to fund necessary resources such as machinery, labor, and physicochemical testing. Alternatively, this liquid fertilizer can also be integrated into irrigation systems to provide nutrients more effectively, enhancing the soil's organic matter.

The influence diagram (Figure 3), created to guide the implementation of this system, optimizes the involved processes, ensuring the proper use of resources and establishing key practices such as regular turning and physicochemical testing. This approach also considers uncertainty factors, such as pH, humidity, and temperature, which are essential for maintaining optimal decomposition conditions and obtaining high-quality compost.

Figure 3: Influence diagram for a composting and vermicomposting integrated system in the Maule Region



Biodiversity Protection through the Establishment of Non-Productive Zones

To mitigate the impact of agricultural activities on biodiversity, Non-Productive Zones (NPZ), or biodiversity islands, can be established. These areas are populated with native vegetation and are located at the edges or within agricultural plots. The benefits of NPZs include:

- Biodiversity Protection: They create landscape diversity and connectivity, providing refuges for wildlife and reducing the agricultural impact on local flora and fauna.
- Climate Change Mitigation: NPZs do not require soil management, fertilization, or pesticides, reducing CO_2 emissions, while their vegetation increases CO_2 capture.
- Resilience: These zones improve water retention, reduce runoff, and help prevent soil erosion and flooding.

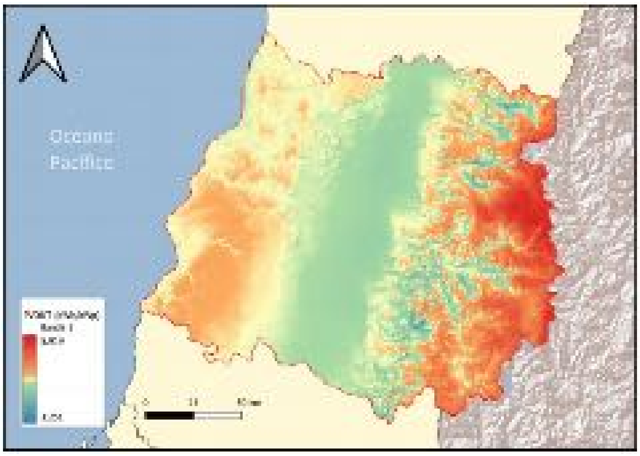
NPZs should prioritize native, non-invasive plants that promote pollinator habitats and flowers year-round. They can be implemented in road ditches, around water bodies, and between parcels. Dry stone walls can also be included as shelters for wildlife.

Researchers recommend setting non-productive areas at 7% for dryland farming, 4% for irrigated land, and 4% for permanent crops to protect biodiversity and restore habitats (Carceller García, 2022). Dedicating 4% of the 305.529 hectares of irrigated land in the region to NPZs could restore 12.211 hectares of native forest, which represents 64,22% of the area currently under protection by CONAF.

Photovoltaic Energy and Agricultural Irrigation

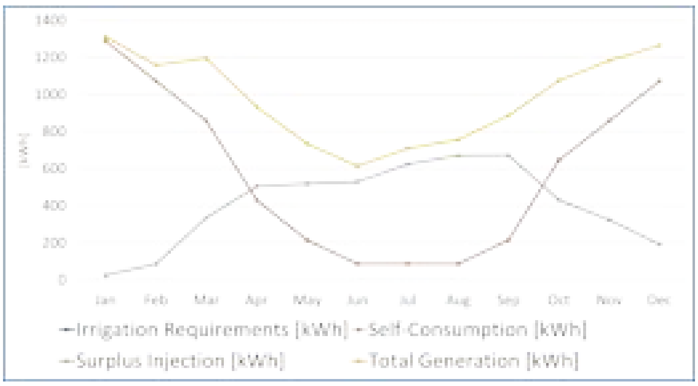
The Maule Region map (Figure 4) shows the photovoltaic potential for energy production, based on solar radiation data from the 1999-2018 period, with values ranging from 3,250 to 5,920 kWh/kWp daily. Photovoltaic energy is particularly useful for irrigation systems, as it is cost-efficient and can power pumps in areas without access to electrical grids. It can also be used in agro-industries with high energy consumption, such as packing plants and warehouses.

Figure 4: Photovoltaic Potential Map



A financial evaluation was carried out for the installation of a photovoltaic system for irrigating 8,5 hectares of vines, the average area for common red varieties in central Chile, and the most abundant crop in the Maule Region (Lima R., 2015). The calculations were based on radiation data, the technical characteristics of a 500 Wp panel, and the energy requirements for drip irrigation, among other assumptions in the model. The calculations suggest that the installation of 18 panels with a total capacity of 9,0 kWp can provide the energy needed to irrigate 8,5 hectares of vines, covering 100% of the energy requirements for irrigation. The calculation considered variations in irrigation hours required by season due to the different phenological stages that characterize this crop throughout the year. Likewise, for electricity generation by the panels, a distribution was considered according to the varying radiation levels throughout the year based on seasonality. Produced energy can be used for self-consumption or injected into the grid during low consumption periods in exchange for economic compensation. The total annual energy generated for irrigation according to this model is 11.822,4 kWh, with 6.910,5 kWh used for self-consumption and 4.911,9 kWh of surplus energy injected into the grid. These values correspond to 58% self-consumption and 42% surplus energy sales. The relationship between generation, consumption, and surplus injection throughout the year can be seen in Figure 5.

Figure 5: Annual Electricity Generation and Consumption of Photovoltaic System in 8,5 ha Vineyard



With the established assumptions, considering an initial investment of around €7.500, the net present value (NPV) of the project, the payback period of investment based on cash flows, and the internal rate of return (IRR) were calculated. It can be observed that the project is profitable according to the economic indicators, with an investment recovery time of approximately 6,53 years.

Table 1: Financial results over 25 years of the photovoltaic system

NPV	€11.377
Payback	6,53 years
IRR	15,94%

Regarding the environmental benefits of the project, the photovoltaic generation is estimated to have an emission factor of 45 kg CO_2 eq/MWh over the entire lifetime of the panels (Desideri, Zepparelli, Morettini, & Garroni, February 2013). On the other hand, the National Electricity System (SEN) of the Ministry of Energy reports an emissions factor of 336,32 kg CO_2 eq/MWh for the energy grid in the central region of the country (Sistema Eléctrico Nacional, 2018). With these values, it is found that the photovoltaic project under study can reduce CO_2 emissions by 3,44 tons annually, equivalent to the annual CO_2 absorption of 158 trees (Garrett, 2023). Additionally, for every MWh generated through photovoltaic energy instead of consumed from the SEN, the release of 291,32 kg CO_2 is avoided.

Utilization of Pruning Biomass as an Energy Source

Comparing the emission factors of two different energy sources, it was calculated that the emission factor of pruning biomass from vineyards is 89,93 kg CO_2/MWh. On the other hand, as previously mentioned, the SEN from the Ministry of Energy reports an emission factor of 336,32 kg CO_2 eq/MWh for the energy supplied in central Chile. It can be deduced that to produce 1 MWh of energy, 3,7 times more CO_2 is emitted when using the electrical energy from the SEN than when using vineyard pruning material, creating an opportunity to utilize this biomass. In other words, for each MWh of energy obtained from vineyard biomass instead of from the SEN, 246,39 kg CO_2 are prevented from being released into the atmosphere.To propose the use of biomass as an energy source, a diagnosis was made to quantify the volume of biomass that can be recovered from the pruning of various abundant varieties in the Maule Region. The pruning energy potential for each of these crops was calculated with information regarding planted surface, common pruning practices, as well as the specific calorific potential which was compiled from various sources that calculated this value according to standardized procedures for determining solid biofuels. The contribution of each crop for pruning biomass as an energy source in the Maule Region can be seen in Figure 6.

Figure 6: Energy potential contribution from pruning biomass for common crops in the Maule Region

With the gathered information, the potential energy of the biomass was calculated, valued at 453.997 MWh, which is equivalent to 1,47 times the total monthly energy consumption in the Maule Region as reported by the INE. It is proposed to utilize this energy through biomass boilers, allowing water heating and thereby replacing the use of natural gas and fossil fuels, primarily in industrial applications within the wine industry.

Agricultural biomass is a local energy source, available annually and more cost-effective than forest biomass, which is more widely used (Vinyes x Calor, 2017). For efficient biomass use, it is essential to establish close cooperation among farmers, which will allow for greater biomass volume while minimizing both energy costs and emissions associated with its collection. This involves developing efficient routes to collection sites and facilities, which should be strategically located to maximize transport capacity. Cooperation among farmers should also promote technical training and support for best pruning practices, ensuring the collection of high-quality biomass for subsequent processing.

Biogas Production from Winery Industry Waste

The following analysis estimates the biogas potential of the winemaking activity in the Maule Region, considering the vineyard area and the liters of wine produced in the region. To do this, a study conducted in Chile was used to estimate the mass of waste generated from the production of 1 liter of red wine considering that 503.177 thousand liters of wine are produced annually in the Maule Region (ODEPA, 2021). By integrating experimentally determined parameters, it is then possible to calculate methane production associated with the anaerobic digestion of organic matter. For all residues, a methane content of 62,5% in the biogas generated was assumed (Montalvo, et al., 2020). With these parameters and data, it was estimated that 11.166.000 m^3 of CH_4 can be generated annually from this activity.

It is proposed to use the biomethane obtained from anaerobic digestion in a cogeneration process to generate electrical energy. Methane has a calorific value of 9,7 kWh/m^3, and it is estimated that the conversion efficiency for the electrical cogeneration process from biomethane is 80% (Endesa, 2022). The estimated annual potential for electricity generation through the cogeneration process from the winemaking industry in the Maule Region is 86.646 MWh, which, considering a regional energy value of 0,109 €/kWh (State Grid Chile Holding SPA, 2022), equates to a value of 9,4 million euros.

As for the reduction of CO_2 emissions associated with this process, it is estimated that, on average, cogeneration processes from methane have an emission factor of 220 kg CO_2/MWh (Zhang, et al., October 2023). Considering the value reported by the SEN for emissions associated with electricity in central Chile, this strategy of winery waste utilization could reduce annual CO_2 emissions by 10.078 tons.

It is worth adding that the anaerobic digestion process also produces high-quality fertilizers, which can be distributed among local agricultural producers to improve soil quality, partially replacing the use of synthetic fertilizers derived from fossil fuels. The main potential challenges that could hinder the implementation of the project are ensuring a constant supply of high-quality organic matter.

Synergies around agroindustry in the Maule Region

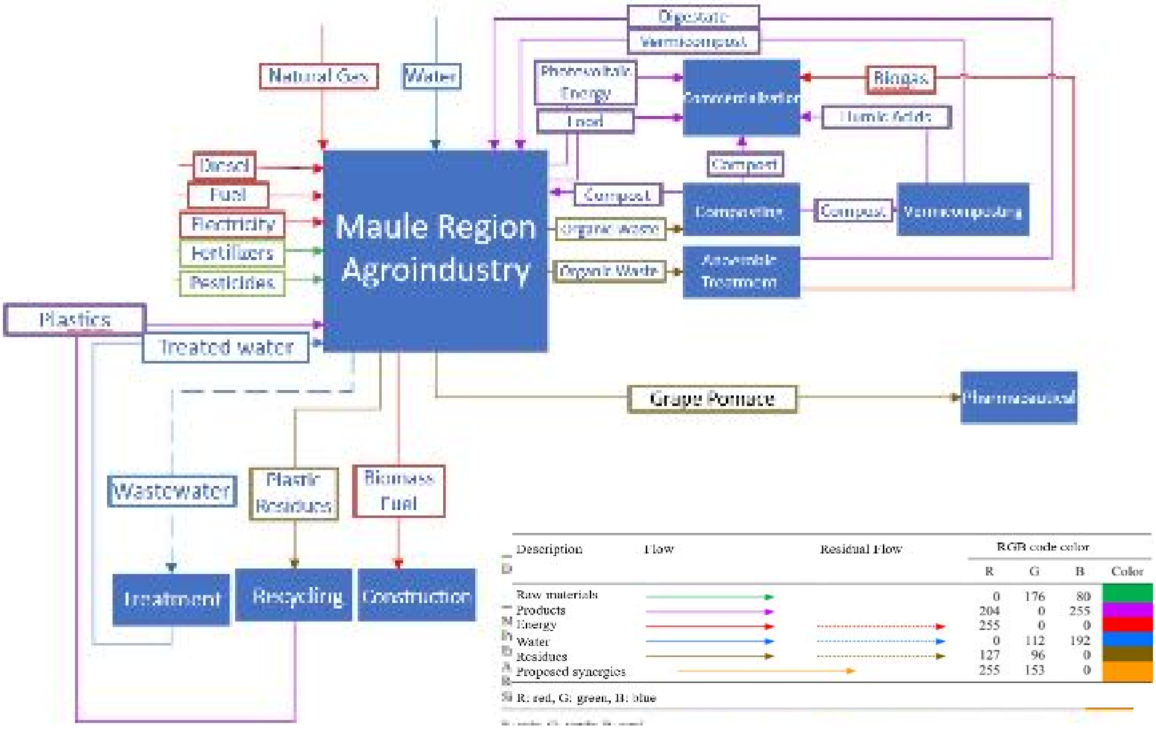
This section analyzes the existing flows related to the agricultural sector of the Maule Region and the synergies with other industries. Similarly, it proposes synergies for the revalorization of waste.

Existing flows and synergies

Agricultural management requires inputs of raw materials, energy, and water for its operations. From agricultural processes, there are many different effluents generated that require management. Established synergies around agroindustry and common crops waste in the Maule Region were identified (Figure 7):

- Organic waste for the production of compost and biogas through anaerobic treatment
- Mature compost used in vermicomposting processes to obtain vermicompost and humic acids
- Combustible biomass for the manufacture of tiles and ceramics in the construction industry
- Plastic waste treated in recycling plants for reconditioning
- Grape pomace used in the pharmaceutical industry

Figure 7: Diagram of existing synergies around agroindustry in the Maule Region



In the synergy diagram, it is observed that the agroindustry of the Maule Region is positioned at the center of numerous material exchange processes, including interactions with other important industries. From the characterized inputs, products for commercialization are produced. These include food for both human and animal consumption, which are the main objectives of the agro-industrial system. Additionally, photovoltaic energy is produced through the installation of panels on agricultural land, generating surpluses that can be commercialized in the national grid system.

Among the organic waste generated, part of it is used in composting and anaerobic treatment processes. Composting, complemented by vermicomposting, produces materials that can be commercialized or recirculated within the agro-industrial system due to their agricultural value. On the other hand, grape pomace is a residue abundantly generated in the wine industry and finds uses in pharmaceuticals due to its bioactive components.

Part of the biomass obtained is utilized as an energy source in the construction sector, for example, in the production of tiles and ceramics. Meanwhile, plastics are recycled and can be reused in agro-industrial processes that require this material.

Proposed synergies

Organic waste in agricultural and agri-food industries is generated across various stages, from harvesting to processing operations, and is characterized by its seasonality. This leads farm managers to seek their quick disposal at the lowest possible cost, either through internal or external solutions. Some residues already have established valorization strategies; however, there are still many underutilized wastes with potential. Below, industrial synergies are proposed for residues that are currently not being properly revalued in the Maule Region (Table 2).

Table 2: Proposals for the revalorization of common agro-industrial residues generated in the Maule Region

Source	Residue	Recovery process	Target Industry	Processed products
Walnuts	Husks	Extraction of juglona	Herbicide Industry	Herbicides (Juglona)
Walnuts	Shells	Ground	Agricultural	Fertilizers, Soil Cover
Olive Oil Industry	Olive pomace	Antioxidant extraction	Pharmacist	Bioactive compounds (antioxidants)
Olive Oil Industry	Olive pomace	Pigment extraction	Cosmetics	Pigments
Hazelnuts	Husks	Prebiotic extraction	Healthcare Industry	Prebiotics
Juice industry	Apple pomace	Incorporation into functional products and manufacture of Apple Flour	Food industry	Snacks, Yogurts, Drinks
Composting	Mature compost	Vermicomposting	Agricultural, Sale	Humic and fulvic acids

In walnut management, prior to nut drying, the hulling process separates the nut from the green husk that covers it. This residue, which represents a significant volume during the post-harvest stage, can be utilized through extraction processes to obtain juglone, a chemical substance with applications in the herbicide industry. On the other hand, walnut shells also have useful characteristics for controlling soil moisture and improving soil quality due to their nutrient content. These shells can be used whole or crushed to enhance nutrient availability.

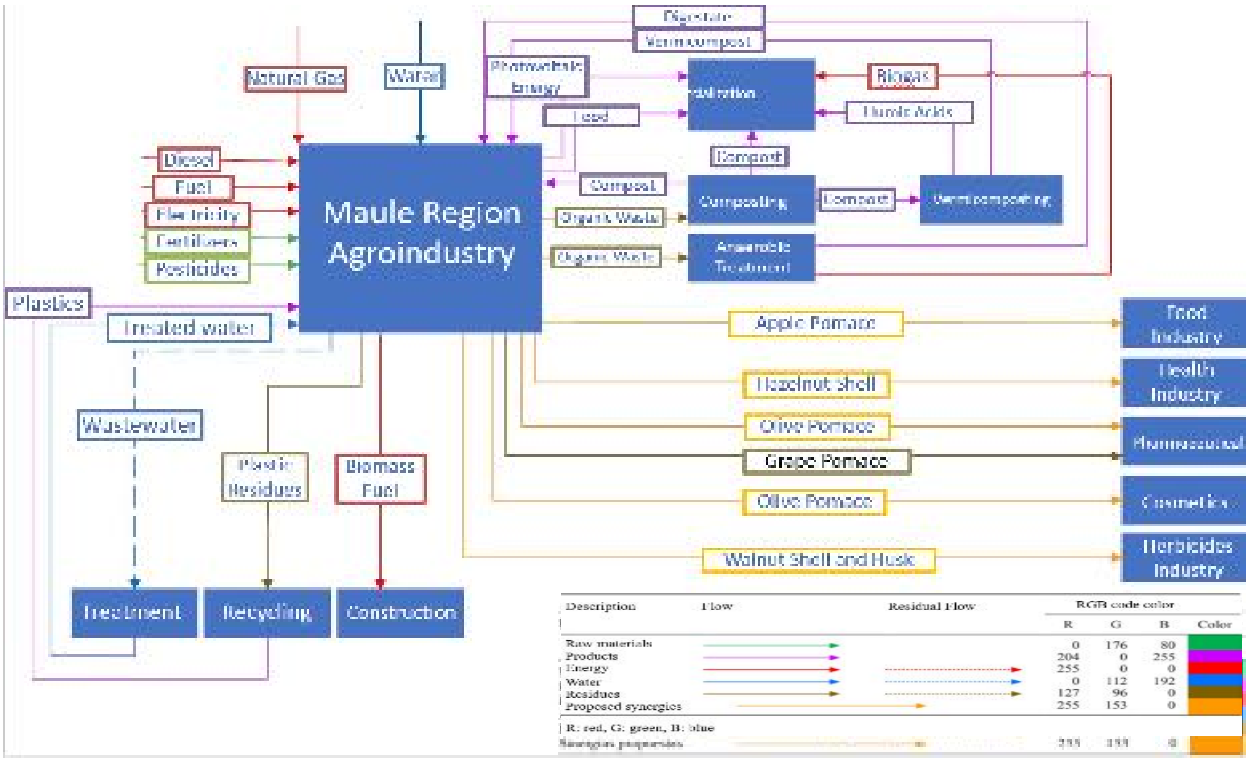
In the case of olive oil production, a byproduct known as olive pomace is obtained, consisting of remnants of pulp, pits, and olive skins. This residue can be valorized through the extraction of bioactive compounds and pigments, which find applications in the pharmaceutical and cosmetic industries. These industries are increasingly interested in integrating natural ingredients associated with good practices into their formulations.

The main waste generated in hazelnut plantations is the shells of the fruit, which are discarded during cleaning and sorting processes. These shells can be processed through extraction techniques to obtain prebiotics, which are used in the health and functional food industries due to their benefits for the gut microbiome.

In the juice industry, waste such as apple pomace is generated during juice extraction and includes pulp, skin, and seeds. This residue can be incorporated into foods like snacks, yogurts, and beverages, taking advantage of its nutrients and characteristic fiber. Through a dehydration process, apple flour can also be obtained, which is a healthy and gluten-free alternative compared to wheat flour.

The establishment of these proposed synergies (Figure 8) creates value from waste that currently mostly end up in landfills or are disposed of informally. Through cooperation and IS, it is possible to generate higher-value-added compounds. At the regional level, this implies greater complexity in the agro-industrial sector, the creation of higher-skilled jobs, and a more competitive industry. In addition to these economic and social benefits, it promotes a more closed-loop material cycle through waste valorization.

<u>Figure 8:</u> Diagram of existing and proposed synergies around the agro-industry of the Maule Region



Sustainable Development Indicators System

The primary function of the agro-industrial system in the Maule Region is to produce food for both domestic and international markets while applying GAP principles. In this context, the proposed system of 34 SD indicators aims to assess the state of the Maule Region's sector regarding the adoption of practices that incorporate sustainability and local development principles. The tables corresponding to the three evaluated aspects—environmental, social, and economic— include the criteria, objectives, themes, and measurement units for each indicator.

Environmental Indicators

The designed environmental indicators (Table 3) are linked to 8 objectives associated with sustainable agricultural management, aligned with some of the most relevant criteria according to GAPs proposed by the FAO (FAO, 2004):

<u>Table 3</u> : Selected Environmental Indicators for Sustainable Development

Environmental Aspects					
nº	Criteria	Objectives	Topics	Indicators	Units
1	Soil Quality Protection	Maintain and improve soil fertility and health	Agricultural Management	Agricultural area with crop rotation	[%]
2			Soil Contamination	Concentration of pesticides and fertilizers in the soil	[mg/kg]
3			Soil health	Deviation of soil organic matter content from the optimum value	[%]
4	Care of the water cycle	Promoting the efficient and sustainable use of water	Water reuse	Percentage of water reuse	[%]
5			Water quality	Levels of nitrates and phosphates in nearby effluents and water bodies	[mg/L]

6	Adoption of sustainable practices	Promoting the transition to sustainable management	Environmental certifications in fruit growing	Percentage of fruit farms (>5 ha.) certified GLOBAL GAP	[%]
7	Protecting biodiversity	Conserve and promote biodiversity	Non-productive zones	Total area of NPZ of native forest over total land	[%]
8			Native species	N° of species and native flora per hectare of NPZ	[#/ha]
9	Air quality	Reduction of emissions into the atmosphere	Reducing emissions from recycling	Reduction of GHG emissions associated with waste recycling	[%]
10			Emissions quantification	CO_2 eq emissions	[kg/year]
11	Transition toward renewable energies	Reduce fossils fuels consumption	Renewable energies	Percentage of energy from renewable sources	[%]
12	Closed material cycles	Minimize residue generation and proper management	Reuse of solid residues	Ratio of solid residues used as raw materials	[%]
13			Recycling solid residues	Ratio of recycled solid residues	[%]
14			Organic residues treatment	Ratio of reused organic residues	[%]
15	Climate change adaptation	Adapt agricultural activity to climate change	Temperature change adaptation	Surface of crops adapted to temperature changes	[%]
16			Transition towards drought resistant varieties	Surface of crops adapted to new precipitation patterns	[%]

The proposed indicators, such as crop rotation, pesticide concentration in the soil, and water reuse, reflect key efforts to maintain soil quality and fertility, as well as to efficiently manage water resources. On the other hand, biodiversity conservation and emission reduction through energy transition are essential for ecological balance and the fight against climate change. As previously discussed, the areas of NPZ occupied by native forests and the number of native species present are important indicators for evaluating conservation efforts and the health of ecosystems surrounding agricultural lands. The Maule Region is home to 27 endemic plant species, while the monitoring of biodiversity by the Integrated Monitoring System of Native Forest Ecosystems (SIMEF) reports 3 critically endangered flora species and 5 critically endangered fauna species in the region.

Social Indicators

The designed social indicators (Table 4) are linked to three objectives and address key aspects for the creation of quality, inclusive jobs that promote individual and community development. As mentioned, agro-industrial activity contributes significantly to the GDP of the Maule Region, while employing 26,2% of the region's workforce. For these reasons, it is crucial that this sector becomes an agent of change toward improving working conditions, promoting education among the population, and fostering social inclusion.

The creation of quality jobs is evaluated based on the percentages of satisfied employees with formal working conditions, which also consider their safety. Providing opportunities for growth for agricultural workers is essential to support the development of local communities. To monitor this, indicators related to training offered by employers and existing opportunities to facilitate access to education are included. Gender parity, inclusion, and support for maternity are also considered measures that contribute to community development and promote equal opportunities among the population.

Table 4 : Selected Social Indicators for Sustainable Development

Social Aspects					
n°	Criteria	Objectives	Topics	Indicators	Units
17	Improving jobs	Improve the quality of life of workers and their families	Satisfaction	Proportion of satisfied employees	[%]
18			Labor rights	Percentage of workers with formal contracts	[%]
19			Occupational safety	Annual rate of occupational accidents per 1,000 workers	N° Accidents*1000 /N° Workers
20			Fair income	Percentage of the average wage of agricultural workers compared to the regional average	[%]
21	Promoting development and education	Provide education and training opportunities for workers	Education and training	Percentage of workers participating in training and training programmes	[%]
22			Access to education programs	Percentage of workers participating in education programs	[%]
23			Best practices	Percentage of jobs created associated with GAP	[%]
24			Education	Worker literacy rate	[%]
25	Promoting inclusion with a gender perspective	Promoting gender equality and social inclusion	Gender equity	Percentage of working women	[%]
26			Inclusion	Number of workers with disabilities	[#]
27			Childcare Support	Percentage of workers with access to childcare services	[%]

Economic Indicators

Table 5 presents the designed economic indicators related to 4 relevant criteria for operational efficiency and the resilience of the agricultural sector in the Maule Region.

Table 5 : Selected Social Indicators for Sustainable Development

Economic aspects					
n°	Criteria	Objectives	Topics	Indicators	Units
28	Obtaining profits from projects with sustainability principles	Obtaining profits from environmental projects	Sale of waste	Proportion of money obtained from the sale of waste wood	[%]
29		Reduce raw material costs	Waste Management	Percentage of money saved by using one's own compost in replacement of fertilizer purchase	[%]
30	Diversification of the economy	Diversifying revenue streams to reduce economic risks	Diversified production	Percentage of farm income from alternative crops	[%]
31			Income from the sale of organic waste	Proportion of money obtained from the sale of organic waste	[%]
32			Energy transition	Percentage of revenue from the sale of electricity from renewable sources	[%]
33	Obtaining profits by reducing consumption	Reduce costs by adopting BPA	Water Use	Percentage of money saved with water-saving projects	[%]
34	Resilience to climate change	Strengthening financial resilience to adverse events	Agricultural insurance	Percentage of agricultural land insured	[%]

With nearly 15% of the regional GDP associated with the agricultural sector and providing a significant number of jobs, it is essential that agriculture establishes long-lasting business models that minimize the risk of the activity regarding unpredictable scenarios.

The implementation of these economic indicators also aims to assign monetary value to GAPs, highlighting the income generated from the sale of residues, the adoption of sustainable management practices, and the energy transition toward non-conventional renewable sources.

At the same time, indicators are proposed to ensure financial resilience. To achieve this, financial and climate risks can be reduced through production diversification and the coverage of farms with insurance against natural risks. In a crisis scenario, these measures could prove crucial for the survival of the sector, also benefiting the local community that depends on these jobs.

Indicator calculation

One indicator for each aspect was calculated to assess the state of the system towards SD.

Among the environmental indicators, No. 6 focuses on calculating the percentage of fruit farms larger than 5 hectares that are certified by GLOBAL GAP, which sets guidelines for good practices aimed at minimizing the sector's environmental impact and ensuring efficient resource use. In the Maule Region, there are 7.800 fruit farms exceeding 5 hectares, of which approximately 1.540 are certified, representing 19,7%. Around 66,4% of the region's fruit production is exported to international markets, therefore, considerable efforts are made to meet international quality standards and expand market opportunities.

Indicator No. 19, focused on the social aspect, aims to assess workplace safety in the agricultural sector to promote higher-quality jobs that prioritize employee well-being. In 2011, the annual occupational accident rate was calculated at 0,88, with 88 severe workplace accidents and 10 fatal incidents reported (Organización Internacional del Trabajo, 2013). Most accidents were related to vehicle incidents and machinery operations. This suggests that this indicator could be improved through promoting responsible driving among workers and providing training programs for machinery operators.

The selected economic indicator for calculation is No. 34, designed to strengthen financial resilience against adverse events, particularly those caused by climate change. The percentage of farms with agricultural insurance was calculated at 8,73%, highlighting the economic and social risk posed by natural disasters. Improving this indicator would require facilitating farmers' access to financing and raising awareness concerning natural hazards.

Conclusions

This work presents an innovative, comprehensive, and systemic vision of the agricultural sector in the Maule Region, aiming to create proposals for GAP based on sustainability, IE and CE principles to address the challenges identified through the characterization of the region. Additionally, it proposes a monitoring system using indicators to measure progress toward the proposed SD goals. Agriculture plays a key role in job creation and is also an economic driver, accounting for 15,44% of the Maule Region's GDP. However, this activity involves high water consumption, negatively impacts regional biodiversity, and generates waste-related issues. Furthermore, the high vulnerability of the region and the sector to changes in temperature and precipitation requires significant measures. Through the implementation of GAPs, it is essential to promote energy transition, protect biodiversity, manage waste properly, and encourage adaptation to climate change.

This work designed an intelligent decision-support system through an influence diagram that enables the implementation of an integrated composting and vermicomposting management plan, considering key decisions and events that influence desired outcomes. This graphic representation serves as an intuitive tool to support informed decision-making and generate efficient management strategies. By implementing NPZs on agricultural lands, it is possible to protect local flora and fauna, including endemic species. Allocating 4% of irrigated agricultural land to NZP could increase native forest areas by 65% compared to the hectares currently conserved by CONAF in the region. These spaces would play a crucial role for regional species, distributing across much of the territory and acting as biodiversity corridors for species.

To promote regional energy transition, the evaluation of photovoltaic panel performance demonstrated that these systems are viable to be incorporated in irrigation structures. In addition to their economic benefits, with even more promising prospects due to increasing solar radiation in the region, their implementation was calculated to reduce emissions by 291,32 kg CO_2/MWh of consumption compared to energy supplied by the SEN.

On the other hand, the emission factor calculated for the use of biomass as a fuel source estimates that SEN's electrical energy emits 3,7 times more CO_2 than vineyard pruning material to produce 1 MWh, making it a management strategy of interest to mitigate the environmental impact of the agricultural sector.

Regarding biogas generation from the wine industry through anaerobic digestion with an electrical cogeneration process, it was calculated that this strategy could reduce CO_2 emissions and contribute to the resilience of the Maule Region. However, implementing these systems requires significant investment and ensuring continuous sources of organic matter, suggesting the establishment of close logistical and financial cooperation networks for their implementation.

The organic waste generated by the agro-industry in the Maule Region offers significant opportunities for incorporation into other industries through IS, promoting the creation of added value, moving towards closed-loop material cycles, and reducing raw material consumption in the system.

Thirty-four SD indicators were designed, from which proposals for improvement can be generated. Defined strategies must be established to identify trends over time and facilitate decision-making and corrective measures. The three calculated indicators reveal key challenges in the agricultural sector, including environmental certification gaps, workplace safety risks, and financial vulnerability to climate-related events. Addressing these issues requires stronger policies, targeted training, and improved access to financial support. Enhancing these aspects will contribute to a more sustainable and resilient agricultural system.

Future work should focus on obtaining experimental results to validate and replace the theoretical values obtained through non-specific bibliographic research for the Maule Region, which were used in the calculations in this report. The proposals generated in this report can create benefits for both the environment and local communities and were developed with careful consideration of ethical implications and their potential consequences.

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Circular Economy and Health Outcomes: An Analysis for the EU

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Abstract : Circular economy (CE) plays a crucial role in the European Union's sustainable development goals, focusing on maximizing resource efficiency and waste recycling. Despite its significance, the impact of CE practices on health outcomes such as healthcare expenditures and life expectancy has been insufficiently examined in academic research. This study aims to evaluate how CE practices affect public health and healthcare expenditures in 27 EU countries over the period between 2013- 2022. Both short- and long-term effects are explored, while controlling for circular economy practising variables. Findings suggest that improvements in waste treatment for circularity and emission reductions affect lower healthcare costs and better health outcomes. On the other hand, study identified that CE practices do not generate a positive long-term impact on life expectancy. This finding does not support the view that waste management would produce favourable effects on health outcomes. The study emphasizes the still need to redesign circular economy policies to account for the negative health impacts of waste management. Furthermore, it highlights the importance of region-specific policies tailored to the unique contexts of EU countries to mitigate health risks and improve long-term health outcomes.

Introduction

The European Union's (EU) effort to enhance circularity and become more sustainable has led to the creation of the Green Deal, which aims to achieve net-zero greenhouse gas (GHG) emissions and carbon neutrality by 2050 while protecting human health In line with this goal, EU countries have committed to achieving at least a 55% reduction in emissions by 2030 compared to the levels recorded in 1990 Transitioning to the Circular Economy (CE), recognized as a new and innovative paradigm, holds significant promise as a viable solution to actively support the Sustainable Development Goals (SDGs) and address environmental challenges arising from the healthcare sector. Within this economic framework, the primary focus is on reducing resource consumption and managing environmental impacts. (European Council, 2029; D'Alessandro et al, 2024)

One of the key requirements for achieving sustainability is the transition to a CE (Schröder, et al, 2020). CE is an interdisciplinary concept that aims to combine ecological well-being with financial growth, providing a framework for sustainable ecological development.

The adoption of Circular Economy (CE) strategies within the healthcare sector serves as a proactive measure against escalating environmental challenges. CE focuses on minimizing pollution and waste while fostering economic benefits by promoting the efficient and sustainable use of resources (Demirel and Danisman, 2019).. Additionally, CE plays a crucial role in aligning economic progress with sustainability objectives. Through the reduction and recycling of natural resource consumption, it establishes a resilient and profitable economic model that reduces dependency on finite resources (Corona et al., 2019).

Transitioning to CE involves mitigating the environmental impact of production processes and maximizing the reuse and recycling of materials. Consequently, the healthcare sector, along with other institutions, has the capacity to actively contribute to the advancement of environmentally friendly policies. The transition to a circular model holds the potential to decouple economic development from resource consumption, paving the way for more sustainable healthcare operations.

In the healthcare sector, the shift towards a Circular Economy (CE) necessitates the adoption of innovative production and operational practices that minimize environmental impacts. These practices include the development of products designed for durability and recyclability, the reduction of single-use materials, and the implementation of waste management systems that prioritize recycling and resource recovery. Furthermore, raising consumer awareness and promoting sustainable behaviors are critical for the successful implementation of CE principles.

As a sector that significantly contributes to environmental pressures, healthcare is uniquely positioned to provide exemplary leadership in advancing environmentally friendly policies. Through the integration of CE strategies, the sector can play a pivotal role in achieving global sustainability goals, enhancing ecological balance, and safeguarding public health for future generations. By embracing a circular approach, healthcare can transform its operations to align with sustainability objectives, ensuring both environmental stewardship and long-term economic viability.

Aspect of the health impacts of CE transition

The health impacts of transitioning to a CE have received limited attention in the development of CE strategies, visions, action plans, and policy initiatives. It is not uncommon for health-related considerations to be overlooked at these early stages; similar trends have been widely observed in other sectors such as transportation, waste management, energy, and emissions.

This delay often stems from the longer time frame required for health effects to become visible or from an insufficient understanding of the complexity of health-related impacts. Policymakers may prioritize environmental and economic benefits while overlooking the positive or negative consequences for public health. However, it is now more widely recognized that circular economy practices have the potential to improve societal health. For instance, reducing resource use, improving waste management, lowering greenhouse gas emissions, and adopting cleaner production processes can positively impact both environmental sustainability and public health.

Today, health-related considerations play a much more prominent role in policymaking and decision-making processes across many sectors, including the circular economy. Fischer et al. (2010) noted, effectively integrating health factors into decision-making mechanisms is a critical element in achieving sustainable development goals. Therefore, incorporating the health dimension into circular economy strategies from the early stages can help maximize long-term benefits. Such a holistic approach would be a significant step toward achieving both environmental and societal sustainability.

The WHO European Regional Office, in its 2018 report, developed a conceptual framework to categorize pathways through which human health and well-being may be influenced. This framework serves as a tool to identify the current and potential positive and negative health impacts of circular economy models and processes, analyze the economic sectors most affected, and address distributional issues. Emphasis was placed on the effects experienced by vulnerable populations. The assessment provided a comprehensive overview of health impacts associated with the healthcare sector, the built environment, and the food industry. The report highlighted that the magnitude and presence of these impacts are highly context-specific and that research in this field remains limited in scope. Consequently, there is an urgent need for robust and systematic investigations to evaluate the quality and breadth of existing evidence on the health implications of circular economy practices and to bridge critical knowledge gaps (WHO, 2018; WHO,2019).

Positive aspects of CE practices

When assessing the positive impacts of circular economy (CE) practices, several significant health benefits can be identified. The reduction in the use of primary resources, the preservation of the highest value of materials and products (achieved through the recycling and reuse of products, components, and materials), and the transition toward renewable energy sources and enhanced energy efficiency collectively hold the potential to generate substantial improvements in public health outcomes. Specifically, these practices contribute to mitigating the environmental impacts of manufacturing processes by improving air, water, and soil quality and reducing greenhouse gas (GHG) emissions. Such environmental improvements, when combined with cost savings in the health sector, can result in comprehensive and tangible benefits (WHO,2019).

Furthermore, shifts in utilization patterns present additional opportunities for advancing health outcomes. For example, integrating performance-based procurement models within the healthcare system could drive efficiency while simultaneously fostering health-related advantages.

Negative aspects of CE practices

Potential adverse health effects are associated with risks arising from the processes of recycling and reusing products, components, and materials. These risks are particularly linked to the challenges of managing chemical substances, such as bisphenol A (BPA) and brominated flame retardants (BFRs), present in various products.

Adverse impacts often disproportionately affect disadvantaged groups. However, the potential of circular economy practices to reduce global environmental pollution could provide significant long-term health benefits for these populations. Vulnerable groups, being more affected by environmental impacts, could positively benefit from the enhanced environmental sustainability promoted by the circular economy (WHO,2019).

Nevertheless, there is a notable lack of knowledge regarding the nature of adverse effects, particularly those related to hazardous chemicals. Therefore, comprehensive research and robust evidence are essential to better understand and mitigate these effects while simultaneously strengthening the positive impacts. Such knowledge will play a critical role in guiding policy development processes.

The transition to a circular economy (CE) presents a significant opportunity to contribute to achieving the Sustainable Development Goals (SDGs) by delivering substantial health benefits. However, this transition also carries the risk of unintended negative health impacts, particularly in processes related to the management of hazardous substances. Therefore, it is crucial to incorporate the health dimension more comprehensively into CE strategies, action plans, and other policy initiatives.

Screening: Key Questions and Approaches

In the preliminary studies conducted by the World Health Organization, the screening stage aims to identify the potential health impacts of a proposed Policy, Plan, Program, or Project and to determine whether a full Health Impact Assessment (HIA) or other types of health-inclusive assessments are necessary. According to this approach, the key questions for screening the potential human health impacts of a Circular Economy-related Policy, Plan, Program, or Project (PPPP) have been addressed quite broadly. However, the core questions that emerge from this can be listed as follows in terms of identifying the impacts:

Identification of Impacts

- Are there possible direct human health impacts of a CE action?
  Includes direct positive or negative impacts on public and occupational health, mental health, and well-being, such as changes in exposure to harmful chemicals.

- Are there possible indirect human health impacts of a CE action?
  Includes indirect impacts via changes in social, economic, and environmental conditions, such as improved air quality due to reduced emissions or better food choices.
- Are there possible direct impacts on the health care sector?
  Includes changes in demand for health and social care services or sector costs, such as savings from sharing platforms in health care.

On the other hand, the core questions that arise from this can be listed as follows in terms of the nature and likely significance of impacts.

Nature and Likely Significance of Impacts

- Will the health impact have differential effects within the population?
  How many people will be affected, and will certain socioeconomic groups, particularly vulnerable ones, be disproportionately impacted?
- Will the negative health impacts be difficult to remedy or have an irreversible effect?
  Consider the type of health impacts (acute, chronic, terminal) and the potential for mitigation.
- Will the health impacts be short-, medium-, or long-term?
  Evaluates the duration and timing of positive or negative impacts.
- Are the negative health impacts likely to generate public concern?
  Consider whether identified impacts could lead to widespread public worry or opposition.

All stages involve the identification of possible pathways (both direct and indirect) that could lead to impacts on human health.

Bridging the Gap: Role of Technology in CE and Health

The transition to circularity is closely linked to digital transformation, as circular practices require the collaboration of human creativity and expertise with smart and precise technologies. Circular economy applications demand innovative designs and processes that incorporate technological advancements to maximize their impact on human health and well-being (Javaid et al., 2024).

For circular economy practices to make meaningful contributions to public health, they must be supported by technology-driven solutions that enhance efficiency, sustainability, and scalability. Eco-innovation, which focuses on fostering new developments in production and technology, plays a vital role in preserving environmental management. This approach aims to mitigate environmental risks, such as pollution and the overuse of resources, while addressing the negative consequences of unsustainable practices. By leveraging digital tools and eco-innovative approaches, circular economy initiatives can achieve significant progress in reducing environmental harm while promoting sustainable development (Takalo and Tooranloo, 2021). The synergy between technology and circularity not only improves resource efficiency but also amplifies the potential for positive health outcomes. This highlights the critical importance of integrating technological solutions into the core of circular economy strategies.

The technology-driven nature of circular economy practices makes these strategies more feasible for high-income countries. High-income countries have easier access to advanced digital infrastructure, technological innovations, and financial resources to support eco-innovations. Furthermore, both the public and private sectors in these countries possess the expertise and institutional capacity required for the implementation of circularity-focused policies. On the other hands, there is limited understanding of what the CE means for low and medium countries, consequently there is a paucity of research that analyses the potential impacts of CE on human health (Wright et al, 2019). The main reason for this is the difficulty in integrating the necessary economic resources and technological development capacity for CE in these countries. The low- and middle-income countries face challenges such as inadequate digital infrastructure, limited financial resources, and a lack of technological knowledge, which can hinder the adoption of circular economy strategies. Therefore, capacity-building initiatives and technology transfer are critical to ensuring an equitable transition on a global scale.

Therefore, it is of great importance to examine the potential impacts of circular economy practices on health outcomes from the perspective of developed countries. European Union (EU) member states provide an ideal case for such analysis, given their advanced healthcare systems, commitment to environmental sustainability goals, and policies aligned with circular economy strategies. This study aims to pave the way for an empirical approach to analyzing the effects of circular economy practices adopted within the framework of the Green Deal on health outcomes in EU member states.

Sustainable Development and Circularity- Limited Health Research

The extensive research is being conducted on the methods for transitioning to circular economy (CE) business models (Elia et al., 2017; Schroeder et al., 2019;). The primary objective of these studies is to transform the linear business model based on the production-consumption-waste cycle into a more sustainable structure characterized by make-use-reuse-remanufacture-recycle (Mhatre et al., 2021). The Organisation for Economic Co-operation and Development (OECD) has proposed four main CE business models: 1) circular supply models, using renewable energy (RE) instead of raw materials; (2) resource recovery models, recycling waste into secondary raw materials; (3) product life extension, repairing and remanufacturing products instead of throwing them away; and (4) sharing models, reducing demand for new products and raw materials through sharing and second-hand principles (OECD, 2018).

The effects of these business models on economic development have been addressed in different studies in the literature for each model. However, it is quite challenging to find experimental studies that directly address health impacts. Nevertheless, it can be argued that if the results of such studies generate positive externalities in development, they could indirectly contribute to improvements in health.

Non-renewable energy sources contribute to greenhouse gas (GHG) emissions, exacerbating global warming (Venkatraja, 2020). Renewable energy (RE) sources play a critical role in both reducing CO2 emissions and achieving sustainable development (Lee, 2019). The decline in RE production costs has made these sources economically more attractive (Sadorsky, 2012). Studies show that RE consumption can have positive, negative, or no impact on economic growth (Fang, 2011). In Europe, RE demonstrates a strong relationship with economic growth and CO2 emissions (Lee, 2019).

Sharing and second-hand policies have significant potential to extend product lifespans and address issues such as overconsumption and income inequality (Mhatre et al., 2021). The rise of online platforms has facilitated the reuse, borrowing, and renting of goods, contributing to sustainable development (Tukker et al., 2016; Plewnia and Guenther, 2018).

Repair and remanufacturing are essential practices in the (CE) aimed at extending product lifespans and preserving resource value. Repair prevents the disposal of products by replacing defective components, while remanufacturing restores products to their original condition using reused parts These processes enhance resource efficiency, reduce environmental impacts, and lower costs by minimizing resource extraction and waste generation. They also decrease CO2 emissions and the need for raw materials. (Hunka et al., 2021). Moreover, these practices can provide indirect health benefits by improving air quality through cleaner production processes.

However, the management of potential hazardous chemicals in reused materials must be carefully addressed due to associated health risks.

Recycling, as a fundamental component of the CE, reduces primary resource extraction and closes the loop by collecting, sorting, and transforming waste materials into new products. Recycled raw materials are particularly beneficial for resource demand reduction in countries dependent on imports (Kostakis and Tsagarakis, 2022a). While recycling is the most widely adopted CE strategy, it is considered the least sustainable due to issues such as increased energy consumption and low-quality recycling. Its impact on economic growth is complex, showing variability depending on context, despite positive contributions in some cases (Razzaq et al., 2021; Guoyan et al., 2022). Therefore, in CE practices, the potential health impacts of recycling models should be interpreted with greater attention compared to other CE models.

Developing countries are the regions with the greatest need for innovative approaches that reduce pollution and waste, enhance health and quality of life, and simultaneously support economic growth and the creation of decent job opportunities. However, research in these areas remains quite limited. Pioneering studies conducted in the context of international development have revealed that circular economy practices have the potential to generate employment, reduce environmental pollution, and save lives in low- and middle-income countries (Gower and Schröder, 2016).

Data and Methodology

Dataset

This study addresses the existing knowledge gap regarding the impact of CE practices on health in the European Union, providing a comprehensive evaluation of the short- and long-term effects of these practices on health outcomes. The European Union has been selected as the focal point of this study due to its pioneering approach to adopting Circular Economy policies on a global scale. The EU's high standards in environmental sustainability and resource management provide an ideal context for analyzing the potential health impacts.

In this study, conceptual relationships are modeled using empirical methods and supported by robust scientific data. With the aim of contributing to literature, the study seeks to concretely demonstrate the effects of CE practices on health outcomes.

The study utilizes a panel dataset from Eurostat (2013–2022) covering 27 EU countries, including variables such as health expenditures, life expectancy, GDP per capita, and Circular Economy (CE) practices. All variables have been log-transformed to ensure consistency and improve interpretability. Detailed information is presented in Table 1.

As dependent variables: HEX: Current healthcare expenditure quantifies the economic resources dedicated to health functions, excluding capital investment as million Euro. LIFE: Life expectancy at a certain age is the mean additional number of years that a person of that age can expect to live, if subjected throughout the rest of his or her life to the current mortality conditions (age-specific probabilities of dying, i.e. the death rates observed for the current period).

As independent variables:

Gross Domestic Product (GDP) per capita at market prices represents the final per capita income resulting from the production activities of resident producer units within an economy, expressed in euros.

OLD: The proportion of the population aged 65 and over is defined as the percentage share of individuals aged 65+ within the total population.

WAST: Total waste treatment- Management of waste by waste management operations and type of material - Disposal - incineration- Recovery - backfilling, recycling (has been calculated in thousands of tonnes and visualized through Sankey diagrams, illustrating material flows within the EU economy, their discharge into the environment, or reintegration into economic processing. The data is based on Regulation (EC) No. 2150/2002, categorizing waste treatment as recovery or disposal by material type.

GHE: Total greenhouse gases emissions from production activities, kilogram per capita. The indicator tracks greenhouse gas emissions from production activities, excluding households, covering CO2, N2O, CH4, and fluorinated gases.

WIM: Material flows for the circular economy, including total imports of waste for recycling, have been calculated in thousand tonnes using waste statistics, trade data, and EW-MFA (Economy-Wide Material Flow Analysis) under EU regulations.

WEX: Material flows for the circular economy, including total exports of waste for recycling, have been calculated in thousand tonnes using waste statistics, trade data, and EW-MFA (Economy-Wide Material Flow Analysis) under EU regulations.

Table 1: Dataset and Definitions

Variable	Definition	Measurement	Resource
HEX	Current total health care expenditure	Million Euro	Eurostat
LIFE	Life expectancy at birth	Year	Eurostat
GDPp	Gross domestic product at market prices	Current prices, Euro per capita	Eurostat
OLD	The proportion of the population aged 65 and over	% share of the total population	Eurostat
WAST	Total waste treatment, material management operations (Disposal - incineration- Recovery - backfilling, recycling)	Thousand tonnes	Eurostat
GHE	Total greenhouse gases emissions from production activities	Kilograms per capita	Eurostat
WIM	Material flows for circular economy-Total imports of waste for recovery - recycling	Thousand tonnes	Eurostat
WEX	Material flows for circular economy-Total imports of waste for recovery - recycling	Thousand tonnes	Eurostat

Table 2: Descriptive Statistics

	Variables							
	HEX	**LIFE**	**GDPp**	**OLD**	**WAST**	**GHE**	**WIM**	**WEX**
Mean	48177.4	76.9	30184.7	18.8196	65649.9	7694.98	4583.45	4399.09
Std. Dev.	85174.9	3.70	20691.6	1.90109	82305.2	2963.29	5448.49	5986.02
Max	465855	81.5	118310	24.6	335216	17544.4	21733	26580

Min	795.04	68	5790	14.2	875	3620.33	15	57
Skewness	0.2050	0.000	0.2459	0.0416	0.1710	0.0049	0.0000	0.0296
Kurtosis	0.0000	0.000	0.0972	0.6441	0.0000	0.0036	0.0015	0.3114
Num. Obs.	270	270	270	270	270	270	270	270

Table 2 shows the descriptive statistics of variables. The mean healthcare expenditure (HEX) is €48,177.4 million, with a standard deviation of €85,174.9 million, highlighting significant disparities across countries. The life expectancy (LIFE) has an average of 76.9 years, with a standard deviation of 3.7 years, and values spanning between 68 and 81.5 years, indicating moderate variability.

GDP per capita (GDPp) averages €30,184.7, with a standard deviation of €20,691.6, ranging from €5,790 to €118,310, which reflects substantial economic differences across EU countries. The proportion of the population aged 65 and over (OLD) has a mean of 18.8%, with relatively low variability, ranging between 14.2% and 24.6%. Waste treatment (WAST) demonstrates significant variability, with a mean of 65,649.9 thousand tonnes and values ranging from 875 to 335,216 thousand tonnes. Greenhouse gas emissions (GHE) have a mean of 7,694.98 kilograms per capita. Circular economy indicators, including waste imports (WIM) and exports (WEX) for recycling, average 4,583.45 and 4,399.09 thousand tonnes.

Furthermore, the variables used in the dataset, skewness values are close to zero, indicating that the distributions are nearly symmetric. Similarly, kurtosis values suggest relatively normal distributions without extreme outliers.

Modelling

In the study, the Autoregressive Distributed Lag (ARDL) method was used to measure the impact of circular economy practices on health expenditures and life expectancy at birth in the short and long term.

The Autoregressive Distributed Lag (ARDL) method is employed to analyze short- and long-term relationships, leveraging its ability to handle both stationary and non-stationary data. Findings aim to guide sustainable, health-focused policy development, enhance healthcare efficiency, and contribute to global sustainability efforts. The ARDL approach, which has asymptotic properties, provides estimates for both stationary and non-stationary series. The ARDL approach enables us to estimate the model with I(0) and I(1) variables. Therefore, there is no need that variables should be stationary at the same level in the ARDL approach. Since the results of health indicators and environmental variables will emerge in the long term, it is possible to better reveal the effects on health expenditures with the ARDL method.

The Pooled Mean Group (PMG) estimator has been used in the study. The PMG model is an important version of the ARDL approach, also the PMG model estimates with likelihood at maximum level (Zaidi and Saidi 2018).

The four different econometric model specifications are presented as follows equations.

The following models are specified with health expenditure as the dependent variable in equations 1-4.

$$\Delta HEX_{it} = \alpha_i + \sum_{j=1}^{m-1} \beta_{ij}\Delta HEX_{i,t-j} + \sum_{l=0}^{n-1} \varphi_{il}\Delta GDPp_{i,t-l} + \sum_{r=0}^{p-1} \gamma_{ir}\Delta OLD_{i,t-r} + \sum_{u=0}^{s-1} \theta_{iu}\Delta W \quad (1)$$

$$\Delta HEX_{it} = \alpha_i + \sum_{j=1}^{m-1} \beta_{ij}\Delta HEX_{i,t-j} + \sum_{l=0}^{n-1} \varphi_{il}\Delta GDPp_{i,t-l} + \sum_{r=0}^{p-1} \gamma_{ir}\Delta OLD_{i,t-r} + \sum_{u=0}^{s-1} \theta_{iu}\Delta WIM_{i,t-u} + \sigma_1 HEX \quad (2)$$

$$\Delta HEX_{it} = \alpha_i + \sum_{j=1}^{m-1} \beta_{ij}\Delta HEX_{i,t-j} + \sum_{l=0}^{n-1} \varphi_{il}\Delta GDPp_{i,t-l} + \sum_{r=0}^{p-1} \gamma_{ir}\Delta OLD_{i,t-r} + \sum_{u=0}^{s-1} \theta_{iu}\Delta WEX_{i,t-u} + \sigma_1 HEX \quad (3)$$

$$\Delta HEX_{it} = \alpha_i + \sum_{j=1}^{m-1} \beta_{ij}\Delta HEX_{i,t-j} + \sum_{l=0}^{n-1} \varphi_{il}\Delta GDPp_{i,t-l} + \sum_{r=0}^{p-1} \gamma_{ir}\Delta OLD_{i,t-r} + \sum_{u=0}^{s-1} \theta_{iu}\Delta GHE_{i,t-u} + \sigma_1 HEX_i \quad (4)$$

The following models are specified with life expectancy at birth as the dependent variable in equations 5-8:

$$LIFE_{it} = \alpha_i + \sum_{j=1}^{m-1} \beta_{ij}\Delta LIFE_{,t-j} + \sum_{l=0}^{n-1} \varphi_{il}\Delta GDPp_{i,t-l} + \sum_{r=0}^{p-1} \gamma_{ir}\Delta OLD_{i,t-r} + \sum_{u=0}^{s-1} \theta_{iu}\Delta W \quad (5)$$

$$\Delta LIFE_{it} = \alpha_i + \sum_{j=1}^{m-1} \beta_{ij}\Delta LIFE_{i,t-j} + \sum_{l=0}^{n-1} \varphi_{il}\Delta GDPp_{i,t-l} + \sum_{r=0}^{p-1} \gamma_{ir}\Delta OLD_{i,t-r} + \sum_{u=0}^{s-1} \theta_{iu}\Delta WIM_{i,t-u} + \sigma_1 HE \quad (6)$$

$$LIFE_{it} = \alpha_i + \sum_{j=1}^{m-1} \beta_{ij}\Delta LIFE_{i,t-j} + \sum_{l=0}^{n-1} \varphi_{il}\Delta GDPp_{i,t-l} + \sum_{r=0}^{p-1} \gamma_{ir}\Delta OLD_{i,t-r} + \sum_{u=0}^{s-1} \theta_{iu}\Delta WEX_{i,t-u} + \sigma_1 HEX \quad (7)$$

$$\Delta LIFE_{it} = \alpha_i + \sum_{j=1}^{m-1} \beta_{ij}\Delta lfe_{i,t-j} + \sum_{l=0}^{n-1} \varphi_{il}\Delta GDPp_{i,t-l} + \sum_{r=0}^{p-1} \gamma_{ir}\Delta OLD_{i,t-r} + \sum_{u=0}^{s-1} \theta_{iu}\Delta GHE_{i,t-u} + \sigma_1 HEX_{i,} \quad (8)$$

The study is based on Pesaran et al. (1999) PMG estimator, which is associated with pooling and averaging of coefficients over cross-sectional data. The PMG estimator enables us to examine long-term homogeneity without parameter homogeneity in the short term (Pesaran et al. 1999).

In this study, the potential impact of cross-sectional dependence on the results of panel regression analysis was taken into consideration. To detect cross-sectional dependence, the Pesaran CD test, developed by Pesaran (2004) and commonly used in panels with a short time series dimension (t<n), was employed. The Pesaran CD test was specifically applied to identify cross-sectional dependence within the dataset. Table 3 shows the results of the test. All variables demonstrate significant cross-sectional dependence (p-value = 0.000), which suggests a common factor or correlation across countries. This result highlights the need to consider methods that account for such dependence, like panel models with cross-sectional dependence adjustments, to avoid biased estimates in the analysis.

Tablo 3: Pesaran CD test

Variables	CD-test	p-value
HEX	54.83	0.000
LIFE	26.49	0.000
GDPp	55.63	0.000
OLD	57.22	0.000
WAST	4.60	0.000
GHE	27.76	0.000
WIM	13.90	0.000
WEX	18.73	0.000

The cross-sectionally Augmented Dickey-Fuller (CADF) test was used to examine the stationarity of the series in panel datasets while accounting for cross-sectional dependence. Considering that traditional unit root tests can produce misleading results in the presence of cross-sectional dependence, the CADF test was preferred. Table 4 shows the unit root test results.

Table 4: Pesaran's CADF test

	Pesaran's CADF test	
Variables	t-bar (at level)	t-bar (diffecences)
HEX	-1.813	-1.988*
LIFE	-1.922	-3.384***
GDPp	-1.434	-1.885 *
OLD	-1.516	- 2.085 **
WAST	-2.139**	-1.484
GHE	-2.428***	-3.074**
WIM	-1.712	-1.956 *
WEX	-2.364***	-1.902

Note: *, **, *** denoted as significance at level 10%, 5%, and 1%

Results

Table 5 presents the results of the Panel ARDL model, analyzing the long-run and short-run effects of explanatory variables, including circular economy practices, on healthcare expenditure (HEX) across four different model specifications.

Long-Run Effects

In all models, GDP per capita (GDPp) is positively associated with healthcare expenditure in the long run, with significant coefficients in Models 1, 3, and 4. The strongest effect is observed in Model 4 ($\beta=0.9284$, $p<0.001$), indicating that a 1% increase in GDP per capita is associated with approximately a 0.93% increase in healthcare expenditure. However, in Model 2, GDPp is not statistically significant (p=0.410).

The proportion of the population aged 65 and over (OLD) consistently exhibits a positive and significant relationship with healthcare expenditure across all models. The highest coefficient is found in Model 2 (β=2.0122, p<0.001), suggesting that aging populations are a key driver of healthcare costs.

For the circular economy practicing variables, the effects vary across models. Waste treatment (WAST) and waste exports (WEX) have significant negative impacts on healthcare expenditure in Models 1 and 3, respectively. Conversely, waste imports (WIM) and greenhouse gas emissions (GHE) show positive and significant effects in Models 2 and 4, respectively.

Short-Run Effects

GDP per capita remains positively associated with healthcare expenditure in the short run, with statistically significant coefficients in all models except Model 2. The strongest short-run effect is observed in Model 3 (β=0.6597, p=0.001).

The proportion of the elderly population (OLD) does not have a statistically significant short-run effect in any model, indicating that the influence of demographic aging may manifest more prominently in the long run.

For the circular economy practicing variables, including waste treatment (WAST), waste imports (WIM), waste exports (WEX), and greenhouse gas emissions (GHE), show no significant short-run effects, except for GHE in Model 4 (β=−0.3213, p<0.001), which suggests a short-term negative impact on healthcare expenditure.

In the short run, the Error Correction Model (ECM) term is negative and statistically significant in Models 2 and 4, confirming the adjustment mechanism toward long-run equilibrium. The magnitude of the ECM terms suggests that deviations from the equilibrium are corrected more rapidly in Model 2 (ECM=−0.2195, p<0.001) than in Model 4 (ECM=−0.1541, p<0.001).

In the short term, the faster equilibrium adjustment mechanism observed in Model 2 suggests that reducing the proportion of the elderly population and minimizing waste imports play a more critical role in lowering healthcare expenditures. Conversely, in the long term, the slower adjustment mechanism identified in Model 4 emphasizes the importance of implementing measures aimed at reducing greenhouse gas emissions to achieve sustainable equilibrium in healthcare expenditures

Table 5: Panel ARDL Model Results- Effects on Health Expenditure

Dependent variables : HEX							
Model 1		Model 2		Model 3		Model 4	
Long-run Results		***Long-run Results***		***Long-run Results***		***Long-run Results***	
GDPp	.7719 (0.000)	GDPp	.0924 (0.410)	GDPp	.8010 (0.000)	GDPp	.9284 (0.000)
OLD	1.233 (0.000)	OLD	2.0122 (0.000)	OLD	1.1302 (0.000)	OLD	0.9192 (0.000)
WAST	-1.0427 (0.000)	WIM	.4895 (0.000)	WEX	-0.9001 (0.000)	GHE	-.4895 (0.000)

Short- run Results		***Short- run Results***		***Short- run Results***		***Short- run Results***	
ECM	-.2289 (0.199)	ECM	-.2195 (0.000)	ECM	-.2289 (0.199)	ECM	-.1541 (0.000)
GDPp	.3572 (0.010)	GDPp	.1485 (0.065)	GDPp	.6597 (0.001)	GDPp	.2855 (0.005)
OLD	-1.0241 (0.272)	OLD	-1.2204 (0.080)	OLD	-0.8111 (0.5431)	OLD	-.9201 (0.120)
WAST	-.05826 (0.315)	WIM	-.03310 (0.490)	WEX	-.0260 (0.432)	GHE	-.3213 (0.000)
Cons.	1.0790 (0.150)	Cons.	-.0742 (0.434)	Cons.	1.3219 (0.012)	Cons.	0.9574 (0.031)

Table 6 presents the results of the Panel ARDL model, analyzing the long-run and short-run effects of explanatory variables, including circular economy practices, on life expectancy at birth (LIFE) across four different model specifications.

Long-Run Effects

GDPp consistently shows a negative and statistically significant relationship with life expectancy (LIFE). This suggests that higher GDP per capita, potentially due to factors such as industrialization or economic activities associated with health risks, might have an indirect negative impact on life expectancy in the long run. Model 4 exhibits the strongest negative impact of GDPp ($\beta = --0.07832$, $p < 0.001$), indicating that economic growth dynamics in this model are more closely associated with life expectancy reductions, potentially driven by environmental or inequality factors.

The results for the proportion of the population aged 65 and over (OLD) indicate a positive and significant relationship with life expectancy in Models 2, 3, and 4. This suggests that EU countries with a higher proportion of older individuals tend to achieve better long-term health outcomes, likely due to advancements in healthcare systems and policies aimed at addressing the needs of aging populations.

Among the variables related to circular economy practices, waste treatment (WAST), waste Import (WIM), and waste Export (WEX) exhibit a negative and significant effect on life expectancy in Models 1, 2, and 3, respectively. These findings indicate that, starting from the current period in EU countries, poorly managed waste processing and material flows in the long term could lead to environmental pollution and negatively impact health conditions. In Model 4, greenhouse gas emissions (GHE) has negative impact on life expectancy ($\beta = --0.0628$, $p = 0.001$). This reflects the long-term harmful effects of industrial emissions on population health.

Short-Run Effects

In the short run, GDP per capita (GDPp) has a positive and significant effect on life expectancy across all models. This indicates that short-term economic growth increases life expectancy through higher healthcare expenditures and improved living conditions.

In the short run, the proportion of the population aged 65 and over (OLD) has an insignificant relationship with life expectancy across all models. This finding suggests that the impact of an aging population on health outcomes tends to manifest over longer time horizons, likely due to the gradual nature of demographic shifts and their cumulative effects on healthcare systems and population health.

For the circular economy practicing variables, waste treatment (WAST), waste imports (WIM), waste exports (WEX), and greenhouse gas emissions (GHE) do not have a statistically significant effect in the short term, except for WEX in Model 3 (β=−-0.0084, p = 0.083) and GHE in Model 4 (β=−-0.0246, p = 0.091), which approach significance. This indicates that while environmental factors are critical in the long run, their immediate impact on life expectancy may be limited or indirect.

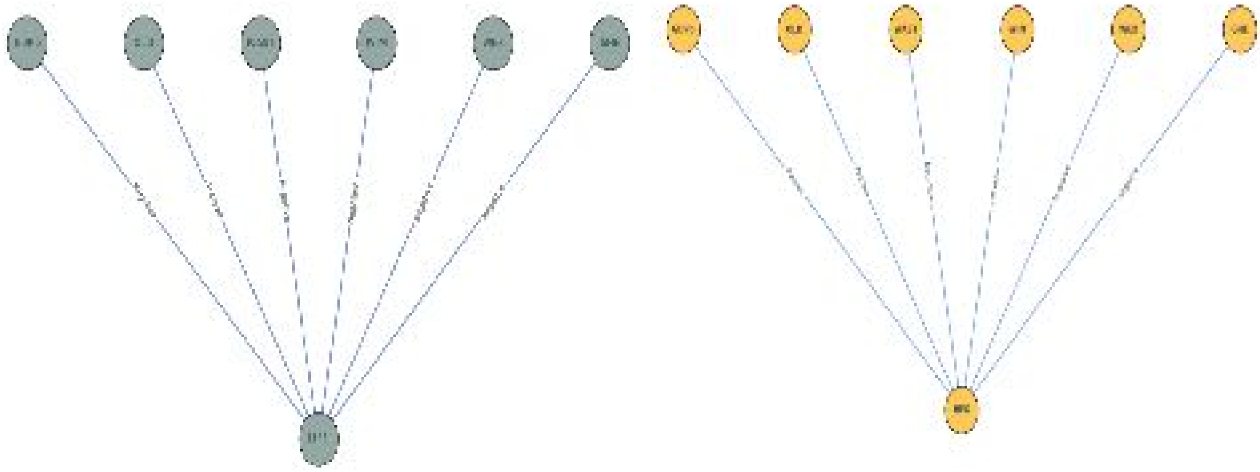
The ECM coefficients were found to be negative and statistically significant across all models, confirming the validity of the long-run relationships. These coefficients indicate that deviations from equilibrium are corrected relatively quickly in each model. The fastest adjustment to equilibrium was observed in Model 1 (ECM = -0.8269, p < 0.001), while the slowest adjustment occurred in Model 4 (ECM = -0.3771, p < 0.001). In the short term, enhancing waste treatment (WAST)within circular economy practices plays a crucial role in improving life expectancy. In the long term, however, reducing greenhouse gas emissions appears to make a significant contribution to life expectancy.

Table 6: Panel ARDL Model Results- Effects on Life Expectancy at Birth

Dependent variables :LIFE							
Model 1		Model 2		Model 3		Model 4	
Long-run Results		***Long-run Results***		***Long-run Results***		***Long-run Results***	
GDPp	-.01615 (0.000)	GDPp	-.0298 (0.003)	GDPp	-.0051 (0.010	GDPp	-.07832 (0.000)
OLD	.0035 (0.063)	OLD	.1075 (0.000)	POP	.0848 (0.00)	OLD	.3758 (0.000)
WAST	-.0094 (0.012)	WIM	-.0553 (0.000)	WEX	-.0061 (0.004)	GHE	-.0628 (0.001)
Short- run Results		***Short- run Results***		***Short- run Results***		***Short- run Results***	
ECM	-.8269 (0.000)	ECM	.-4175 (0.000)	ECM	-.82137 (0.000)	ECM	-37713 (0.000)
GDPp	.09872 (0.000)	GDPp	.0435 (0.005)	GDPp	.0891 (0.000)	GDPp	.09275 (0.000)
OLD	-.0841 (0.574)	OLD	-.0985 (0.414)	OLD	-.0364 (0.713)	OLD	-.09669 (0.333)
WAST	-.0258 (0.189)	WIM	-.0128 (0.305)	WEX	-.0084 (0.083)	GHE	-.0246 (0.091)
Cons.	-3.5308 (0.000)	Cons.	-2.002 (0.000)	Cons.	-3.443 (0.000)	Cons.	-1.7244 (0.000)

Figure 1 summarizes the long-run impacts of GDPp, OLD, WAST, WIM, WEX, and GHE on LIFE and HEX.

<u>Figure 1</u>: Long-Run Impacts on Life Expectancy (LIFE) and Health Expenditures (HEX)



Conclusion

Recent studies, particularly the comprehensive discussions initiated by the WHO Regional Office for Europe (2018), emphasize the need to more effectively integrate health considerations into CE strategies and implementation mechanisms. Although CE policies are primarily designed to address environmental and economic challenges, they also exert significant impacts on public health outcomes. Within the context of EU member states, where ambitious sustainability goals such as the European Green Deal are shaping policy agendas, integrating health priorities into CE strategies emerges as both timely and critically important.

Existing evidence largely focuses on the potential risks and adverse health effects of CE interventions, such as inadequate waste management or exposure to hazardous materials during recycling processes. However, there is a notable research gap in understanding the health benefits of well-designed CE practices, including improved waste management systems, pollution reduction, and the promotion of sustainable production and consumption patterns. Addressing this gap is crucial for EU member states to align CE policies with broader public health objectives. Such alignment can help mitigate health risks, improve health outcomes, and reduce healthcare expenditures. A holistic approach to CE strategies can further support EU countries in achieving long-term sustainability and societal well-being goals. This research, which examines the impact of CE practices in EU member states, makes a valuable contribution to this discourse.

The findings highlight the significant role of CE variables in shaping healthcare expenditures within the EU. Improvements in waste management, such as effective waste treatment and increased waste exports, are associated with reduced healthcare costs. These advancements help mitigate pollution-related health risks and alleviate the financial burden on healthcare systems. Conversely, higher greenhouse gas emissions consistently lead to increased healthcare expenditures, reflecting the adverse health impacts of environmental pollution. In the short term, greenhouse gas emissions and waste imports are critical factors influencing healthcare costs. Reducing emissions yields immediate health and economic benefits, while minimizing waste imports could ease short-term environmental and healthcare pressures. These results illustrate the interconnected nature of environmental health and economic policies, demonstrating that sustainable waste management and emission control directly contribute to improved health outcomes and reduced expenditures.

Over the long term, waste treatment and the import and export of waste exhibit a negative relationship with life expectancy, underscoring the health risks associated with inadequate waste management systems and poorly regulated material flows. The findings emphasize the direct impact of environmental practices on public health, where insufficient waste processing contributes to pollution and adverse health outcomes. Additionally, greenhouse gas emissions emerge as a critical determinant of reduced life expectancy, highlighting the long-term detrimental effects of industrial pollution. These results underscore the urgency of implementing robust environmental policies tailored to the unique policy and demographic contexts of the EU. Although circular economy variables show limited immediate effects on life expectancy, the rapid adjustment mechanisms observed in the models reinforce the pivotal role of sustainable environmental practices, particularly in waste management and greenhouse gas reduction.

EU policymakers should integrate health considerations into circular economy frameworks to address both environmental and public health challenges. Prioritizing sustainable waste management, such as investing in eco-friendly solutions to reduce emissions from disposal and incineration, is essential. Reducing greenhouse gas emissions through robust policies is critical for improving public health and controlling long-term healthcare expenditures. Enhanced monitoring of CE practices and their health impacts is necessary to identify effective interventions and ensure scalability across EU member states. Future research should focus on understanding the health benefits of well-implemented CE practices, examining regional variations, assessing both short- and long-term impacts on health, and evaluating the economic co-benefits of sustainable CE practices.

In conclusion, the impact of CE practices on health has broad and widespread outcomes that cannot be limited to just one country or region. This is because health is a global public good, and the externalities created by health policies, by their very nature, form an interconnected process that affects every country. Although CE practices are currently focused on high-income countries, it is essential to carefully consider how low-income countries can be integrated into these processes to ensure that their inclusive impacts are effectively addressed.

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Different strategies for improving contractor's maturity of transformation towards circular economy construction

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Abstract : A transition of the construction industry towards Circular Economy (CE) represents a critical shift in achieving sustainability and resource efficiency. The paper explores various strategies to enhance a contractor's maturity in embracing CE principles, emphasizing the importance of a structured transformation model. The proposed model serves as a tool to assess a company's readiness and inclination towards implementing CE concepts. It comprises multiple dimensions, each representing a pillar of evaluation that can guide the transformation process. These dimensions include performance of management in seven main areas: materials, energy, water, waste, emissions, 3R policies, and overall factors of transition to CE. By evaluating these scales, companies can identify gaps in their current practices and develop targeted strategies to enhance their maturity in CE practices. This approach mirrors similar methods used in other industries. The paper also highlights the pivotal role of expert opinions in shaping and refining transformation scenarios. Experts can provide valuable insights that help contextualize the model to specific industry realities, making it more applicable and effective. Their perspectives are crucial in identifying potential challenges and opportunities, ensuring that the proposed strategies are both feasible and impactful. Different transformation scenarios, ranging from incremental changes to radical shifts, are examined to illustrate how companies can navigate the complex journey towards CE. The involvement of experts ensures that these scenarios are grounded in practicality and aligned with industry trends. Such a solution can provide a basis for further modelling extensions, including in the field of the smart city concept and artificial intelligence.

Introduction

In recent years, environmental protection policy at various levels – from the global perspective, through the regional, to the national level – has become increasingly important in the context of more efficient use of the resources available to humanity than before. The negative effects of widespread overproduction demonstrated by economists, manifested by multiple imbalances, as well as the temptation to waste the production produced, are one of the basic lines of criticism of the consumerist lifestyle prevailing in many countries of the world. Those who oppose the economy of excess, as it is commonly referred to as an economy in which there is a disproportionate increase in supply to the possibility of increasing demand, point to the advantages of a different economic model, based on sustainable development, which is consistent with an inclusive socio-economic pattern, guaranteeing minimal interference with the natural environment through the promotion of low-emission and energy-efficient production processes, as well as technologies that eliminate waste.

All these rational postulates were accepted by the European Union and written down in the form of a new strategy entitled The "European Green Deal", which has pro-innovation and pro-ecological assumptions leading to ensuring resource security and stable development of all member states in the coming decades. The crucial climate neutrality of the European Union by 2050 can be ensured by ceasing the extensive use of resources, especially non-renewable ones, and therefore on the condition of switching to production systems consistent with the concept of the CE. From a socio-economic perspective, this model means that the greatest possible prosperity is achieved with the lowest possible resource consumption and the lowest costs. This applies to all sectors of the economy, including its significant part, namely construction. The goals of the transformation towards CE in the construction sector are to reduce waste and unnecessary resource consumption and to reuse or refurbish products leading to their extension, as well as to recycle materials used in all parts of the value chain (Hoibye, Sand, 2018)

A remodelling of the construction industry to make it more focused on CE marks a pivotal step in achieving sustainability and resource efficiency (Gorecki, Nunez-Cacho, Corpas-Iglesias, Molina, 2018, Gorecki, Nunez-Cacho, Corpas-Iglesias, Molina, 2019). This paper investigates diverse strategies to adopt CE principles (Gorecki, 2019), focusing on the development of a structured transformation model (Nuñez-Cacho, Górecki, Molina-Moreno, Corpas-Iglesias, 2018). The model is designed as a practical tool to evaluate a company's readiness and capacity for implementing CE practices. It encompasses multiple dimensions, each representing a critical pillar of the transformation process. These dimensions assess management performance across seven key areas: materials, energy, water, waste, emissions, 3R policies, and overarching factors driving the CE transition. Through this evaluation, companies can pinpoint deficiencies in their current operations and craft tailored strategies to improve their maturity in CE adoption. This framework aligns with approaches utilized in other industries (Esbeih, Molina-Moreno, Núñez-Cacho, Silva-Santos, 2021).

However, the study underscores the importance of integrating expert insights to refine transformation scenarios, ensuring the model's relevance and adaptability to specific industry contexts. Experts offer essential perspectives, enabling the identification of challenges and opportunities that make the proposed strategies both practical and impactful. The research examines various transformation pathways, from gradual changes to significant overhauls, providing guidance for companies navigating the complexities of CE integration. By grounding these scenarios in expert knowledge and industry trends, the solutions become more effective and actionable. Additionally, the paper suggests potential extensions of the model, including its application to smart city initiatives (Utrilla, Gorecki, 2023) and the integration of artificial intelligence (Núñez-Cacho, Mylonas, Kalogeras, Molina-Moreno, 2024)

End of abundance

A better understanding of the essence of CE is facilitated by familiarizing oneself with the historical context of the issue of the economic development of the world. For centuries, its pace was relatively slow, and resulted from evolutionary changes in technology, work organization and materials science. The first industrial revolution, which began in the 18th century, brought about radical changes. The transition from the era of manufacture to the era of industrialization allowed for an increase in the efficiency of production processes on an unprecedented scale (Von Weiszäcker, Ayres, 2013). Thanks to the new capabilities of steam engines, it was possible to increase production efficiency, and the wide availability of natural resources, including hard coal, did not herald the need to assume any other scenarios than constant growth. The next century, rich in innovative solutions, including groundbreaking product innovations such as the telephone, the gas engine, and various electrical devices, became the beginning of a period referred to in literature as the second industrial revolution. Both social processes (including growing urbanization associated with mass migration of people from the countryside to cities, the construction of an industrial society, and the concentration of people in urban agglomerations) and economic changes (including growing demand for cheap raw materials, the discovery of new sales markets, the pressure of profitability, the cult of efficiency) are a direct effect of the modernization of the economy based on the industrial revolution, the effects of which are noticeable today. The motto of such a development model was, of course, further "acceleration" of the economy and the homage to the idea of growth. Thanks to the increasingly widespread use of science to solve production problems, and through continuous improvements, the rate of economic growth outpaced demographic growth for the first time in world history, while the industrial revolution increasingly began to contribute to the widening wealth gap between the wealthy West and the rest of the world (Jasiak, 2021).

It seems, therefore, that the pursuit of prosperity, which has fascinated humanity for centuries and has been the source of numerous legends and symbols, is a road to nowhere. From ancient times, through various eras, to the present day, the idea of abundance has become an integral part of human existence. The mythical cornucopia, symbolizing wealth, can be a metaphor for abundance in a broad sense - from the availability of material resources to spiritual well-being. Its presence in mythology, religion, art and literature testifies to the deep meaning that has been attributed to it over the centuries. It is therefore worth looking at various aspects of abundance - from the cultural context to the practical implications for the economy and society. Selected sources, even in a somewhat catastrophic style (De Gregori, 1985), describe that humanity has begun to experience a stage of civilization development in which natural resources are no longer consumed locally, and therefore have become increasingly limited, and their use has increasingly negative effects on the environment and people (Meadows, Meadows, Randers, Behrens III, 1972). Economic growth is a fundamental economic issue and the subject of research for many years, however, the pace of change can sometimes be surprising, especially in the context of the use of fossil fuels, which - as non-renewable energy sources - have been used on a large scale since the beginning of the industrial revolution (Kelly, 1977). At the same time, overconsumption, which is a negative manifestation of economic growth, leads to the use of natural resources that is not justified by real needs, which results in deepening environmental degradation (Wasilik, 2014)..

The end of abundance may mean the advent of times of scarcity or generally a limited access to goods. However, understood as comfort (e.g., of life, of work) may also mean challenges of a different nature, such as changing previous consumer habits, conceptualizing new technologies, constantly improving skills, giving up previous privileges, etc. The end of abundance in a construction sector may mean the need to reorganize the entire technological and organizational context related to the implementation of construction projects. Prosperity, understood as the ability to maintain the status quo based on the linear economy model, is slowly fading away due to the predominance of negative aspects over positive ones (Uemur & al., 2021, Dsilva, Zarmukhambetova, Locke, 2023). Revolutionary changes are often necessary, the subjects of which must be all project participants. The most important role should be played by the market, which would set the tone for 'circular' changes. However, building consumer awareness through education is crucial (Bertozzi, 2022). People should be informed about the impact of their consumer choices on the environment and natural resources. Understanding the consequences of one's own actions can encourage more conscious choices. It is also necessary to inform designers and contractors (Bertozzi, 2022) that development based on a sustainable model may require certain resignations, e.g. from the use of plastic products or packaging, and may also mean the need to choose ecological products or limit the scale of investment in line with the 3R (reduce–reuse–recycle) principle.

Methods

CE is a dynamic concept, which includes general aspects and indicators reflecting the idea of transition to a new production model (Nuñez-Cacho, Górecki, Molina-Moreno, Corpas-Iglesias, 2018). This study builds upon the dimensions outlined in the CE building scale, as described in prior research (Nuñez-Cacho, Górecki, Molina-Moreno, Corpas-Iglesias, 2018). These dimensions encompass key performance areas such as materials, energy, water, waste, emissions, 3R (reduce, reuse, recycle) policies, and overall factors influencing the CE transformation. The scale integrates statistical analyses, including confirmatory factor analysis (CFA) and Delphi rounds, to validate its structure and ensure its relevance. The finalized model (Figure 1) reflects weighted scores for each dimension, providing a comprehensive tool for assessing a company's readiness and maturity in implementing CE principles. These dimensions serve as the foundation for developing transformation scenarios tailored to construction companies.

Figure 1: Core structure of the study model

			Number of Expert with Rating					
Final Dimension of the Scale	$\bar{X}$	S	1	2	3	4	5	POSITION
Energy	1.273	0.689	25	7	1	0	0	1º
3R, Reduce, Reuse and Recycle	1.364	0.558	22	10	1	0	0	2º
Water management	1.364	0.747	25	6	1	1	0	3º
Waste Management	1.424	0.938	24	7	1	0	1	4º
Management of materials	1.455	0.906	21	10	1	0	1	5º
Emissions generated	1.576	0.902	18	10	2	0	1	6º
Transition to Circular Economy	1.606	0.703	17	11	4	0	0	7º

Using the validated CE building scale, a framework is proposed to facilitate the creation of tailored transformation scenarios. This idea incorporates critical steps companies should perform to achieve their goals and objectives and implement the most effective strategies, enabling a structured analysis of companies' readiness for CE adoption. The process begins with assessing current practices and identifying gaps in the seven key performance areas. The framework then employs a scenario-based approach, enabling the exploration of various pathways for transitioning to CE, becoming a sort of the roadmap for decision-makers. The scenarios range from incremental improvements to groundbreaking changes, offering managers a spectrum of strategies that align with their organizational goals and resource capabilities.

To further enhance the applicability of the framework, a decision-making strategy matrix (Figure 2) is utilized to classify transformation plans into four behavioural categories. This matrix considers two key axes: reliability level and time segments. Based on their positioning, the plans are categorized into less and more risky ones (from 'risk-averse' to 'risk-seeking') as well as less and more progressive schemes (from 'stepping stones along the way' to 'final destination/big picture') constituting one of four classes: the "Low risk–Short term" (LS) strategy, the "High risk–Short term" (HS) strategy, the "Low risk–Long term" (LL) strategy, or the "High risk–Long term" (HL) strategy. This matrix-based approach ensures that the scenarios are both actionable and aligned with the unique challenges and opportunities of individual companies, facilitating more effective decision-making during the CE transition process. Each class (matrix cell) is associated with a specific recommendation mix that guides decision-makers in selecting the most suitable transformation pathway for their organization.

Figure 2: Decision-making strategy matrix for transformation to CE process

These recommendations were developed through a structured brainstorming session involving experts from the construction sector. The session included two experienced construction advisors and two active construction managers, ensuring a blend of theoretical knowledge and practical insights. The experts leveraged their extensive industry experience to identify actionable strategies tailored to each behavioural class. By aligning the recommendations with real-world industry conditions, the matrix provides decision-makers with a practical and evidence-based framework to navigate the complexities of the CE transition process. This approach not only enhances the applicability of the framework but also ensures that companies are equipped with the guidance needed to achieve their CE objectives effectively.

Results

The first class of transformation scenarios identified through the strategy matrix is characterized by the LS strategy (Figure 3). This approach focuses on incremental adjustments, representing a conservative pathway for organizations to begin their transition towards CE. Companies in this category aim to minimize risk and resource expenditure while achieving short-term, measurable outcomes. These strategies are particularly suited to organizations at the initial stages of CE adoption, where the emphasis is on maintaining stability while initiating foundational changes.

Figure 3: 1st class of transformation scenarios according to strategy matrix

To better understand the practical implications, Figure 4 provides a visual summary of selected – the most important according to the experts – decisions recommended for organizations adopting the LS strategy. These recommendations reflect a cautious yet forward-thinking approach, enabling companies to gradually build their capacity for CE practices. The results highlight how targeted, low-risk actions can serve as stepping stones toward achieving broader, long-term CE goals while minimizing disruption to existing operations.

Figure 4: Chosen specific decisions based on the first class of transformation scenarios

MATERIALS

- Switching to suppliers offering recycled materials for non-structural elements.

ENERGY

- Gradually replacing old equipment with energy-efficient alternatives during regular maintenance cycles.

WATER

- Installing water-saving fixtures on a pilot project basis to assess viability.

WASTE

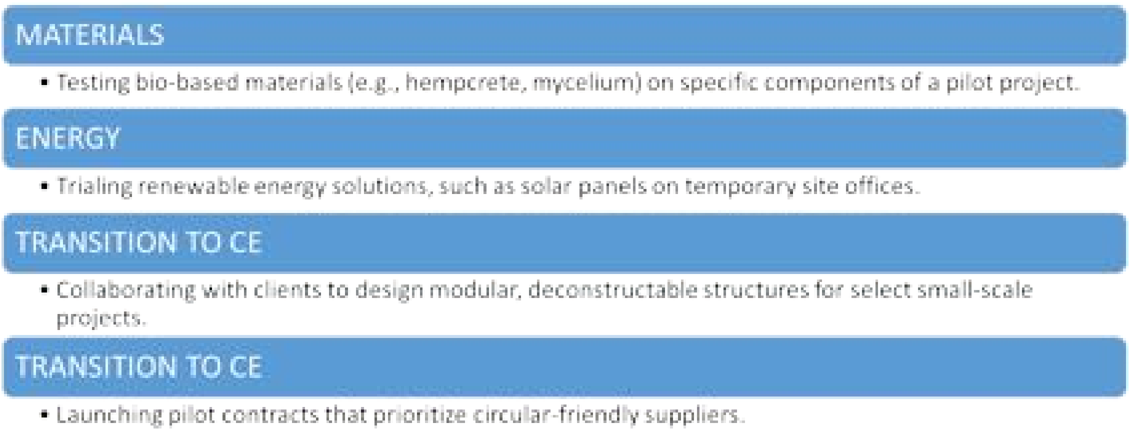
- Introducing a basic on-site sorting system for construction debris.

The second class of transformation scenarios identified through the strategy matrix is characterized by the HS strategy (Figure 5). This approach emphasizes a higher level of risk-taking, where organizations focus on introducing experimental innovations while gradually evolving their practices. Companies in this category demonstrate a willingness to invest in new technologies and methods, aiming to achieve significant progress in adopting Circular Economy (CE) principles over a short-term horizon.

Figure 5: 2nd class of transformation scenarios according to strategy matrix

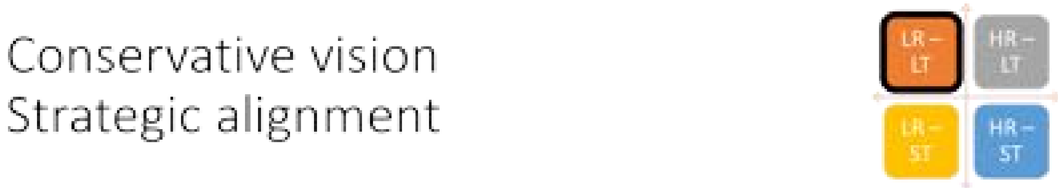
This strategy is particularly suitable for organizations that have already established a foundational level of CE adoption and are prepared to explore innovative solutions. The focus is on balancing risk with potential rewards, fostering a culture of experimentation while maintaining operational stability. To better understand the practical implications, Figure 6 provides a visual summary of selected decisions recommended for organizations adopting the HS strategy.

Figure 6: Chosen specific decisions based on the second class of transformation scenarios



The third class of transformation scenarios identified through the matrix is termed the LL strategy (Figure 7). This approach combines long-term planning with careful alignment of organizational goals to CE principles. Unlike the previous classes, this strategy is rooted in a measured and forward-looking perspective, where companies prioritize aligning their business strategies with CE objectives while minimizing operational disruptions.

Figure 7: 3rd class of transformation scenarios according to strategy matrix



Organizations adopting this approach are typically characterized by a strong commitment to sustainability but proceed cautiously, ensuring every action aligns with their broader strategic vision. This pathway is especially suitable for enterprises seeking to balance operational priorities with a gradual introduction of CE principles. The practical implementation of this strategy is illustrated in Figure 8, which outlines specific decisions recommended for companies pursuing the LL strategy.

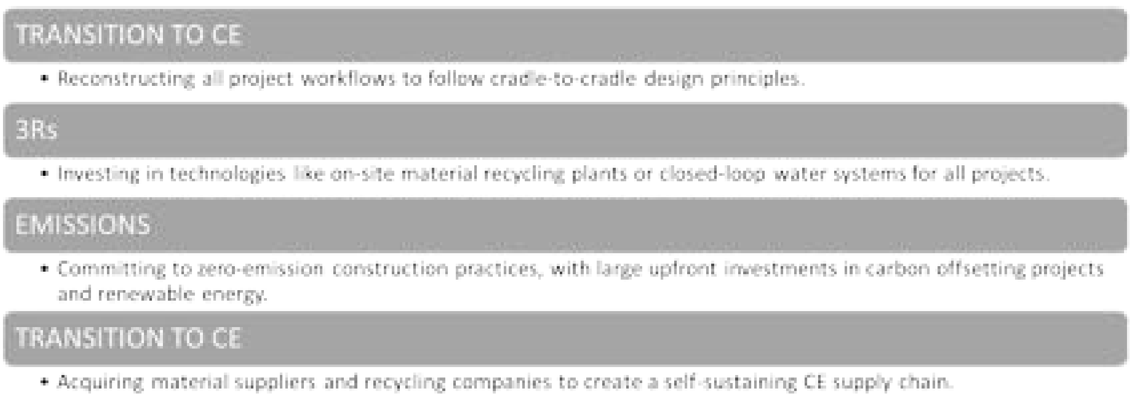
Figure 8: Chosen specific decisions based on the third class of transformation scenarios

The fourth and final class of transformation scenarios identified through the matrix is called the HL strategy (Figure 9). It represents a bold and transformative approach, where organizations prioritize comprehensive and systemic changes to fully integrate CE principles into their operations. Companies in this category are driven by the ambition to become industry leaders in sustainability, embracing high levels of innovation and risk to achieve long-term competitive advantages.

Figure 9: 4th class of transformation scenarios according to strategy matrix

This pathway is best suited for organizations with significant resources, visionary leadership, and a strong commitment to redefining their business models. The focus is on creating disruptive changes that set a new standard for CE practices in the construction sector. Figure 10 illustrates specific decisions recommended for organizations pursuing the HL strategy. These decisions reflect high-impact actions designed to overhaul traditional practices and integrate CE at every level.

Figure 10: Chosen specific decisions based on the fourth class of transformation scenarios



These aforementioned four classes of transformation scenarios, ranging from cautious incrementalism to radical innovation, provide a comprehensive framework for organizations to navigate their unique paths toward adopting CE principles in the construction sector.

Discussions and conclusions

The study highlights the value of a structured, multi-dimensional transformation model as a practical framework for assessing and guiding construction companies in their journey toward CE maturity. This seems to be consistent with other studies (Gorecki, 2021, Pigosso, Rodrigues, McAloone, 2017). By addressing seven key dimensions—materials, energy, water, waste, emissions, 3R policies, and overall factors—carefully described before (Nuñez-Cacho, Górecki, Molina-Moreno, Corpas-Iglesias, 2018), the model provides a comprehensive approach to identifying gaps and designing tailored strategies for CE adoption. Results offer a versatile roadmap that accommodates diverse organizational contexts and capacities.

It can be noted that CE maturity and transformation to CE are distinct yet interconnected concepts. While maturity represents a state of readiness or achievement, transformation is a dynamic and ongoing process that requires the definition of critical steps companies should perform. Achieving CE maturity involves the use of robust metrics, and the seven-dimensional scale provides a reliable framework for assessing a contractor's current state. Transformation strategies, on the other hand, can be designed using a two-dimensional matrix, offering flexibility and adaptability to various business contexts, while specific recommendations may be based on the scale.

In practice, extremes are rare; most organizations operate within a spectrum of strategies, reflecting the complexity and diversity of real-world conditions. The involvement of experts is crucial in this pursuit, as their insights help ensure that strategies and models are practical, context-specific, and aligned with industry realities. The notion of a universally effective strategy is a fallacy—success depends on specific business conditions, including the contractor's risk tolerance and readiness for change. Whether through small, incremental steps or radical developments, each strategy plays a crucial role in progressing toward CE. By aligning transformation efforts with organizational capacities and goals, companies can navigate this journey effectively, contributing to a more sustainable future for the construction sector.

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Digital technologies as enablers for the Circular Economy transition: A pathway for transitioning industries

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Abstract : The Circular Economy (CE) is increasingly recognized as a transformative model for achieving sustainable resource management by minimizing waste and extending product life cycles. However, despite the growing interest, the transition from linear to circular models remains complex, requiring advanced tools to facilitate material tracking, optimize resource utilization, and foster collaboration across industrial value chains (VC). Digital technologies (DTs) are key enablers of the CE transition, as they provide the necessary infrastructure for data collection, integration, and analysis to drive circular business models. The European photovoltaics (PV) industry presents a compelling case study to explore this intersection, given its rapid expansion, geopolitical competition, and the growing challenge of managing End-of-Life (EoL) PV waste streams. With projections estimating 33 million tons of decommissioned PV modules in Europe by 2050 (Czajkowski et al., 2023), integrating DT-driven circular strategies is not only necessary but urgent to master the CE transition. First, this chapter contextualizes DTs for data collection, integration, and analysis, followed by an exploration of their applicability across different VC stages. Next, it examines the role of digital platforms in uniting diverse DTs and industry stakeholders to collaboratively advance circularity, illustrated through a case study from the solar industry. Finally, the chapter concludes with policy recommendations to support the adoption of DTs and platforms for circularity. The findings, while grounded in the PV sector, offer transferable insights to other industries striving for digitally-enabled circularity.

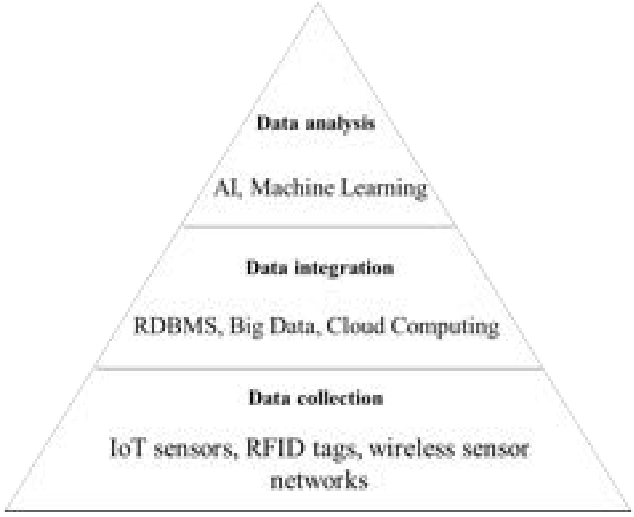
Digital technologies for data collection, integration, and analysis

Kristoffersen et al. (2020) introduced a three-layered framework for "smart circular economies", categorizing DT applications into data collection, data integration, and data analysis (Figure 1). This framework highlights the need for a holistic approach to CE digitalization, moving beyond isolated implementations toward fully integrated digital ecosystems (I. S. Khan et al., 2021; Rusch et al., 2023). The first layer, data collection, focuses on gathering real-time information through sensors, IoT devices, and machine-readable identifiers. These technologies enable continuous monitoring of products and resources, capturing critical information on material composition, condition, location, and usage patterns to ensure essential information throughout the VC, facilitating traceability and circular decision-making after the first life cycle (Fraga-Lamas et al., 2021; Gligoric et al., 2019).

The second layer, data integration, ensures accessibility and interoperability by leveraging relational database management systems (RDBMS), Big Data, and cloud computing. As data is collected from multiple sources across the VC, it must be stored and structured in a way that enables seamless sharing among stakeholders. Cloud-based platforms provide scalable storage solutions, while Application Programming Interfaces (APIs) enable multiple information systems to communicate and exchange information efficiently (Kristoffersen et al., 2020).

The third and top layer, data analysis, utilizes Machine Learning (ML) and Artificial Intelligence (AI) to derive actionable insights for circular decision-making. By analyzing vast amounts of data, ML models improve demand forecasting, enabling businesses to plan for secondary markets and optimize VC logistics. Furthermore, AI algorithms can identify patterns, predict product failure rates, and optimize material recovery processes (Wilson et al., 2021). In addition to that, advanced analytics facilitate EoL decision-making by determining the most suitable pathways for reuse, refurbishment, or recycling based on product condition and market demand (All Noman et al., 2022; Awan et al., 2021).

Figure 1: Digital technologies along the three layers of data collection, integration and analysis



Source : Kristoffersen et al. (2020)

Digital technologies in circular value chains

It becomes evident that digital technologies provide numerous opportunities to enhance value chain circularity by improving transparency, efficiency, and collaboration among stakeholders (S. A. R. Khan et al., 2022). To fully harness the power of DTs, it is essential to integrate them across all stages of the value chain, ensuring seamless data exchange and interoperability. Taking the example of the European PV sector, industrial VCs generally comprise three stages, including the up- mid- and downstream VC (Garlet et al., 2020). While industries aiming to enhance circularity require a holistic approach to DT integration, the impact and benefits of these technologies vary across different VC stages.

In the upstream stage, which includes material sourcing and production, product identifiers such as RFID tags and Digital Product Passports (DPPs) improve traceability by embedding material composition, sustainability metrics, and lifecycle data directly into products (Radavičius et al., 2021). This ensures that materials can be effectively reintegrated into new production cycles, supporting a closed-loop system (Adisorn et al., 2021; Honic et al., 2019). Additionally, blockchain technology enhances transparency by creating immutable records of material flows, reducing supply chain fraud and ensuring compliance with environmental regulations (Erol et al., 2021).

In the midstream stage, which involves product use and maintenance, IoT sensors, real-time monitoring, and predictive maintenance tools optimize product lifetimes to reduce premature replacements (Gligoric et al., 2019). IoT-enabled smart monitoring systems track product condition in real time, allowing service providers to detect early signs of degradation. AI-driven predictive maintenance further enhances this process by analyzing operational data to forecast system failures, enabling timely interventions and preventing premature replacements. Cloud computing and digital twin technologies also contribute to performance optimization by simulating product behavior under different conditions, allowing for adjustments that extend product lifetime (Z. Chen & Huang, 2021; Olawumi & Chan, 2022).

In the downstream stage, which focuses on EoL management, Big Data analytics, AI-driven material recovery systems, and blockchain-based transparency mechanisms streamline waste management and enhance reuse and recycling efficiency. AI-powered sorting technologies improve the classification and separation of materials, ensuring that valuable resources are efficiently recovered (Fraga-Lamas et al., 2021). Blockchain technology enhances waste management by tracking the movement of discarded products, ensuring compliance with regulatory frameworks, and preventing illegal exports (Erol et al., 2021). Additionally, data-driven forecasting models leverage historical waste data to predict future EoL volumes, enabling policymakers and businesses to plan and scale recycling infrastructure accordingly.

However, despite their potential, the widespread adoption of digital solutions remains limited due to fragmented and siloed data sources, lack of standardized frameworks, and insufficient cross-sector collaboration. Addressing these issues requires the implementation of interoperable platforms and regulatory guidelines that ensure transparency and accessibility across VC actors (Nyffenegger et al., 2024).

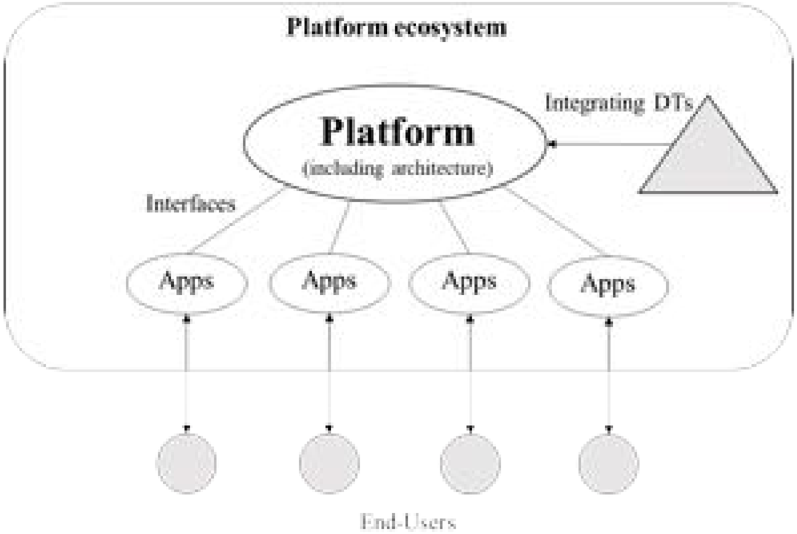
The role of digital platforms

Digital platforms have undergone significant transformation in recent years, emerging as enablers of value creation, innovation, and collaboration across industrial value chains (Parker et al., 2016). But this "platform revolution" is not unfounded: the most valuable companies of the world, including Apple, Microsoft, Amazon, and Google incorporate digital platforms in their business model (Brecht et al., 2022). In the context of the CE, digital platforms serve as technological infrastructures that connect diverse DTs and stakeholders to facilitate circular value co-creation (Aarikka-Stenroos et al., 2021; Autio, 2022; Bonina et al., 2021). Their ability to collect, integrate, analyze and distribute data across multiple actors makes platforms particularly valuable in overcoming information asymmetries, optimizing resource flows, and fostering circular business models (Konietzko et al., 2020). The success of digital platforms is largely driven by network effects, where the value of the platform increases as more users engage and contribute. This scalability is essential for circularity, as it enables coordination between manufacturers, service providers, recyclers, and consumers (Autio, 2022; Gawer & Cusumano, 2014; Karhu et al., 2024).

Digital platforms emerge in various organizational contexts, ranging from internal firm-specific applications to industry-wide ecosystems that span entire value chains. In the CE domain, the predominant focus has been on market intermediaries, where the platform acts as market place for facilitating transactions between different user groups, such as buyers and sellers (Berg & Wilts, 2019; Täuscher & Laudien, 2018). Digital marketplaces, such as eBay, play a key role in enabling circular value creation by connecting parties with surplus products and materials to those seeking secondary resources (Blackburn et al., 2023; Ciulli et al., 2020; Franzò & Urbinati, 2023). However, while digital marketplaces have been widely studied, the broader potential of platform ecosystems for driving circularity remains underexplored.

Platform ecosystems (Figure 2) extend beyond simple marketplace transactions by creating industry-wide networks that enable deeper collaboration, interoperability, and innovation (Thomas et al., 2014). Their architectural openness allows multiple stakeholders to develop and integrate complementary products and services, significantly expanding the opportunities for CE implementation (Autio, 2022; Parker et al., 2017; Tiwana, 2013). Platform ecosystems consist of the platform, which provides a common technological foundation, and the ecosystem, which comprises a network of interoperable applications and interfaces that enhance the platform functionalities (Gawer & Cusumano, 2014; Tiwana, 2013). Scholars emphasize the integration of various DTs into the infrastructure of platform ecosystems, including IoT, mobile and sensor-based technologies, cloud computing, APIs and AI (Gawer & Cusumano, 2014; Maruping & Matook, 2020). Beyond technological integration, governance mechanisms play a crucial role in ensuring platform scalability and effectiveness. These mechanisms include role-based access control, data flow management, and standardized information provision. Ensuring that governance mechanisms are clearly defined within platform ecosystems, enhances participation, minimizes data security risks, and promotes compliance with circularity-related regulations (L. Chen et al., 2022; Jovanovic et al., 2022; Konietzko et al., 2020).

Figure 2: Platform ecosystems, based on (Tiwana, 2013), including the platform and its architectural openness to integrate diverse DTs and users to collaboratively work towards a shared circular vision

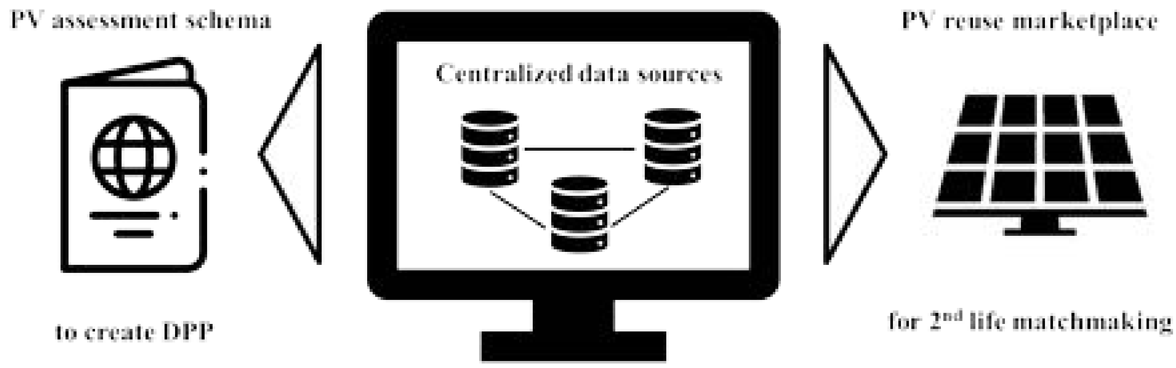


To sum up, platform ecosystems – unlike pure marketplaces – integrate diverse DTs into their architecture, allowing them to offer a wider range of services that enhance CE implementation. A few examples include: AI-powered recommendation engines utilize product life cycle data, captured in DPPs, to improve circular decision-making. Material flow analysis tools can enable manufacturers to optimize their resource streams. Additionally, platforms integrating automated compliance checks can streamline regulatory reporting to reduce administrative burdens for businesses (Boukhatmi & Groesser, 2023). Therefore, by providing interoperable and service-driven solutions, platform ecosystems enhance circular innovation by facilitating more effective knowledge sharing and stakeholder engagement (Jovanovic et al., 2022). As the CE transition accelerates, digital platforms will continue to play an increasing role in reinforcing circular VCs, driving collaboration and large-scale adoption of circular strategies (Aarikka-Stenroos et al., 2021; Autio, 2022).

CE Platform Case Study Example from the PV Industry

Having outlined a few examples of how DTs and platforms can enhance circularity across the different VC stages, the key challenge remains their efficient integration. In the European PV industry, the absence of standardized data-sharing mechanisms has impeded the adoption of circular strategies, restricting businesses to effectively track and manage products throughout their life cycle (Nyffenegger et al., 2024). To bridge this gap, the study by Boukhatmi et al. (2023) developed the prototype of a platform ecosystem which serves as a centralized infrastructure for collecting, integrating, and sharing product life cycle data. The prototype is designed around two primary use cases that directly address the key barriers to circularity in the PV industry (Figure 3). The first use case presents a "circular certification", which allows manufacturers to register and maintain comprehensive product information for creating a DPP. This ensures that crucial data regarding material composition, design specifications, and environmental performance remain accessible throughout a PV module's entire VC. By embedding these records within a standardized framework, the platform not only supports regulatory compliance but also facilitates circular decision-making and enhances reuse and recycling efficiency. The second use case is built around a "reuse marketplace", a matchmaking system that connects PV plant operators, recyclers, and second-life buyers to facilitate the repurposing of decommissioned PV modules. Through data-driven analytics and automated recommendations, the platform identifies PV modules with high second-life potential and matches them with suitable reuse applications.

Figure 3 : Illustration of the two use cases of the digital platform artefact



Source : Boukhatmi et al. (2023)

Policy and Regulatory Considerations for Digital Circularity

The previous chapters have outlined the relevance of DTs, and digital platforms in supporting the CE transition. However, for these digital solutions to be fully effective, robust policy and regulatory interventions are required. Ensuring interoperability, data security, and incentivizing DT adoption are critical steps for fostering digital circularity at scale. This section outlines key policy considerations, including the importance of open data and standardization, regulatory incentives for platform adoption, and governance mechanisms for secure and transparent digital infrastructures.

Standardized Data-sharing Frameworks

A fundamental prerequisite for digital circularity is the availability of standardized, high-quality data across value chains (Mulhall et al., 2022). The effectiveness of digital platforms, product tracking systems, and predictive analytics largely depends on access to consistent, high-quality datasets that can inform decision-making at every VC stage. Therefore, standardized data-sharing frameworks should be introduced to improve traceability, ensuring that information on material composition, environmental impact, and EoL pathways is systematically documented and made accessible across VC actors. Standardized DPPs can help businesses to optimize resource flows, enhance traceability, comply with regulations, and strengthen consumer confidence in circular products (Adisorn et al., 2021). First initiatives, such as the Ecodesign for Sustainable Products regulations (ESPR) have made relevant steps towards introducing DPPs in various industry sectors (European Commission, 2022). However, a mandatory DPP for PVs has not yet been introduced. Furthermore, open data policies should be promoted to facilitate industry-wide data access. Many current CE initiatives are hindered by data silos and proprietary information constraints, limiting transparency and collaboration. Policymakers should therefore further encourage open-data repositories and publicly available datasets that allow stakeholders across industries to access relevant product life cycle information while ensuring compliance with data privacy regulations. However, this transition must also be industry-driven, as manufacturers often exhibit a high reluctance to disclose product data (Nyffenegger et al., 2024). Therefore, establishing the right business incentives is crucial to encourage data sharing and foster greater transparency across VCs. For example, the Gaia-X initiative serves as a suitable example of how regulatory support can provide competitive advantage while ensuring a common, secure, and interoperable data infrastructure (Gaia X, 2024).

Regulatory Incentives for Platform Adoption

The adoption of platform-based ecosystems is essential for scaling circularity, yet many businesses hesitate due to high implementation costs, regulatory uncertainty, and a lack of financial benefits (Nyffenegger et al., 2024). To accelerate adoption, governments should introduce targeted incentives that encourage businesses to integrate platforms into their operations (Ren & Albrecht, 2023). One approach is to provide tax incentives and subsidies that support businesses in transitioning to platform-based CE models. CE companies investing in digital infrastructure, such as cloud-based life cycle tracking, real-time monitoring, or AI-driven material recovery, should be eligible for financial benefits to offset initial costs. Additionally, Extended Producer Responsibility (EPR) regulations should be revised to incorporate data-driven compliance mechanisms. Traditionally, EPR policies have placed financial and operational burdens on producers without fully leveraging digital tools for monitoring and optimization. By requiring businesses to integrate life cycle data tracking and reporting mechanisms into platforms, EPR policies can become more effective, ensuring that producers take greater accountability for their products beyond the point of sale. Examples like the RepTool by the WEEE Forum demonstrate that establishing clear circularity targets, combined with digital tools for tracking relevant data, serves as a crucial mechanism for ensuring regulatory compliance while simultaneously advancing CE implementation (Seyring et al., 2015).

Addressing Governance and Security Concerns

As digital circularity solutions expand, concerns related to data security, governance, and trust must be addressed to ensure widespread adoption. The reliance on interconnected digital infrastructures poses risks related to cybersecurity breaches, data privacy violations, and misuse of proprietary information. To mitigate these risks, strong cybersecurity regulations should be enforced to protect data integrity within platform-based ecosystems. Companies must implement encryption standards, role-based access control, and secure authentication mechanisms to prevent unauthorized access to critical product and life cycle data (Li et al., 2015). Moreover, public-private collaborations should be established to maintain trust in digital circularity infrastructures. Governments, industry associations, and research institutions should work together to create transparent data governance frameworks that define access rights, ownership structures, and compliance protocols. By fostering trust among stakeholders, these governance structures will help overcome resistance to data sharing, ensuring that CE platforms function effectively (Akomea-Frimpong et al., 2023).

Conclusion

This chapter explored the opportunities that digital technologies and platforms offer in accelerating the CE transition. However, it also highlighted key challenges, including limited data-sharing willingness due to competitive concerns and trust issues, as well as fragmented infrastructures that hinder data consistency and system interoperability. Additionally, as most businesses still operate within a linear economy, transitioning to circular business models often requires identifying viable economic incentives. In this context, DTs and platforms not only enhance but also enable the creation of circular business models by fostering new value streams. Moreover, through collaborative policymaking, standardized data-sharing frameworks, and targeted incentives, digital circularity can drive circular innovation while ensuring economic sustainability.

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Circular economy initiatives in the tire industry, the case study of recycled PET[1]

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Abstract : This paper presents a novel approach to strategic project management in the context of circular economy initiatives. The objective is to define steps for selecting key indicators at the company level that impact the economy, environment and society by integrating Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis with the Cross-Impact Matrix (CIM). This combined methodology provides both qualitative and quantitative results, achieving a deeper understanding of potential future forecasts and help to define key indicators to follow up in each domain. A case study involving a recycled Polyethylene Terephthalate (rPET) project demonstrates this approach, incorporating brainstorming sessions with project stakeholders and analyzing 182 indicators from relevant frameworks, including Cost-Benefit Analysis (CBA), Life Cycle Sustainability Assessment (LCSA), Sustainable Development Goals (SDGs), circular economy and the company-specific performance indicators. This paper emphasizes the broader application of the methodology, providing valuable insights for future research and strategic planning within circular economy initiatives.

Introduction

In 2015, The European Commission adopted its first Circular Economy Action Plan (CEAP) : closing the loop (EU, 2015). This action plan should "*boost the EU's competitiveness by protecting businesses against scarcity of resources and volatile prices, helping to create new business opportunities and innovative, more efficient ways of producing and consuming…; create local jobs… save energy and help avoid irreversible damages to climate, biodiversity, soil…*". The EU's transition to a circular economy aims to reduce pressure on natural resources and to stimulate sustainable growth and green jobs. It is also a prerequisite to achieve the EU's 2050 climate neutrality target and to halt biodiversity loss. The new action plan announces initiatives along the entire life cycle of products. It targets how products are designed, promotes circular economy processes, encourages sustainable consumption, and aims to ensure that waste is prevented and the resources used are kept in the EU economy for as long as possible. 54 actions have been designed and regularly implemented in production (product design, production processes), consumption, waste management, resources (secondary raw materials and water reuse) and priority areas (plastics, food waste, critical raw materials, construction and demolition, biomass and bio-based products, innovation and investments, monitoring progress). In a few years, CEAP became one of the main building blocks of the European Green Deal (2019) and Europe's new agenda for sustainable growth (2020). In march 2020, the European Commission adopted the New Circular Economy Action Plan (NCEAP). This new plan announced "*initiatives along the entire life cycle of products. It targets how products are designed, promotes circular economy processes, encourages sustainable consumption, and aims to ensure that waste is prevented and the resources used are kept in the EU economy as long as possible*" (UE, 2020). The objectives of NCEAP aim to make sustainable products the norm in the EU, empower consumers and public buyers, ensure less waste, make circularity work for people, regions and cities, lead global efforts on circular economy, focus on sectors that use most resources and where the potential for circularity is high such as electronic and ICT, batteries and vehicles, packaging, plastics, textiles, construction and buildings, food, water and nutrients.

This chapter deals with circular economy initiatives in the tire industry, more especially the use of PET (Polyethylene Terephthalate). PET is the third most used polymer in the world with more

[1] This study was carried out as part of the European Whitecycle project : CL6 - 2022 - 2026 - CIRCBIO. https://www.whitecycle-project.eu/. 17 partners are involved in this project.

than 82 Mt produced worldwide (2019). It is used in many applications: (1) textiles accounting for around 63 % of total applications with about 33 Mt in clothing (100% PET and multicomponent clothing), about 3Mt in technical fibres used in tyres, hoses, belts, geotextiles, etc. and about 16Mt in other applications (carpets, nonwoven etc.); (2) plastics accounting for around 37 % of total applications with about 23 Mt in packaging (about 13.5MT of clear bottle, around 6.5 Mt opaque and coloured bottles and flasks and around 3.5 Mt multilayer rigid packaging) and about 7MT in other applications (flexible components). Although PET recycling processes are quite commonly implemented for easy-to-collect and pure mono-material products, such as clear bottles, only 7 Mt of recycled PET (r-PET) were produced in 2017 worldwide, accounting for only 10% of the overall annual production of PET. Of this 10% being recycled, 71% was downcycled to make trays and low-quality fibres without any possibility to carry out a second recycling loop at the EoI. In fact, most PET waste is landfilled or burnt. Hence, there is an urgent need for developing a solution to retrieve the high-value PET from these wastes.

The possibility of replacing natural PET with recycled PET (rPET) raises environmental, social, economic and technological issues (impact study). To understand the advantages and disadvantages of the circular process, this study proposes an integrated methodology for assessing the economic, social and environmental impact of such an innovation. Firstly, we carried out a literature review of various tools that can be used to carry out an impact study on the launch of a new technology. This framework introduced SWOT Analysis, Cross Matrix Impacts (CMI), Life Cycle Sustainability Assessment (LCSA), Circular Economy principles (10Rs) and Sustainable Development Goals (SDGs) reporting. We identified indicators to challenge sustainability and circularity. Secondly, we applied the SWOT Analysis on the basis of a table of indicators approved by all the stakeholders to receive the most voted impactful indicator for each domain (economic, social, environmental). Thirdly, to obtain the quantitative forecasts, we used the Cross Matrix Impacts method and compiled a dashboard of indicators, validated by all project partners, to measure the economic, social and environmental impact of the case study.

Literature Review

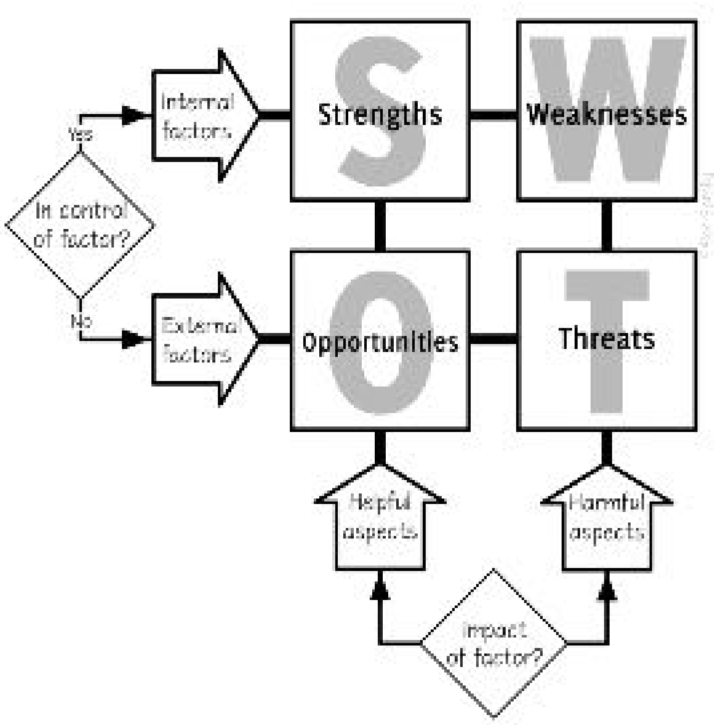
SWOT analysis and *Cross Matrix Impacts* are decision making techniques used in strategic planning and competitiveness framework. Connected with *Life Cycle Sustainability Assessment* (LCSA) and *SDGs indicators*, they open up a large number of possibilities in terms of circular economy.

SWOT analysis

Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis has become a powerful tool to develop a more comprehensive understanding of the project's potential and make informed decisions about its future. For Nunes Silva (2005, p. 445), "*it is a strategic management tool designed for use in the preliminary stages of decision making processes and is usually associated with strategic planning*". More generally, SWOT analysis is used by organizations to analyze internal and external environments, particularly during periods of strategic decision-making (Rozmi et al., 2018; Wu, 2020).

SWOT analysis focuses on four key elements (Aldehayyat et al., 2008; Fleisher et al., 2003; Lee et al., 2008; Shrestha et al., 2004): (i) *Strengths:* Internal attributes that facilitate achieving organizational goals; (ii) *Weaknesses:* Internal shortcomings that hinder organizational success, (iii) *Opportunities:* External factors that can be leveraged to achieve goals. These go beyond positive environmental aspects and encompass the ability to address existing gaps and initiate new activities and (iv) *Threats:* External elements that pose, or potentially pose, barriers to achieving objectives.

Figure 1 : The Basic SWOT Diagram



Source : Sarsby (2016, p. 7)

A SWOT analysis is helpful to explore possibilities or solutions to problems, to identify opportunities for success and clarify choices, to make decisions about the best pathways to follow, to highlight if changes are possible and how to drive them, to define end-point and mid-points in a strategic plan (Yong & al., 2019, Helms & Nixon, 2010, Valentin, 2001). As SWOT analysis does not provide a measurable evaluation of a project's potential, a more robust evaluation could combine SWOT with TOWS analysis (Escalona et al., 2022). TOWS for Threats, Opportunities (in the environment), Weaknesses and Strengths (of the organization) proposes a new order as a problem solving sequence (Watkins, 2007, Weihrich, 1982). The starting point is that managers should firstly identify all the threats from the environment to screen business opportunities (Kulshrestha, Puri, 2017). For this chapter, SWOT is applied as a starting point to identify key factors and potential events surrounding a project and then additionally exploring the interdependencies between these factors by using a Cross Impact Matrix (CIM) which can provide further insights into potential risks and opportunities in quantitative value.

The Cross-Impact Matrix (CIM)

The Cross-Impact Matrix (CIM) is a tool used to assess the potential consequences of a decision or event. It is based on the idea that one event can cause a chain reaction of other events (Chao, 2008). The goal of CIM is to identify and understand these potential consequences so that they can be mitigated or avoided (method of forecasting).

The relationships between events can be categorized into 3 types: (i) **Unrelated**: when one event occurs, it does not affect the probability of other events happening; (ii) **Enhancing**: when one event occurs, it increases the probability of other events happening subsequently; (iii) **Inhibiting**: when one event occurs, it decreases the probability of other events happening or prevents them from occurring altogether. There have been 4 major categories as followed.

Type 1. Qualitative Description of the trend-scenario

Some applications of CIM involve only qualitative descriptions of the relationships between events or trends. Analysts use this approach to identify causal chains and potential scenarios without assigning numerical values. Instead, they focus on understanding the nature of interactions and their implications for future developments.(Ratcliffe, 2001)

Type 2. Trend Value Assessment

In this category, CIM assigns numerical values to represent the magnitude of impact between events or trends. These values are often scaled to indicate the strength and direction of influence with the changes in initial probability assumptions allowing for quantitative analysis of the matrix. (e.g. Gordon et al., 1968; Weerakkoday et al., 2003).

Type 3. The Conditional Probability

Another category of CIM which involves the use of conditional probabilities to quantify the likelihood of one event occurring given the occurrence of another event. Analysts assign probabilities to each cell in the matrix, reflecting the likelihood of interactions between events. This approach provides a probabilistic framework for assessing the uncertainties associated with future developments.(Dalkey, 1972; Enzer, 1972; Gordon, 1994)

Type 4. The Conditional Probability method combines both the level of impacts and their probability of occurrence

By considering both factors, impact and possibility of occurrence then making a matrix procedure, the method provides a more comprehensive understanding of future development. (Kenneth, 2008) presents the procedure by the study of trend value of indicators impact to the family welfare with the proposed approach as shown below.

$$XP = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & \cdots & \cdots & \vdots \\ \vdots & \cdots & \cdots & \vdots \\ x_{n1} & \cdots & \cdots & x_{nn} \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_n \end{bmatrix} = \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_n \end{bmatrix} = S$$

$$\begin{aligned} s_i &= \sum_{j=1}^{n} x_{ij} p_j \\ &= \sum_{j=1}^{n} (a_{ij} b_{ij}) p_j \\ &= \sum_{j=1}^{n} (a_{ij} b_{ij}) P(E_j) \end{aligned}$$

The equation XP = S, illustrates the process of calculating expected impact (S) by multiplying a matrix of impact events (X) with a vector of initial probabilities (P). Matrix X captures the impact of each event. Each element "x_ij" represents the impact of the "j"th event on the "i"th outcome by multiplying the corresponding element "a_ij" from matrix A (impact events) with the corresponding element "b_ij" from matrix B (conditional probabilities).

Connection between SWOT and CIM Analysis

Effective strategic planning is crucial for organizational success, and the SWOT method is one of the techniques that provides a static snapshot of an organization's current position by identifying internal Strengths and Weaknesses, as well as external Opportunities and Threats in the environment (Gurel E., 2017). However, traditional SWOT analysis often fails to capture the complex interrelationships among these factors and their potential impacts on strategic outcomes. Using SWOT as a data collection tool before applying another powerful analytical method is mentioned in the literature (Tony C., 2006; John W., 2004). This chapter proposes a novel approach by combining SWOT analysis with Cross-Impact Matrix (Proctor, 2000). By integrating these two methods, we aim to achieve a deeper understanding of potential future scenarios by exploring the cause-and-effect relationships between various impact indicators identified in the SWOT analysis. The interrelationships between impact factors will be the next step used as key indicators for each domain to follow up in the next study.

LCSA, Circular Economy and SDGs

In this part, we investigate indicators derived from established frameworks, such as Life cycle sustainability assessment (LCSA), Circular Economy, Sustainable Development Goals (SDGs), Circular economy and Company-level reporting. At the end, in collaboration with stakeholders, we select impactful indicators along the project's supply chain.

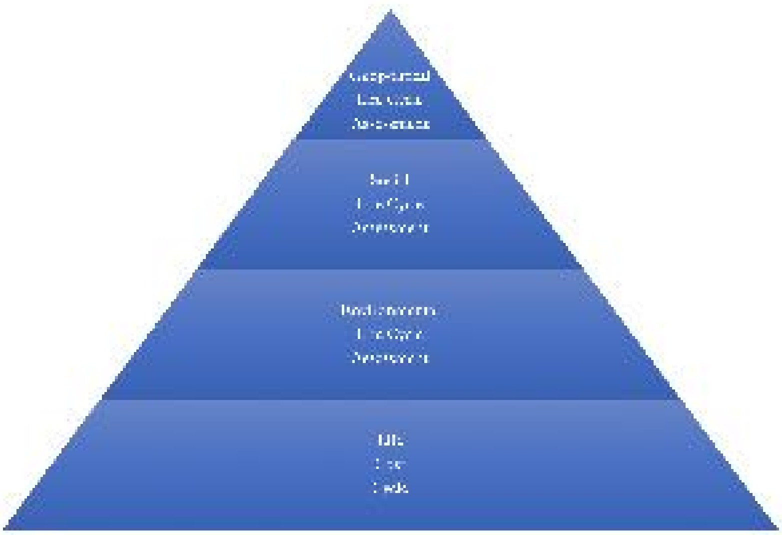
Life Cycle Sustainability Assessment (LCSA)

Life Cycle Sustainability Assessment (LCSA) is one of the key value product chains (Diemer, 2023). Every sector (electronic, battery and vehicles, packaging, plastics, textiles, construction and building, food, water and nutrients, etc.) is concerned and has to contribute to the sustainable product policy framework (Finkbeiner, Schau, Lehmann, Traverso, 2010). Kloepffer (2008) proposed the following scheme that LCSA comprises three main components: Environmental Life Cycle Assessment (ELCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (SLCA).

$$LCSA = ELCA + LCC + SLCA$$

In a recent publication (Diemer, Durand, Sourgou, 2025), we introduced one more component; the Geopolitical Life Cycle Assessment. Critical Raw Material (CRM) for new technology and more especially renewable energy (battery, solar panel, wind power…) are localized and concentrated in few countries (such as China). Geopolitical conflicts or economic wars may impact the use of natural resources into the production process and the profitability of the value chain.

Figure 2 : Life Cycle Sustainability Assessment (LCSA)



For this study, we just used the three main components of the LCSA. To identify indicators relevant to the rPET analysis, a literature review was conducted. Several indicators emerged, with some appearing across different frameworks. For instance, greenhouse gas emissions, a key concern within the circular economy and Sustainable Development Goals (SDGs) framework, might also be found within a Life Cycle Sustainability Assessment (LCSA) under the term "Global Warming Potential" (GWP). The example of the Environmental Impact Category for Michelin Company may help to identify key drivers.

Table 1 : Example of environmental indicator from EPD

ENVIRONMENTAL IMPACT CATEGORY

			PRODUCT STAGE			[illegible] STAGE	USE STAGE	END OF LIFE STAGE	
[illegible]	UNIT	TOTAL	[illegible]	TRANSPORTATION	MANUFACTURING	DISTRIBUTION	TYRE USE	[illegible]	[illegible]
Global warming potential	kg CO_2eq	2.81E+01	2.42E-01	2.90E-02	1.92E-02	2.02E-02	2.78E+01	6.44E-05	3.21E-05
Acidification potential	mol H+eq	9.58E-02	2.04E-03	3.91E-04	6.33E-05	7.86E-05	9.33E-02	2.24E-07	3.01E-07
Eutrophication potential (freshwater aquatic)	kg Peq	2.57E-04	1.14E-04	1.47E-07	4.12E-06	1.98E-07	1.39E-04	3.27E-10	1.33E-08
Photochemical ozone formation potential	kg NMVOCeq	8.89E-02	8.87E-04	2.52E-04	1.03E-04	8.07E-05	8.76E-02	2.12E-07	3.68E-07
Ozone depletion potential	kg CFC-11eq	5.10E-06	4.05E-08	5.18E-09	8.10E-09	3.65E-09	5.04E-06	1.19E-11	4.63E-12
Abiotic depletion potential	kg Sbeq	1.31E-05	6.93E-06	5.93E-09	2.34E-08	8.10E-09	6.17E-06	1.55E-11	1.42E-11

Source: EPD 225/45 R17 91V MICHELIN e•PRIMACY (2021)

OECD and PSILCA are other examples of valuable reference for LCSA indicators in research. Table 2 and 3 present an example of indicators relevant to rPET.

Table 2 : List of environmental indicators

Emissions and drivers

- Greenhouse gas emissions: levels, intensities, by source, by sector
- GHG emissions footprint: production-based and demand-based GHG emissions, intensities, productivities
- Energy use: energy supply and mix, intensities, share of renewables

Impact & Risks

- Annual temperature change
- Annual precipitation change
- Population exposure to hot days
- Cropland exposure to drought

Policy measures and instruments

- Climate actions and policies
- Taxes relevant for climate change: revenue raised and tax base structure
- Fossil-fuel support: fossil-fuel subsidies and other support measures
- Net effective carbon rate
- Official development assistance for climate: mitigation, adaptation

Source : OCDE (2025)

<u>Table 3</u> : List of social indicators for PSILCA

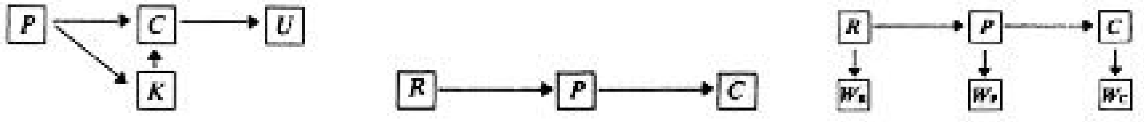
STAKEHOLDER	SUBCATEGORY	INDICATOR	Unit of measurement
WORKERS	CHILD LABOUR	Children in employment, male (% of male children ages 7-14)	%
		Children in employment, female (% of female children ages 7-14)	%
		Children in employment, total (% of all children ages 7-14)	%
	FORCED LABOUR	Evidence of forced labour	Text
		Frequency of forced labour	%
	FAIR SALARY	Living wage, per month	local currency
		Minimum wage, per month	local currency
		Sector average wage, per month	local currency
	WORKING TIME	Hours of work per employee, per day	h
		Hours of work per employee, per week	h
		Standard weekly hours	h
		Standard daily hours	h
	DISCRIMINATION	Occurrence of discrimination	Text
		Women in the labour force (% of economically active female population)	%
		Men in the labour force (% of economically active male population)	%
		Ratio of salary of women wages to men	%
	HEALTH AND SAFETY	Accident rate at workplace	#/100,000 workers
		Fatal accidents at workplace	#/100,000 workers
		Occupational risks	Text
		DALY due to indoor and outdoor air and water pollution	DALY/1,000 persons
		Presence of sufficient safety measures	# of security incidents
	SOCIAL BENEFITS, LEGAL ISSUES	Social security expenditures out of the total GDP	%
		Evidence of violations of laws and employment regulations	#/yr h
		% of workers with a contract	%
	FREEDOM OF ASSOCIATION, COLLECTIVE BARGAINING, RIGHT TO STRIKE	Trade union density (% of employees organised in trade unions)	%
		Right of association	index value
		Rigth of collective bargaining	index value
		Right to strike	index value
		Existence of standard rates	Y/N
LOCAL COMMUNITY	ACCESS TO MATERIAL RESOURCES	Level of industrial water use (% of total withdrawal)	%
		Level of industrial water use (% of total actual renewable)	%
		Extraction of material resources (fossil fuels, biomass, ores, minerals)	t/capita
		Presence of certified environmental management systems	#
		Description of (potential) material resource conflicts	Text
	RESPECT OF INDIGENOUS RIGHTS	Presence of indigenous population	Y/N
		Human rights issues faced by indigenous people	Text
		Respect of indigenous rights	Text
	SAFE AND HEALTHY LIVING CONDITIONS	Pollution level of the country	index value
		Contribution of the sector to environmental load	Text
		Drinking water coverage (% of the population)	%
		Sanitation coverage (% of the population)	%
	LOCAL EMPLOYMENT	Unemployment rate in the country	%
		Work force hired locally	%
		Percentage of spending on locally based suppliers	%
	MIGRATION	Migrant workers in the sector	%
SOCIETY	CONTRIBUTION TO ECONOMIC DEVELOPMENT	Economic situation of the country	index value
		Contribution of the sector to economic development (in % of total GDP)	%
	EDUCATION	Public expenditure on education (% of GDP)	%
		Illiteracy rate, male (% of male population)	%
		Illiteracy rate, female (% of female population)	%
		Illiteracy rate, total (% of total population)	%
	HEALTH AND SAFETY	Health expenditure out of the total GDP of the country	%
		People affected by natural disasters (as % of population)	%
		Life expectancy at birth	Years
	PREVENTION AND MITIGATION OF CONFLICTS	Risk of conflicts with regard to the sector	Text
VALUE CHAIN ACTORS	FAIR COMPETITION	Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	Text
		Presence of policies to prevent anti-competitive behaviour	Y/N
	CORRUPTION	Corruption index of country	index value
		Evidence of an active involvement of the enterprises in corruption and bribery	%
	PROMOTING SOCIAL RESPONSIBILITY	Presence of codes of conduct that protect human rights of workers among suppliers	index value
		Membership in an initiative that promotes social responsibility along the supply chain (number of enterprises)	#
	SUPPLIER RELATIONSHIPS	Interaction of the companies with suppliers (payment on time, sufficient lead time, reasonable volume fluctuations, appropriate communication...)	Text
CONSUMERS	HEALTH AND SAFETY	Presence of management measures to assess consumer health and safety	Y/N
	TRANSPARENCY	Presence of certifications or labels for the product/sites sector	Y/N
	END OF LIFE RESPONSIBILITY	Strength of national legislation covering product disposal and recycling	Text

<u>Source</u>: JRC (2015, p. 44)

The Circular Economy (from 4Rs to 10Rs)

The circular economy is mainly inspired by the precepts of ecological economics and industrial and territorial ecology (Ghisellini et al., 2015), incorporating in the process the economy of functionality (Stahel, 1977, 1982) and the sharing economy (Henry et al., 2021). In the book *Economics of Natural Resources and the Environment,* Pearce and Turner (1989) explain the transition from the traditional linear or open economic system to the circular economic system. In Chapter 2, they describe a circular economic model based on the assumption of a high degree of interdependence between the economy and the environment that if we ignore the environment, then the economy is assimilated to a linear system. Production, P, is intended to produce consumer goods, C, and capital goods, K. In turn, the capital goods will produce consumer goods in the future. The aim of consumption is to create utility. In such a scheme, natural resources R have their rightful place.

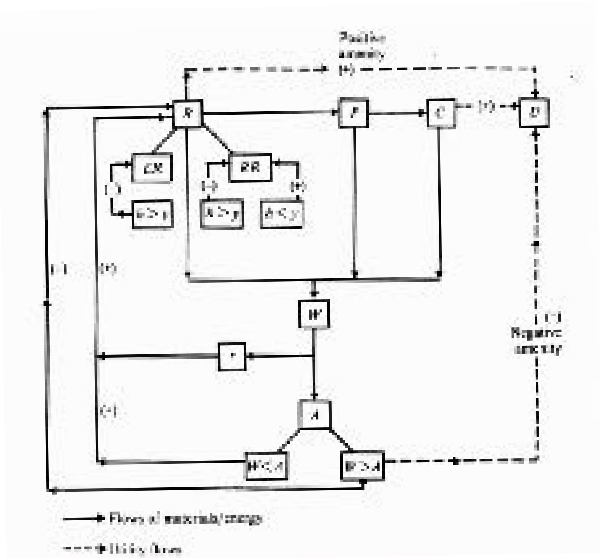
Figure 3 : Representation of a linear system



Source : Pearce, Turner (1990, p. 35-36).

While this initial representation of a linear system makes it possible to identify the relationship between flows (production, consumption) and stocks (natural resources), it remains incomplete because it does not include waste, W, which can appear at all stages (natural resources, production and consumption). But waste represents only a very small part of the relationship between the environment and the economy (Diemer; Sarr, 2023). Figure 4 presents the circular economy described by Pearce and Turner. Flows of materials and energy follow the laws of thermodynamics in a closed system . Flows of utility are interconnected with consumption. Pearce and Turner added this flow to highlight the third function of the environment: it supplies utility directly in the form of aesthetic enjoyment and spiritual comfort but if waste is excessive from assimilative capacity, A, the economic process should damage the function of the environment.

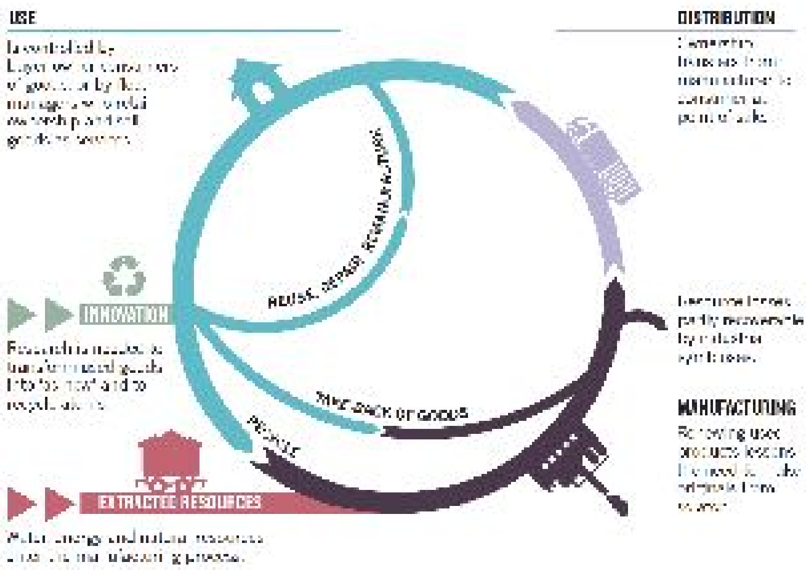
Figure 4 : Framework of a circular System



Source : Pearce, Turner (1990)

Systems thinking is useful to go deeper in the understanding of circular economy. In a system, entities (persons, companies, infrastructures, flows, stocks…) interact with each other. These entities develop functional relations (extraction of natural resources, production of goods, distribution, consumption of goods, recycling of waste). The goal of circular economy is to close the loops and improve the performance of the system (reducing natural resources extraction, GhG emissions and waste, optimising production process or minimizing the full cost). Some interactions (feedback loops) may reinforce (positive polarity, Reinforcing loop) or regulate (negative polarity, Balancing Loop) the circular process.

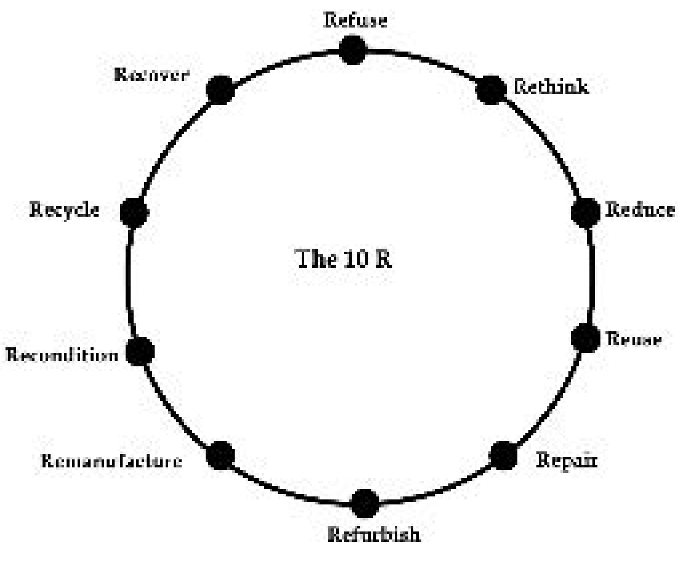
Figure 5 : Closing the loops with Circular Economy



Source : Stahel (2016, p. 436)

In business strategy, the circular economy may take the form of the relative framework such as the 3Rs "Reduce, Reuse and Recycle" (Ghisellini et al., 2015) the 4Rs "Reduce, Reuse, Recycle, Renewable" (Debladis et al., 2019) or the 10Rs "Refuse, Rethink, Reduce, Ruse, Repair, Refurbish, Remanufacture, Recondition, Recycle, Recover" (Diemer, 2012).

Figure 6 : The 10 Rs



Source : Diemer (2012)

If *Refuse* can be complicated to implement in a value chain, the European Green Deal makes the claim to *Rethink* production and consumption patterns in the EU by increasing sustainability of products, reducing environmental impacts, creating new jobs and improving human health. Eco-design, industrial and territorial ecology, the economy of functionality… are the different pillars on which the circular economy is based. Extended Producer Responsibility or extension of lifespan of products are illustrations of the new Circular Business Models (CBM). CBM may help shift consumer patterns and behavior towards less resource use and smaller environmental impacts (Henry & al., 2020, EPA, 2021). Table 4 and figure 7 give an overview of circularity strategies (Potting, Hekkert, Worrell, Hanemaaijer, 2017, Henry & al., 2020, EPA, 2021) associated with the different Rs.

Table 4 : Typology of circularity strategies based on different Rs

Smarter creation and use of products	R0 Refuse	Turning a product redundant by cancelling its function, or by substituting it with a radically different product.
	R1 Rethink	Intensifying product use (e.g. via product sharing or multifunctional products).
	R2 Reduce	More efficient use and/or manufacture of products through the use of fewer natural resources and materials.
Extending the lifespan of products and parts	R3 Reuse	Reuse of discarded yet still usable product, for the same purpose, by a different user.
	R4 Repair	Repair and maintenance of broken or malfunctioning product, to enable continuation of its original function.
	R5 Refurbish	Refurbishing and/or modernising an older product, so that the improved version can be used in the product's original function.
	R6 Remanu-facture	Using parts of a discarded product in a new product of the same function.
	R7 Repurpose	Using discarded products or their parts in new products with a different function.
Usefull application of materials	R8 Recycle	Processing of materials to achieve the original high-quality or reduce to low-quality.
	R9 Recover	Incineration of materials, recovering their energy.

Source : EPA (2021, p. 10)

Figure 7 : Categorisation criteria and definition for CSU typologies

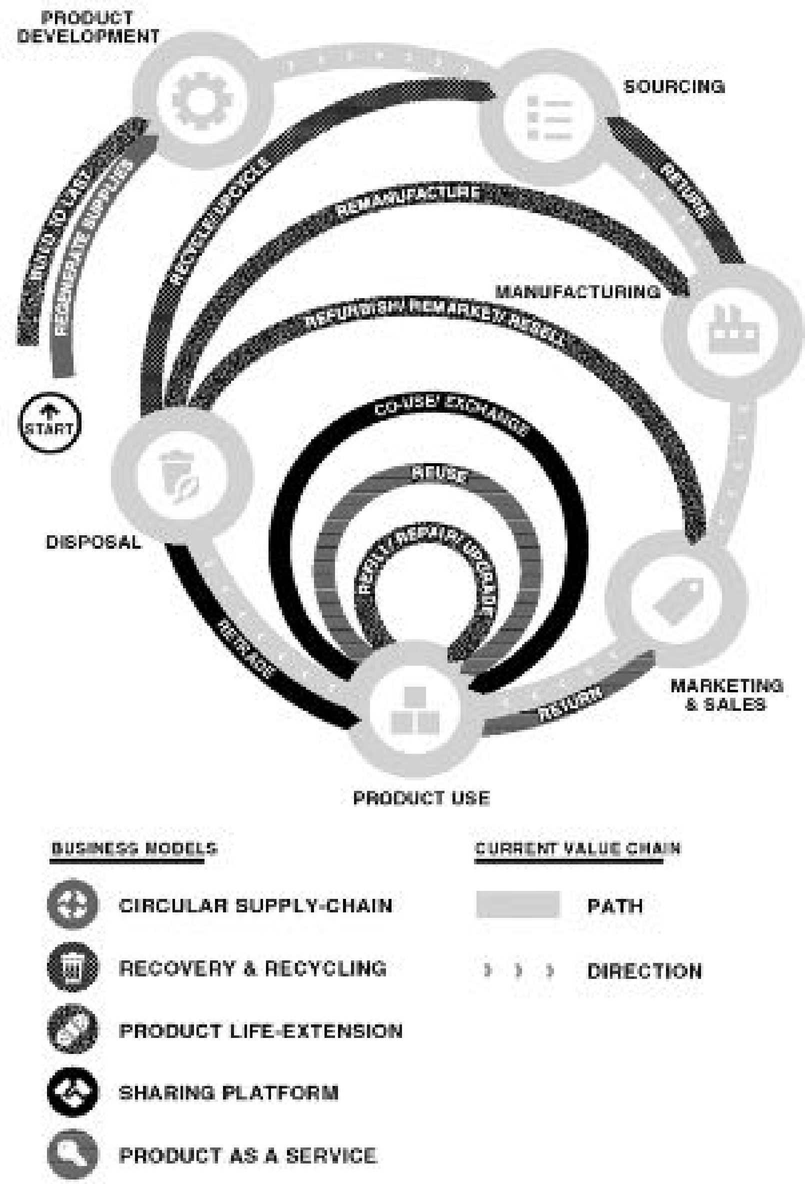
CSU archetype	CBM strategy	Innovation category	Definition	Share of data sample (n = [illegible])
Design-based	Reduce/ Reuse	Core technology	[illegible]	[illegible]
Waste-based	Recycle, Recover	Industrial symbiosis	Waste-based CSUs [illegible]	27%
Platform-based	[illegible]	Enabling technology	Platform-based CSUs [illegible]	18%
Service-based	[illegible]	PSS	Service-based CSUs [illegible]	5%
Nature-based	Regenerate	Various	Nature-based CSUs [illegible]	6%
Other	Reduce, Reuse, Recycle	Various	CSUs [illegible]	3%

Note: [illegible]

Source : Henry, Bauwens, Hekkert, Kirchherr (2020, p. 11)

This typology of circularity and criteria is very complementary to that proposed by Lacy and Rutqvist (2015) for Circular Business Models. Five models have been described : (1) *Circular supply chain*: replacing traditional inputs with bio-based, renewable or recovered materials, (2) *Recovery and Recycling :* producing secondary raw materials from waste streams (recycling and recovery of resources from waste to close material loops); (3) *Product life extension*: extend product life by ensuring that circularity of material and components is considered at the design phase to allow for direct reuse, maintenance, repair, refurbishment and remanufacturing, recyclability, use of secondary resources for the production; (4) *Sharing platform:* promote the use of underutilised consumer assets more intensively (private owners can share their assets as houses and cars with strangers in exchange for a payment). (5) *Product as a service* : combining a physical product with a service component while ownership remains with the supplier (this model provides customers an access to a product's function, instead of selling the product).

Figure 8 : The five Circular Business Models



Source : Lacy, Rutqvist (2015, p. 118)

OCDE (2019) and EPA (2021) used this typology of CBM to challenge circularity (key characteristic, drivers, sectors), to identify strategies of companies when they decide to adopt combinations of circular business models (circular supply chain with Service as a system) rather than one or to compare (benchmarking) the organization of different sectors (metals sector mainly focused on recovery and recycling, Pinto, Diemer, 2020).).

Table 5 : Circular Business Models

	Circular supply	Resource recovery	Product life extension	Sharing	Product service system
Key characteristic	Replace traditional material inputs with renewable, bio based, recovered ones	Produce secondary raw materials from waste	Extend product lives	Increase utilisation of existing products and assets	Provision of services rather than products Product ownership remains with supplier
Resource efficiency driver	Close material loops	Close material loops	Slow material loops	Narrow resource flows	Narrow resource flows
Business model sub types	Cradle to cradle	Industrial symbiosis	Classic long life	Co-ownership	Product oriented
		Recycling	Direct reuse	Co-access	User oriented
		Upcycling	Repair		Result oriented
		Downcycling	Refurbishment		
			Remanufacture		
Main sectors currently applied in	Diverse consumer product sectors	Metals	Automotive	Short term lodging	Transport
		Paper and pulp	Heavy machinery	Transport	Chemicals
		Plastics	Electronics	Machinery	Energy
				Consumer products	

Source : OCDE (2019, p. 25)

The project of recycled PET concerns the first group of models (circular supply chain) with indirect loop effects on Product Life Extension, Resource Recovery and Product Service Systems (Michelin doesn't sell a good - the tire - but a service, how many kilometers do you use the tire ?). Life Cycle Assessment (Diemer, 2023; Pinto, Sverdrup & Diemer, 2019) and SDGs reporting complete the methodological framework and literature review.

Sustainable Development Goals (SDGs)

The United Nations Sustainable Development Goals (SDGs) have become a reference point for policy-making processes worldwide. The SDGs provide a shared vision for sustainable development which essentially indicate the need to protect the social and environmental equilibrium in the process of economic development. Their implementation is possible due to the global goals set, which in a more or less precise manner indicate the directions in which organizations and people should follow to care for both the environment and each other (Aneta, 2023). The first step was the publication of the report Our Common World (so called Brundtland Report), sustainable development has to meet the needs of present and future generations in full compliance with the natural environment (WCED, 1987). The concept of sustainable development has evolved over time from the Millennium Sustainable Development Goals (MDGs) in 1992 and to the current version named 2030 Agenda goals (SDGs) which was drawn up in 2015 with a 15 year period of implementation planned. Refer to Table 6, it outlined 17 goals, 169 associated targets and 231 unique indicators.

Table 6 : SDGs, Targets and Indicators

Goals and targets (from the 2030 Agenda for Sustainable Development)	Number of targets	Number of indicators
Goal 1. End poverty in all its forms everywhere	7	13
Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture	8	14
Goal 3. Ensure healthy lives and promote well-being for all at all ages	13	28
Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	10	12
Goal 5. Achieve gender equality and empower all women and girls	9	14
Goal 6. Ensure availability and sustainable management of water and sanitation for all	8	11
Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all	5	6
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	12	16
Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	8	12
Goal 10. Reduce inequality within and among countries	10	14
Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable	10	15
Goal 12. Ensure sustainable consumption and production patterns	11	13
Goal 13. Take urgent action to combat climate change and its impacts3	5	8
Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development	10	10
Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	12	14
Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels	12	24
Goal 17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development/	19	24
Total	169	248*

Source: https://unstats.un.org/sdgs/indicators/indicators-list/

*The global indicator framework includes **231** unique indicators. Please note that the total number of indicators listed in the global indicator framework of SDG indicators is 248. However, thirteen indicators repeat under two or three different targets

Traditionally developed with national governing organizations for applications on a policy level, SDGs became a great challenge for companies, especially for those who wanted to contribute to these goals. According to the UN Global Compact Strategy 2024–2025, the strategy for business practice on the SDGs can be divided into three group (figure 9):

(1) 'Lead and shape'; (2) 'Cooperate with others' (3) 'Follow and amplify'

Figure 9 : Summarises SDGs priorities in three general categories

Source: UN Global Compact Strategy 2024–2025

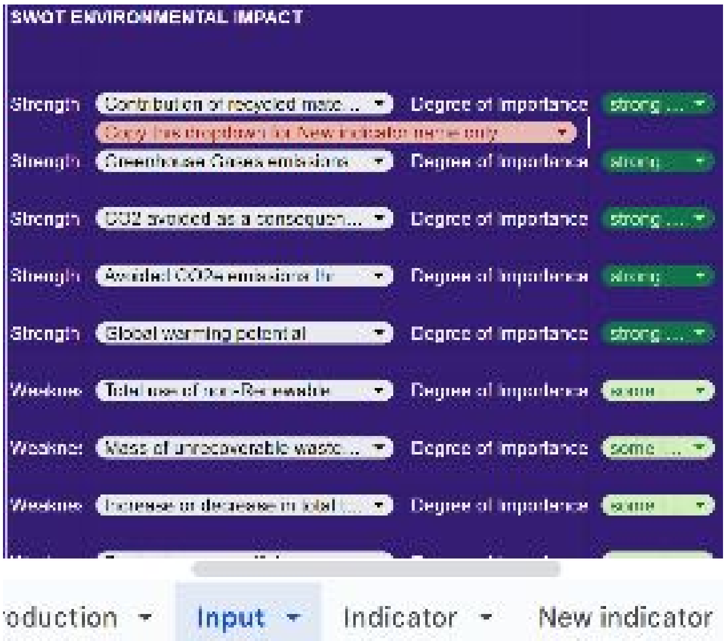
There are several studies researching SDGs in business practice. KPMG (2022) investigated the world's 250 largest companies across all sectors. The result reveals that three SDGs are in the focus of companies: 8: Decent Work and Economic Growth; 12: Responsible Consumption and Production; and 13: Climate Action.

Methodology

The study employed both qualitative and quantitative data collection techniques and design proceeds in three steps: (1) Indicator Identification, (2) SWOT Matrix Development and (3) Cross-Impact Matrix Analysis. The first step, analyze five relevant frameworks to source key indicators impacting the economy, environment, and society for the projects. These frameworks include: Indicator from company, Cost-Benefit Analysis (CBA), Life Cycle Sustainability Assessment (LCSA), Sustainable Development Goals (SDGs), Circular Economy principles

The second step of the analysis involved conducting a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis to assess the factors influencing the success of the project. A questionnaire, created using Google Sheets, was distributed to project partners. The partners were tasked with identifying the five most impactful indicators for each SWOT category. Additionally, partners were asked to evaluate the impact level of these indicators on the project, categorizing them as either "some impact" or "strong impact. The scale for positive factors (Strengths and Opportunities), a strong impact was assigned a value of 2, while some impact was assigned a value of 1. Conversely, for negative factors (Weaknesses and Threats), a strong impact was assigned a value of -2, and some impact a value of -1. For this step, by limiting the scale of impact value -2 to 2 is to prevent single high-value responses from disproportionately outweighing multiple lower-value responses and ensures that consensus among team members is more accurately reflected in the final analysis. To ensure comprehensive input, partners were also given the option to suggest new indicators not included in the original list. The questionnaire, along with detailed instructions and indicator definitions, was made accessible to all partners through Google Drive (Figure 10).

Figure 10 : Example of SWOT questionnaire and sheets



Source : The Authors

The third step of the analysis involved selecting an appropriate CIM method to forecast potential interactions between the identified economic, environmental, and social factors related to the project. For this purpose, the three most impactful indicators from each domain, as determined in the previous step, were utilized in the method Type 4: the Conditional Probability method combines both the level of impacts and their probability of occurrence. To obtain quantitative forecasts, project partners were asked to vote on both the level of impact and the probability of occurrence for each indicator in relation to the project, as well as its interactions with other indicators. The impact level was measured on a broader scale ranging from -5 to +5 with the definition in Table 7. The application of a broader scale (-5 to 5) is in line with the study of research (Kenneth, 2008) which allows for more quantitative impact values, providing a more detailed assessment of the previously identified key indicators. The probability values and their corresponding definitions are presented in Table 8.

Table 7: The impact level and definition

Impact level	Definition
-5	The most negative impact to factor
-3	Negative impact to factor
-1	Slightly negative impact to factor
0	No impact
1	Slightly positive impact to factor
3	Positive impact to factor
5	The most positive impact to factor

Source : Kenneth (2008)

Table 8 : The probabilities value and definition

Scale	Probability	Probability score	Scope
VLO	<10%	0.1	Very unlikely to occur
LO	10 - <30%	0.3	Unlikely to occur
MED	30 - <50%	0.5	May occur about half of the time
HI	50 - <70%	0.7	Likely to occur
VHI	≥70%	0.9	Very likely to occur

Source : Project risk analysis and management guide, 2nd edition (2007)

Sequence of the study

Step 1 Key indicators impacting the economy & financiers, environment, and society for the WHITECYCLE projects

Step 2

S (Strength factor) S1, S2, S3

W (Weakness factor) W1,W2, W3

O (Opportunity factor) O1, O2, O3

T (Threat factor) T1, T2, T3

Step 3

Vec (Vector representing the expected impact of indicators to economy)

Ven (Vector representing the expected impact of indicators to environmental)

Vs (Vector representing the expected impact of indicators to society)

Results and discussions

SWOT and CIM

A detailed list of the indicators and their respective references are shown in Appendices A (Economic), B (Environmental), and C (Social). In total there are 182 indicators across three key domains: Economic, Environmental, and Social. The economic domain contains 55 indicators, the environmental domain includes 87 indicators, and the social domain comprises 40 indicators.

Tables 9, 10, and 11 show examples of top three Environmental, Social, and Economic SWOT analyses based on partner votes. These indicators are retained for the next step. It should be noted that the examples below are hypothetical situations created to illustrate the method's application. They do not represent the actual of any project result. The Strengths, Weaknesses, Opportunities, and Threats presented may be hypotheses proposed by partners without quantitative support. Then these hypotheses require follow-up and confirmation through indicator results at a later stage.

Table 9 : Environmental SWOT

SWOT Summary	
Main Strengths	**Main Weaknesses**
Tons of waste avoided	**Energy (and Exergy) Consumption**
CO2 emission avoided as a consequence of recovery and reuse of materials	Mass of unrecoverable waste generated when producing recycled feedstock for a product
Circular material use rate	Increase in total thermal energy consumption
Main Opportunities	**Main Threats**
Tonnage of waste diverted via reuse and upcycling activities	Acidification potential
Evolution of the tonnage of plastics collected in the city	Product (with recycled material) end-of-life treatment
Recycling rate of municipal waste	Eutrophication potential(freshwater aquatic)

Table10 : Social SWOT

SWOT Summary	
Main Strengths	**Main Weaknesses**
Number of new jobs	**Employee Engagement rate**
Increase number of partnerships with municipalities/distribution	Diversities and Inclusion Management Index
Number of connection between companies	Number of technologies transferred
Main Opportunities	**Main Threats**
Worker skill development	Local community acceptance, such as complaints from society
Numbers of articles published creating positive publicity	Cost of training and education programmes per employee
Improvement in well-being of worker	Turnover and workforce of organizations working in the circular economy

Table 11 : Economic SWOT

SWOT Summary	
Main Strengths	**Main Weaknesses**
New revenue models related to the circular economy	**Operational Cost (OPEX)**
Avoided cost for the waste disposal	Capital Cost (CAPEX)
Investment in research for increasing circular knowledg and expertise	Investment to maintain product quality
Main Opportunities	**Main Threats**
Material import dependency	Energy cost
Total cost savings due to avoided GHG emissions	Material cost
Gross value added in environmental goods and services sectory	Labor cost

Source : The Authors

Building upon the SWOT assessment, the nine most impactful indicators (three from each domain in bold), were subjected to further analysis in CIM. Next step, project partners were asked to vote on both the level of impact and the probability of occurrence for each indicator in relation to the project, as well as its interactions with other indicators. Table 12-13 presents an example to illustrate the procedure of CIM. The recycled PET has the following level cross-impact matrix on social domain as follows.

Table 12 : Conditional probability cross-impact matrix of Social-related indicators

The probability of impacting from indicator to other indicators	Weak employee Engagement rate (0.7)[1]	Increase number of new jobs (0.7)	Increase worker skill development (0.9)
Weak employee Engagement rate	1	0.5	0.9[2]
Increase number of new jobs	0.5	1	0.5
Increase worker skill development	0.9	0.5	1

[1] The initial probability (0.7), from definition in table 5, means that Weak employee Engagement rate has 50-70% chance of occurring in project

[2] The probability 0.9, from definition in table5, indicates that there is >70% chance that the Increased worker skill development will impact the weak employee engagement rate.

Table 13 : Cross-impact matrix of Social-related indicators

Affect this/ How does this	Weak Employee Engagement rate	Increase number of new jobs	Increase worker skill development
Weak employee Engagement rate	-3[3]	-1	3[4]
Increase number of new jobs	1	3	1
Increase worker skill development	-3	1	3

[3] The value -3, from definition in table 4, means that weak employee Engagement rate has negative impact to project

[4] The value 3, from definition in table 4, means that Increase worker skill development has the positive impact to Weak employee engagement rate

So the operation of cross-impact matrices is as followed:

$$A = \text{Impact vector} = \begin{bmatrix} -3 & -1 & 3 \\ 1 & 3 & 1 \\ -3 & 1 & 3 \end{bmatrix} \qquad B = \text{Conditional probability vector} = \begin{bmatrix} 1 & 0.5 & 0.9 \\ 0.5 & 1 & 0.5 \\ 0.9 & 0.5 & 1 \end{bmatrix}$$

then,

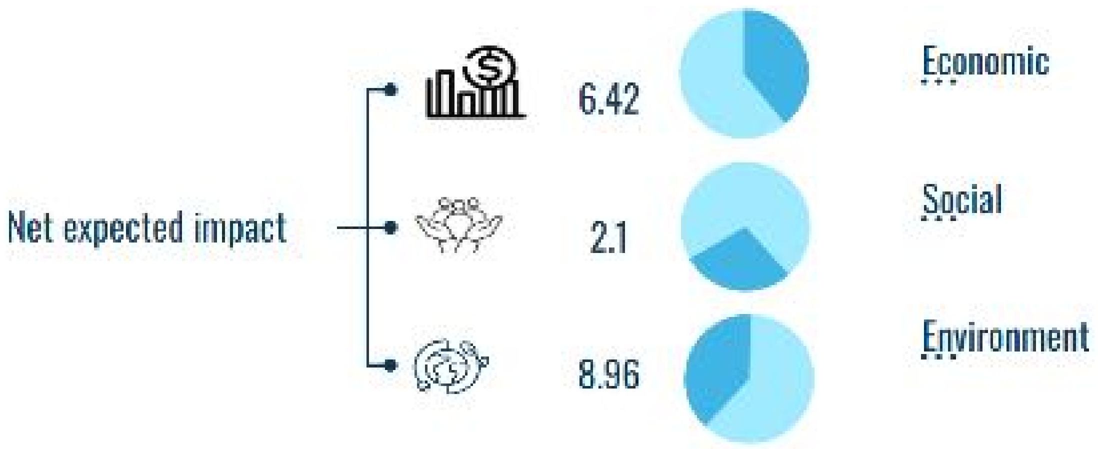
$$\begin{bmatrix} -3 & -0.5 & 2.7 \\ 0.5 & 3 & 0.5 \\ -2.7 & 0.5 & 3 \end{bmatrix} \times \begin{bmatrix} 0.7 \\ 0.7 \\ 0.9 \end{bmatrix} = \begin{bmatrix} -2.94 \\ 2 \\ 3.04 \end{bmatrix}$$

X = Likely cross-impact vector P = An initial probability vector S = Expected impact vector

These calculations show that : (i) the expected impact of three indicators, economic value of recovered material, investment in research for increasing circular knowledge and energy cost, on the WHITECYCLE project are positive; (ii) Investment in research for increasing circular knowledge has the highest expected positive impact on the WHITECYCLE project, with a value of 3.5; (iii) the sum of the expected impact vector is 8.54, representing the net economic expected impact derived from the CIM.

At the end, a dashboard of net expected impact from the cross impact matrices can be revealed as shown in Figure 11. Analysis of the results can show that among three domains which one demonstrates the highest cumulative impact to the project when compared to others domains. This result suggests that the project is likely to have its most significant influence in that sector, which can serve as a key indicator for evaluating the project's future development and success. The nine most impactful indicators identified through this analysis, along with their corresponding impact values, can be retained as critical variables for incorporation into another study such as future dynamic model studies. This approach will enable a more comprehensive understanding of the project's potential long-term effects and interactions across various domains.

Figure 11 : Dashboard of net expected impact from the cross impact matrices



Source : The Authors

Conclusions, study limitation and future research

This paper presents a novel approach to strategic management for projects involving rPET by integrating SWOT analysis with CIM. This combined method provides a more comprehensive and dynamic framework for identifying key impact indicators, understanding their interrelationships, and developing effective strategies for maximizing project success. While the specific results from the WHITECYCLE project are confidential, the paper showcases the broader applicability of the methodology, serving as a valuable resource for future research and strategic planning in the field of circular economy initiatives. By adopting this approach, stakeholders can make informed decisions, mitigate potential risks, and seize opportunities to advance the transition towards a more sustainable future.

Concerning limitations and future research, three key areas warrant attention. First, the limited number of simulation scenarios and their restricted domain scope represent a constraint. While the two half-day workshops with partners proved sufficient for the current study, future research could benefit from a more comprehensive simulation incorporating a dynamic model to evaluate impacts. Second, the absence of standardized impact value thresholds hinders the establishment of clear impact value to trigger specific actions. The decision to take action on impact indicators relies on team judgment. Third, challenges remain in comprehensively capturing cause-and-effect relationships for some indicators, necessitating careful interpretation. Subsequent indicator selection and action definition will be guided by team interests, project strategy, and targets.

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System Dynamics Modelling for implementing Life Cycle Sustainability Assessment of recycled PET (polyethylene terephthalate) in the tire industry

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Abstract : This chapter consists of assessing the impacts of Polyethylene terephthalate (PET) recycling supported by the WHITECYCLE project of the European Union Commision. The goal of this study is to analyze how System Dynamics (SD) modeling can help to minimize environmental, social and economic adverse impacts of PET recycling and to foster a circular economy of PET recycling (rPET) supply chain. We use System Dynamics method to describe the organization of actors, the flow of complex wastes from tires, hoses and multi-material clothing treated by each actor across the PET recycling chain. Also, it consists of identifying the inputs used in waste treatment such as energy, chemical, water, infrastructure, vehicles, … in order to assess the sources of impacts and how much these impacts are. Then, the SD analysis is in line with Life Cycle Assessment (LCA) analysis in the fact that we will take into account the rPET products' life cycle stages in the impact assessment in terms of costs and advantages for the environment and also social and economic.

Introduction

Polyethylene terephthalate (PET) is widely used in plastics and textiles leading to over 20 Million tonne/year (Mt/y) of complex waste (textile, tire, hose, …) worldwide. The absence of closed-loop recycling for complex waste makes that most complex waste is landfilled (Muringayil et al., 2024) particularly in less developed countries which do not allow the extraction of new natural resources, reduce water pollution and soil quality degradation. These wastes are incinerated which is not a viable solution to reduce natural resources depletion and environment quality degradation. Then, there is an urgent need to develop a circular solution to convert complex PET wastes from plastics and textiles back into high-added value products. Plastic and complex waste recycling are more than necessary to tackle GHG emissions, biodiversity loss, water and soil pollution, and the demand for virgin raw materials. A viable closed loop for PET recycling of complex waste is an important solution to address the challenges of a sustainable economy. It is for this reason that the European Union (EU) aims to implement an innovative European project to process and recycle PET from complex waste named "WHITECYCLE[1]". The ambition of the project is to combine strong scientific and industrial know-how to implement a full circle loop to recycle PET from real complex waste contributing to increase uptake of recycled plastics and contribute to the more sustainable use of plastics. It is envisioning the redefinition of the plastic value chain namely tire, lay-flat hoses and multicomponent textiles to make it 100% circular by 2050. The achievement of this ambitious project will contribute to avoid up to 1.8 Million tons of plastic landfilling or incineration each year, and avoid up to 2 Million tons CO2 emissions. It will not only contribute to reducing pollution from waste but also, to reduce the negative impacts of waste on human health and to create value added to waste. Then, in this deliverable, the reason to use System Dynamics (SD) tools is to understand the

[1] This study was carried out as part of the European Whitecycle project : CL6 - 2022 - 2026 - CIRCBIO. https://www.whitecycle-project.eu/. 17 partners are involved in this project.

influence of the "new" technology WHITECYCLE is developing on the PET industry, by demonstrating the dynamics emerging and to assess social, economic and environmental impacts of this new technology that interests to recycle PET from complex waste. It consists of developing a SD model which will map the organization of stakeholders along the PET value chain and the interactions between them through the flow of resources and information. By designing the model, we expect to identify the different inputs used in the recycling processes by industries and to estimate the environmental, social and economic costs of the different activities realized in the PET recycling value chain. The SD modeling approach is useful to describe the PET waste recycling system and to show how SD modeling can help to create a new "circular value chain".

The first part of the paper consists of presenting SD based on Industrial Dynamics (Forrester, 1968) and a literature review of the use of SD in industry operations. The second part focuses on the description of the PET supply chain in SD view by using the PET recycling steps apprehended by different Work Package (WP), to identify also some social, economic and environmental impacts that could have occurred in the implementation of the project. The last part of the paper concerns the calculation of some indicators at the company level by referring ourselves to SDGs indicators on which the company can based to create a standardized framework for performance comparison, to promote transparency and sustainable investment.

System Dynamics Literature

Goal and Scope of System Dynamics

Industrial Dynamics (1961) is one of the first books talking about System Dynamics. Forrester describes how the interactions of different areas of management can lead to its success or failure. The information-feedback systems come from the fact that the management environment leads to a decision process that generates an action which modifies the environment. This process is continuing over time within a closed loop and is materialized by non-linear interconnections. The industrial system is constituted by many components and the principal functions are production and transformation, transportation, distribution, and retail. These components are interrelated by six main flows of information, money, materials, orders, labor and capital investment. Then, the interactions between these elements determine the system structure or organization, the policies applied, the material and informational delays within the industrial system. The continual and non-linear process is a characteristic of the most part of business activities that are interconnected by various components with complex information-feedback systems. According to Meadows (2008), a system is foremost an interconnection of a set of elements that are well organized and interact to achieve a goal. The interactions are not static but dynamic such a way that the change of one influences others. The non-linearity processes are very crucial to sustain or not the system over time. Nowadays, the manufacturing systems operating within factories become more and more complex, so, the managers must be trained to understand the different characteristics of feedback-informations that emerge from systems, their use to implement better management systems and deal with incertitude (Baines & Harrison, 1999). It is for this reason that Forrester developed the System Dynamics (SD) approach to study the behavior of the industrial system. It is to analyze how the industry system is organized, how policies, decisions and delays interact to influence the industry growth, stability and fall. The first objective of the method is to guide business managers in their understanding of the business cycle and how they can deal with incertitude. But with time, this technique has been improved and applied into the social sciences areas and for the purpose to be applied to any situation.

Nowadays, various sectors in economic, social and environmental domains behave similarly like the industry dynamics. They evolve with more instability and their "*causal structures are determined by* *physical or social constraints, goals, rewards and pressures*" (Cosenz & Noto, 2016). These things impact their behaviors and create more risk for the future. SD applications that are relevant in issues investigation than discrete event simulation models can help to find the drivers in and/or out of sectors of the causes and to develop strategic management and planning to address issues. To do it, SD helps managers and policymakers to learn the historical behaviors of industry components, identify the main factors which are in the origin of the instabilities, find solutions and strategies to deal with these drivers to minimize or prevent troubles in the industry systems. Beyond Forrester's work, SD is used to analyze industry activities in primary, manufacturing, services and any sectors. For Baines & Harrison (1999), the scope of these applications are applied in the operations level concerning manufacturing system modeling, production planning, operations management. Secondly, in business level for business planning, forming strategies, testing, marketing and financial scenarios, corporate planning. Thirdly, it is applied at the global level (and national level) through political policy planning, national strategies and world issues. In the literature, SD is mostly used to analyze natural resources management at a global and national level due to ecological problems and environment pollution. At the manufacturing level, System Dynamics is less developed and the most part of papers is applied in the operations scope for the purpose to control the detail aspects of manufacturing components and to analyze the sources of problems and business cycles (Baines & Harrison, 1999).

However, such as an interaction between various components, the behavior of systems is based on its component structures which further depend on the types of elements that compose them. Indeed, the overall dynamic of systems is one hand dependent on the organization of their components and the other hand, on the interrelationships between component's elements (Sterman, 2000). For example, the waste management value chain goes from raw material, the production of waste and collection to its valorization. Its dynamic depends on the organization of these components and the different elements that composed them. Also, the actions and policies implemented in the system, the innovations made by the system actors have some impacts on the behavior of the system. Because the purpose of these actions, policies and innovations implemented is to shift the functioning of the system towards a desirable direction for the actors. In the end, the delays mean that in real life the flow of physical materials and information takes time from one point to another. So, the interactions between system's components and elements sometimes are not systematic. It takes time to order a service and to be delivered, it takes time to develop or acquire a new innovation for a manufacturer and to train its employees to use that technology in the production process. So, in the modeling process it is important to consider these delays that are one characteristic of real life relationships. Forrester (1961) considers that "*System Dynamics provides a framework by integrating the different functional areas of management to analyze how their interactions cause industrial behavio*r". So, the System Dynamics (SD) method is one of the frameworks which enables us to describe system behaviors over time, to show the interrelations and interactions between the functional areas of management and their elements. SD modeling method consists of using a digital computer to analyze the information-feedback concepts generated by the different components of the manufactory. This process is called "*simulation*" and is the general description of the system by using mathematical models to learn more about the characteristics and the behavior of the system. It consists of "*describe the conditions at one point in time that lead to subsequent conditions at later points in time and the behavior is observed and experiments to answer specific questions*" (Forrester, 1961). By using the cause and effect (causality) approach, the SD method provides two tools to describe system behavior. These two tools give an understanding of how system's elements are interrelated and how a variation of one can affect the other's state and changes to determine the performances of systems. The first tool is the *Causal Loop Diagram* (CLD) which uses the relation of cause and effect to understand the problem (Haraldsson, 2004). It is a qualitative descriptive giving a shared understanding both the generic and the specific of a system's organization. This organization or structure is shown by connecting the key elements in the core of the system, its drivers and exogenous elements with arrows while showing the sign of evolution of the destination variation when the starting variable changes. The second tool is the *Stock and Flow Diagram* (SFD). The SFD is a quantitative representation of both the pattern and the event of the system behavior (Meadows, 2008). It consists of using a computer, the values and mathematical equations of the system's elements to simulate their trend and to determine globally the performance of the system. This part of the modeling process allows us to visualize the trend of each element during the simulation time and to see how the change of one element affects other trends.

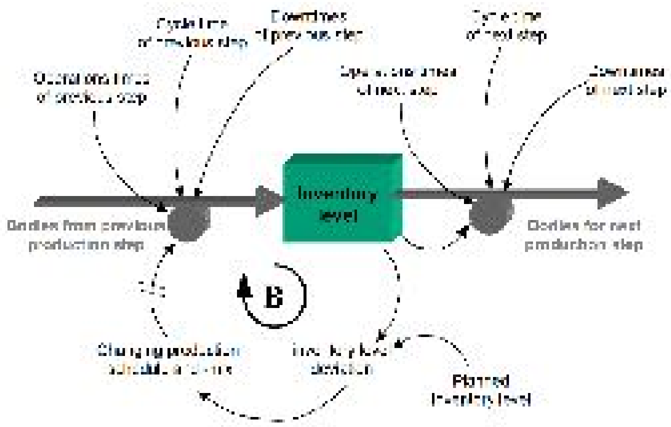
Then, these two tools analyze the structure of the system's elements that allow us to understand the functioning of systems in their environment which can lead to identifying some leverage points for decision taking and actions implementation. The SFD step of system dynamics distinguishes the nature of the system's elements such as stock and flow. Stock elements are the accumulation of physical and non physical or informational resources and represent "*the memory of the history of changing flows within the system*"(Meadows, 2008). They are measurable at one point of time and are built up and depleted by its inputs and output. Flows are the rates of stock gaining (inflow) and losing (outflow) (Richmond & Peterson, 2001). They represent activities or processes that cause change in the system, they are measured by considering two points of time. Converters are the variables or parameters that their value is not determined by the functioning of the system itself. We can consider them as drivers which have impacts on the system behavior but the system can not influence their value at any time. Then, we see that the functioning of the overall systems is given by the behavior of stocks and flows within systems, it means that recognising the difference between stocks and flows is crucial to understanding systems.

Indeed, the stocks and flows are the infrastructure of systems (Richmond, 1994). Their evolution in the past determines the behavior of systems in the future. However, the interactions of elements are materialized by retroactivity of feedback loops. System behaviors are persistent and run themselves through feedback loops. These feedback loops are two types: the first one is positive feedback loops and called reinforcing feedback loops and the second one is negative feedback loops and called balancing feedback loops. The reinforcing feedback loops are vicious or virtuous circle that can lead to destruction or growth. A reinforcing loop enhances the direction of change for the entry variable. However, the balancing loops run to stabilize (stability-seeking) or to reach a goal (goal-seeking). They intervene "*to keep the stocks at a given value or within a range of values*" (Meadows, 2008). These feedback loops sometimes act on the system behavior with a delay. The delay can be physics or informational showing that in human relationships and activities, things take time to be realized. They are not systematic facts all the time and the modeling process we have to consider this reality of delay that impacts the system behavior.

As a modeling method, SD is based on an interdisciplinary thinking called System Thinking (Goodman, 1997). It refers to recreate System behaviors and to explore their dynamics that are realized inside and outside the system through time. That responds to three objectives (Randers, 1973): first, it allows us to create models that are useful to explain the past and predict the future through the elaboration of various scenarios (Haraldsson, 2004). This type of prediction is to give a qualitative prediction of future behavioral tendencies of a system by considering almost all drivers that could influence the system functioning. This prediction consists of describing the behavior mode of a system based on the feedback loop structure. The second objective is to describe real-world phenomena. Even though it is difficult to model reality into its single aspects, SD modeling is useful to describe phenomena by focusing on the important factors that shed light on the problem. The third objective is the generation of insight. It is to give an overall view and understanding of the problem by using precise concepts, and in that case a mathematical model is a useful tool for intuitive analysis and to give effective communication. In sum, system dynamics modeling " *is constructed to increase the understanding of the real world and aid control of the human environment*" (Randers, 1973). In that case it is a management tool to improve decision effectiveness according to Forrester thanks to the system feedback loop structure.

Singularly used in its beginning, SD modelling is widely applied in strategic decision-making to address social, economic and environmental issues in national global and manufacturing levels (Diemer et al., 2022) even though its application in industry operations controls remains low (Baines & Harrison, 1999; Listl & Notzon, 2000). At the manufacturing level, the operation controls become more and more complex due to the occurrence of many constraints and drivers. Manufacturers have to account the operations time, the constraints to the deliveries, the changes in demand and other drivers and the various time delays. Listl & Notzon (2000) developed a SD model for inventory management at BMW (figure 1).

Figure 1: Causal Loop Diagram for Inventory Management



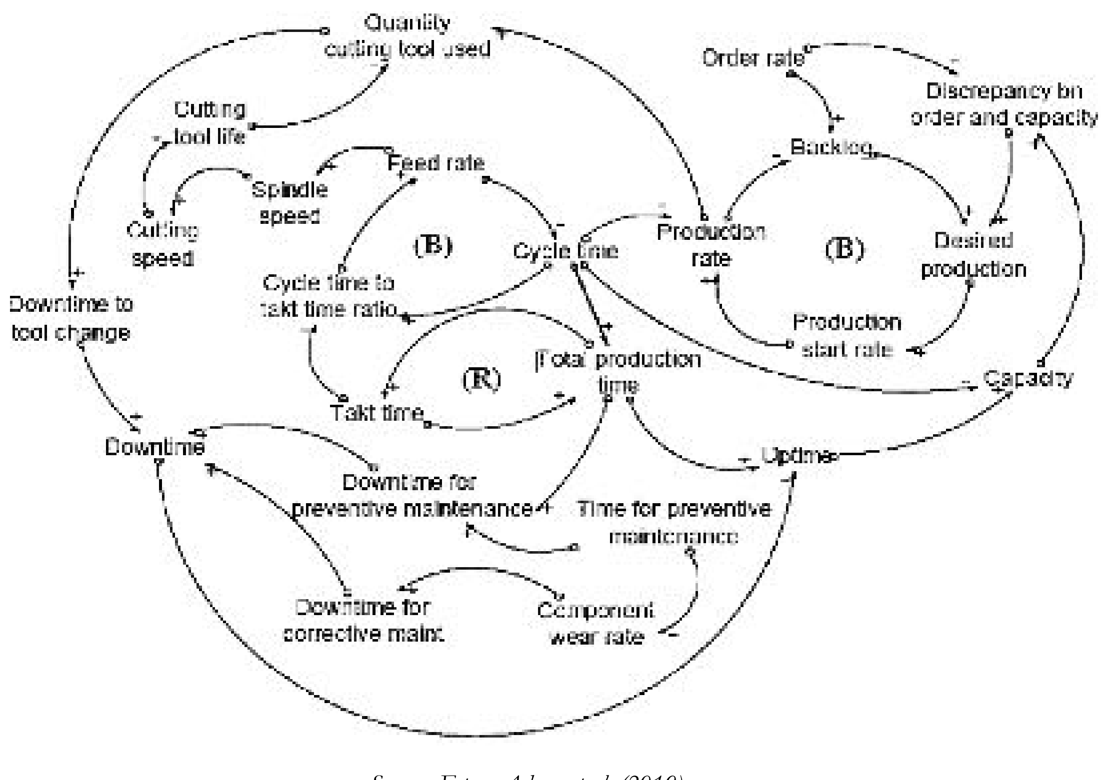
Source: Listl & Notzon (2000)

The purpose of their model is to support decision making on production schedule which takes into account "*the risk associated with different inventory policies and improves the management of inventories and production schedules*"(Listl & Notzon, 2000). The production schedule considers the operation times in each production department, cycles times to process a car body in one workstation and downtimes (the time when a machine is broken or the workers cannot work because components are not available, causing production losses) that impact the rate of production.

The model developed includes the flows of the body shop, the paint shop and the assembly shop of the manufactured bodies. So this tool enables the teams to discuss changes in the production schedule and test different scenarios by changing parameters to analyze their impacts on the inventory levels of the white body and the painted body stacker to meet the long term production and inventory goals. The use of the model helps the production department to monitor the inventory levels on a day-to-day basis and provides reports to other production which is not the case when the model is not implemented. Also, the production department could extend the inventory levels for the next few days to anticipate critical situations and to take actions and decisions in advance. The experience of using the SD simulation tool has been a great success for the production-planning department at BMWs plant in Regensburg leading the manager to say that : "*The simulation tool used within our department enabled us to increase our production output for more than 2000 units this year. This was achievable, because the simulation tool showed us in advance the possibilities of increasing the production by introducing extra shifts in the production schedule*" (Listl & Notzon, 2000). The 2000 units were needed to satisfy customer demands and contribute to increasing the net income of more than 15 millions US$.

In today's fast-moving business environment, manufacturers must strive to satisfy customer demands and desires (product designs or characteristics) at the most cost-effective price possible in order to make a profit. Without forgetting, the scarcity of raw materials for work-piece material, policy regulatory requirements for climate change, all these things cause turbulence affecting the manufacturing system performance. System Dynamics has the capacity to model system complexity, it is a potential tool helping to investigate and analyze the performance of the manufacturing system. Then, it is used by Fetene Adane et al. (2019) to analyze the capacity of the manufacturing system to control machining system parameters – based on current engine block production for the vehicle manufacturing industry. The objective of the SD application in this case consists to "*enable companies to implement improved potential manufacturing system optimization that responds during unexpected demand fluctuations. In addition, it will help in understanding the complex interaction between the process and operational parameters of a manufacturing system and help identify those critical parameters, ones that can lead to an optimizing strategy in the manufacturing standards of engine block production*" (Fetene Adane & al., 2019). .

Figure 2 : Causal Loop Diagram of the manufacturing dynamics

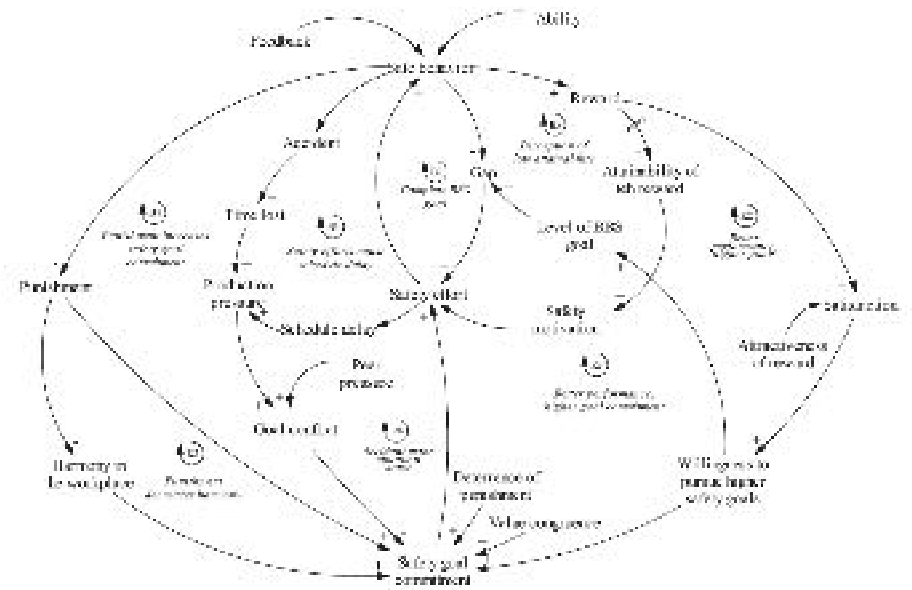


Source: Fetene Adane et al. (2019)

By referring to the CLD in the figure 2, they developed a SFD of the manufacturing system of an engine block considering the machining process that analyzes the performance of Dedicated Manufacturing Systems (DMS) and Flexible Manufacturing Systems (FMS) in machining for a given set of features notably the input fluctuations that can be determined by changing in the quantities of the demand. With an increase, decrease and cyclic demand variations the simulation results showed that SD can support the manufacturing system by proposing a new manufacturing strategy of policy for the purpose to reduce cost of production and improve productivity to satisfy customers demand requirement and fluctuation. Also, SD is a viable methodology that can be used "*to assist in the selection of manufacturing systems that will meet the future requirements of part production*" (Fetene Adane et al., 2019).

System Dynamics has been applied in the behavior-based safety (BBS) program which aims to support the Singapore construction industry to promote safe behavior of workers (Guo et al., 2018). Through the balancing (goal seeking) and reinforcing (amplification) theories, CLDs were developed to describe the changes of behavior by workers.

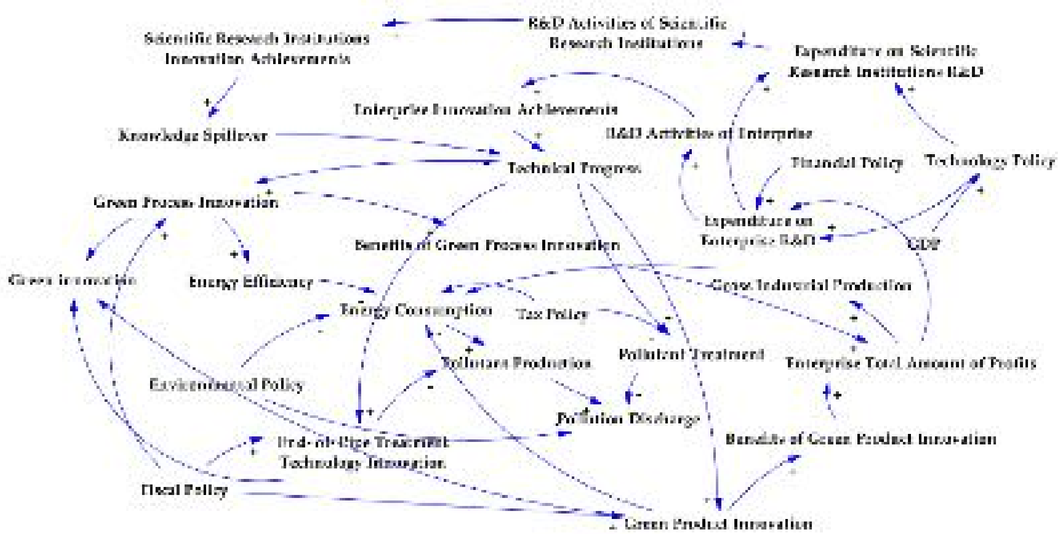
Figure 3 : An integrative causal loop diagram for safe behavior



Source: Guo et al. (2018)

Figure 3 shows that safe behavior by workers can be reached through workers' safety effort that has three drivers such as workers effort rewarding (monetary incentive), punishment and their safety goal commitment. Wu et al. (2021) showed how a green innovation can be reached by using the SD model in the Chinese manufacturing industry (figure 4). They found that a high level of the green innovation performance could be obtained through the implementation of synergic policies such as technology policy, financial policy, tax and fiscal policy and environmental policy. These policies have meaningful impacts on green product innovation, green process innovation and end-of-pipe treatment technology innovation which are the components variables for the green innovation variable.

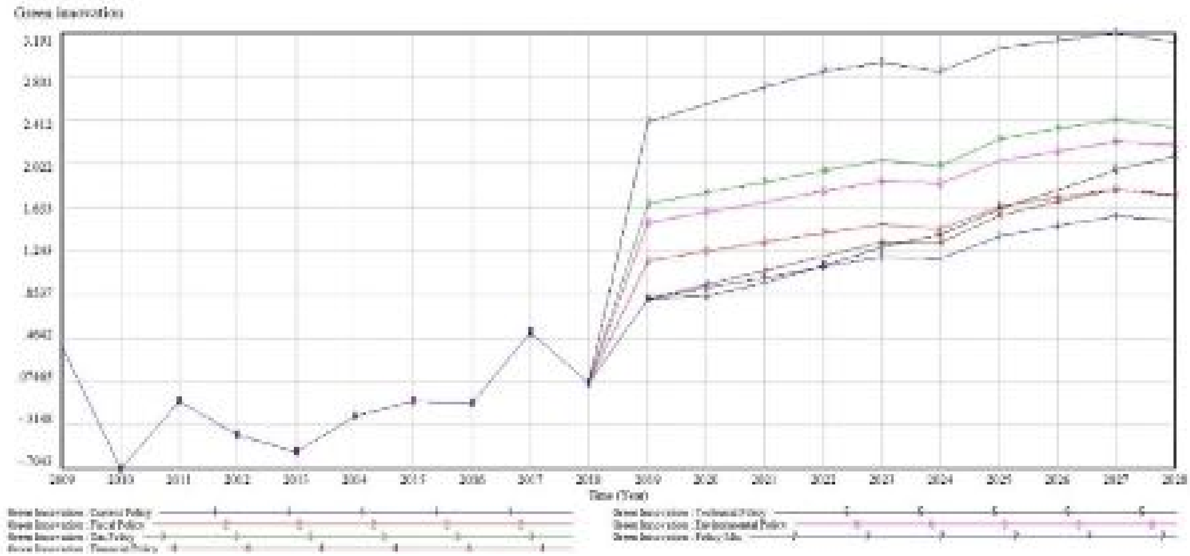
Figure 4 : Causal loop diagram of green innovation



Source : Wu et al. (2021)

Figure 5 shows the level reached in green innovation following the implementation of a certain number of policies (fiscal, technology, financial, tax, environmental policies) by Chinese manufacturing companies and the government which aim to enhance innovation. The different policy implementation strengths represent the input variables and the green innovation level is the output variable. The time frame of study is 2009-2028 and the data from 2019 to 2028 represent the prospective evolution of green innovation following the implementation of these policies. At the end, we see that the policy mix scenario that combined the five different policies' impact is higher than the impact of the single policy.

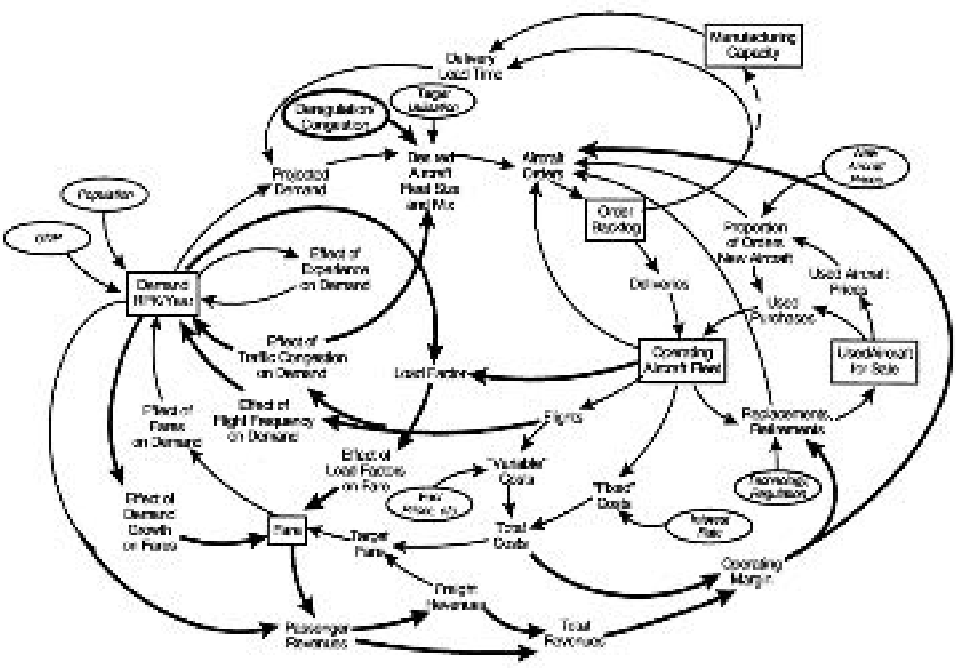
Figure 5: Curve of the policy mix simulation



Source: Wu et al. (2021)

As a prediction model and more of a prospecting model, SD is used in the manufacturing industry to forecast the behavior of industry variable performances in the future on which most of present decisions and policy are made. By using SD, Lyneis (2000) analyzed how it can help the aircraft industry to forecast short-to-mid term performances, to make better decisions than statistical models, to understand the causes of aircraft industry behavior and changes in industry structure and to elaborate some reasonable scenarios to decisions and policies. He developed the CLD represented in the figure 6 to analyze the causes of the cycling boom or over expansion and the bust of manufacturer production capacity. The results of his study show that the behavior of the causes of the cycles in the aircraft manufacturing industry are caused on the one hand by external factors such as the dynamics of GDP, population, fuel and other prices, interest rates and the target fleet use of the airlines. On the other hand, the cycles are also caused by internal aircraft industry dynamics resulting from the dynamics in passengers' demand to travel which affects fares, airlines orders for the replacement of tired aircrafts and delivery delay.

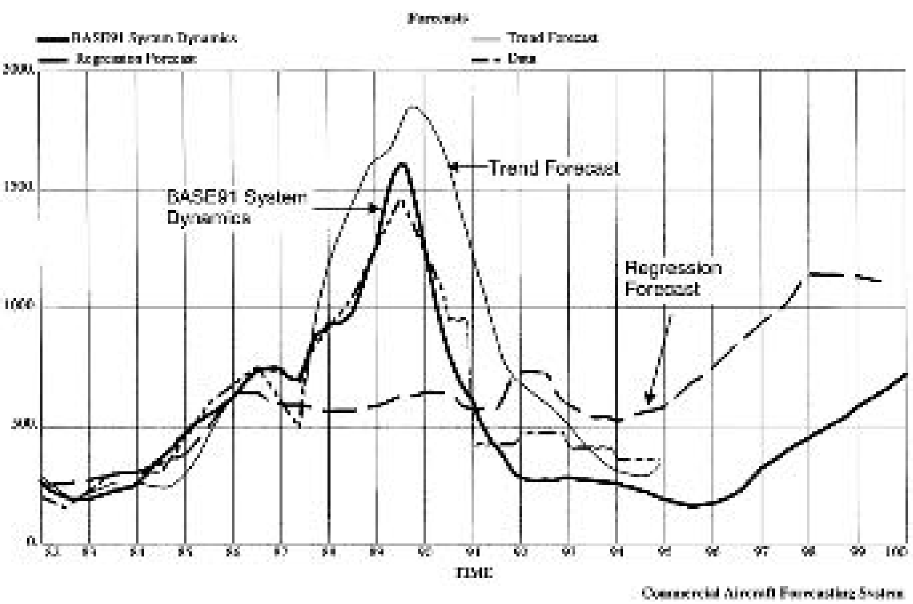
Figure 6: used market and financial dynamics reinforce cycles



Source: Lyneis (2000)

Figure 7 shows the best fit of historical data with the forecasting trend of new aircraft orders of linear regression, System Dynamics and trend extrapolation. The simulation results show clearly that only System Dynamics forecast is reasonable to match the historical trend of new orders. The linear regression forecast misses the peak caused by the changes in GDP and fuel price, also the trend forecast overshoots the peak by overestimating the impact of GDP and fuel price changes on new aircraft orders.

Figure 7: commercial aircraft forecasting comparison



Source : Lyneis,(2000)

As a tool to support decision making systems, the modeling process must obey many steps. By following the different steps proposed by Forrester (1968) and Roberts (1962), we can synthetize them in four main steps that encompass the different steps that we will discuss more in the next part of the paper. The first step is the definition of problem and objective. The second step refers to the theory description and the visualization of the dynamic system. The third is the mathematical model development by using a computer to simulate the system interactions. The fourth step is the implementation of the simulation results, the elaboration of policy and actions strategy for change and to create more desirable behavior of the represented system. Let's note that the third step includes data collection, calibration and sensitivity analysis to increase the model credibility. The step fourth includes also, the scenario elaborations to show optimist and pessimist behavior of the system represented.

Different steps for System Dynamics Modeling

SD modeling is a meticulous exercise which obeys to the cause and effect principle. This principle of direct effect and cause allows us to identify the information-feedback characteristics within the system and to identify the sources of problems or phenomena within feedback loops. It will help us to integrate the various components of the PET value chain, to analyze how they interact to achieve a vicious or virtuous circle for the PET recycling project (WHITECYCLE project). Once we identify the archetypes that provide opportunities to change or improve the behavior of systems, we will suggest some leverage points that can lead the system towards a virtuous circular value chain. Many lists of steps are proposed in the literature (Randers, 1973) but we focus our work on the list elaborated by Forrester, 1968 in ID. Table 1 shows that the modeling process starts by identifying a problem, the elements of the system that could be at the origin of the problem, the development of a SD model to assure that the assumed relations of selected elements could reproduce the problem through a simulation process. Finally, iterations processes will come for the model improvement and new results or knowledge construction from the first model designed.

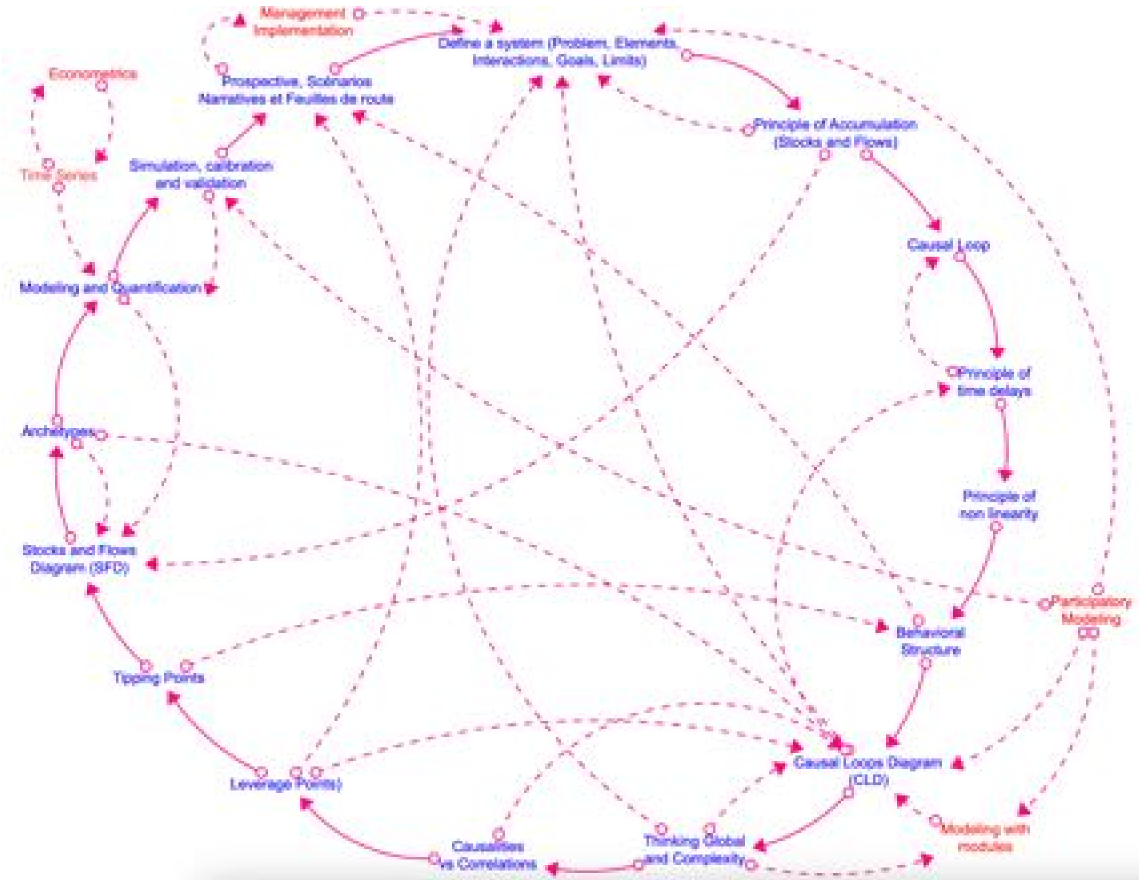
Table 1: Steps for SD modeling

1- Defining the objectives of the system under study
2- Observing symptoms
3- Detecting the real problem
4- Visualizing the system at issue
5- Estimating the boundaries within which lie the causes of the trouble
6- Selecting the factors to be dealt with
7- Constructing a formal model of the preceding
8- Using the model to simulate system interactions under selected conditions
9- Interpreting the significance of the simulation results
10- Inventing system improvements
11- Repeating all of these steps to move closer and closer to the true problems and to better management policies

Source: Forrester (1968)

More recently, Diemer (2023) proposed to split the System Dynamics Methodology into 16 steps (Figure 8). Starting to design the system (define goals and limits), identify the principles of accumulation, causal loops, time delays, non linearity interactions, behavioral structure, causal loops diagram, thinking global and complexity, casualties vs correlations, leverage points, tipping points, stocks and flows diagram, archetypes, modeling and quantification, simulation, calibration and validation, prospective, scenarios, narratives and roadmaps.

Figure 8 : 16 steps to improve System Dynamics Methodology



Source : Diemer (2022)

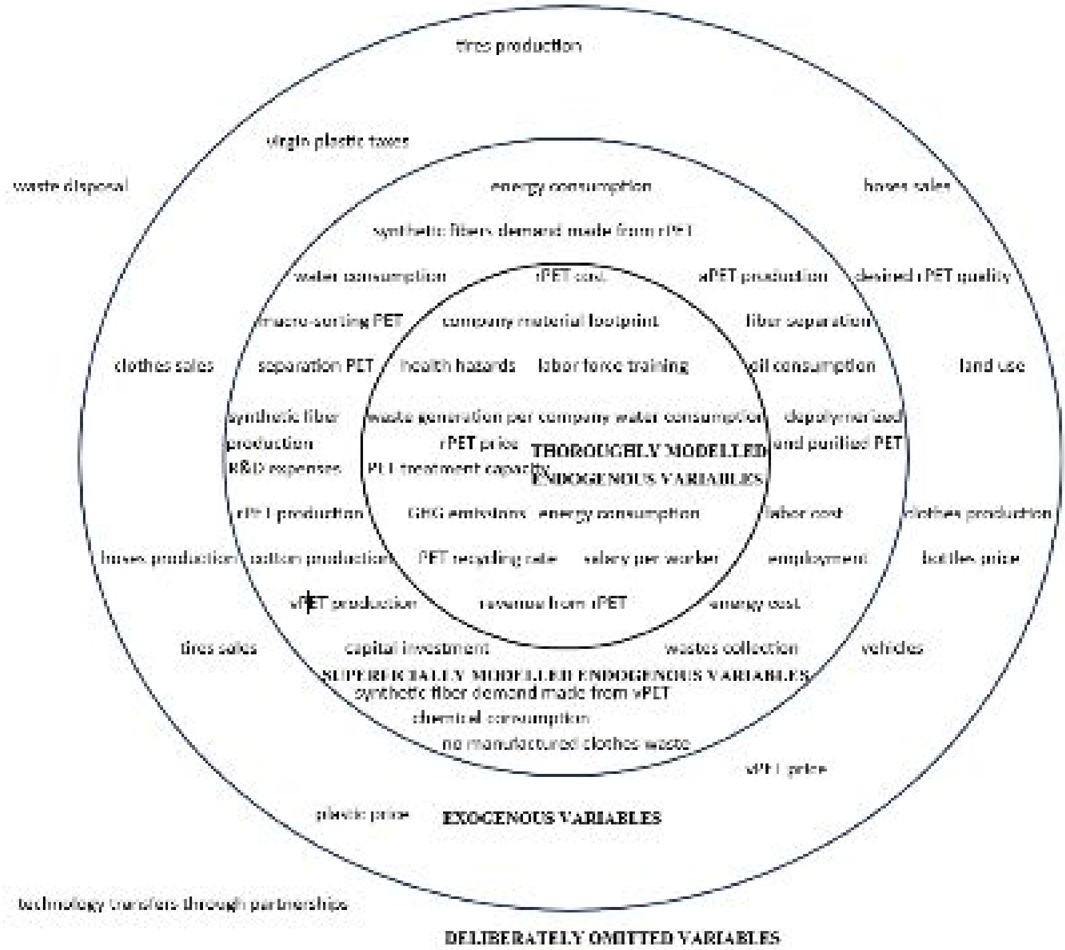
Four practices are relevant to improve the method : system dynamics participatory modeling, modeling with modules (especially when the model has a lot of variables), econometrics (to validate the model with time series) and management implementation (to convince managers to apply system dynamics methodology).

For our project, methodology consists to build a model that helps to understand the different mechanisms existing in PET recycling. The design of the model must help to describe the PET recycling value chain in order to optimize resources using, to improve better management, to give awareness and training, to reduce waste negative impacts and to propose some solutions for a better future of waste recycling. So, these different steps of system dynamics methodology will be the road-map of our work. The purpose is to describe the organization of partners along the PET value chain through the interrelation between PET recycling activities, to develop a quantitative model allowing us to measure the dynamics of flows between actors, to assess the potential impacts of PET recycling activities and end to propose some leverage points of changes thanks to the system structures and behavior to optimize the system performance in terms of green circular supply chain.

Systems Thinking, LCA and LCSA

Considered as a modeling tool to assess the environmental impacts of products and processes, Life Cycle Assessment or Analysis (LCA) is widely used to show how product recycling is important to fix natural resources' rarity and depletion (Diemer, 2023). It provides some clues to protect environmental quality, to keep or build a competitive economy and to reduce pollution effects on human health. In the industrial system, it helps to assess the environmental impacts from raw material extraction, the intermediary steps to waste using (valorization or disposal). Nowadays, LCA is an integrated assessment tool that considers the environmental impacts, the economic cost and social hazards associated with all stages of a manufactured product (Diemer, Durand, Sourgou, 2025). It is methodology "that can support the transition of the construction and real estate industry to a circular economy" (Larsen et al., 2022). With a system thinking approach, the purpose of the whitecycle project is to assess the different impacts of PET recycling in the environment, social and economic areas. It is meant to conduct a Life Cycle Sustainability Assessment (LCSA) task which involves a thorough inventory of different inputs and material used in the PET production, manufacturing, using and recycling. Then, the LCSA framework is the creation of a synergistic framework that takes into account Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (LCSA) frameworks in an integrated impact assessment framework. In this sense, we see that LCSA is rooted from System Thinking which is "a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects" (Arnold & Wade, 2015). This definition of System Thinking (ST) includes two interesting terms such as "systems" and "synergistic" that refer to the interaction of elements which work together in a way to produce a total effect that is better or desirable than the sum of the individual elements. It brings us back to the conception of sustainability that is the interaction between the environment, economic and social domains (Raworth, 2012). Indeed, these domains interact dynamically over time which are not linears because environmental resources are extracted and used in economic activities. These economic activities take place within the society and the natural environment from which social resources are drawn in order to generate economic value. Then, there are feedback links between resource extraction, economic resources accumulation, social resources use and environmental quality. In this context, using a non linear model such as System Dynamics to assess these interactions is more appropriate than a linear model. This is why we use SD in this work to assess the environment, economic and social impacts of PET recycling projects by considering the different steps of Life cycle Assessment meaning from PET raw material extraction (oil extraction), transportation, processing, manufacturing, distribution, use and recycling and reuse. The building of this circular economy involves taking into account the inputs of energy, labor, capital, investments, land, chemical, waste PET for recycling, … and outputs of emission, quantity of rPET, PET revenues, PET prices, ... Then, the Bull's Eye Diagrams below is an overview of the some elements of the PET value chain on which we decided to categorize by endogenous variables, exogenous variables and deliberately omitted variables. The Bull's Eye Diagram's purpose is to identify the key elements of the recycling project and to determine a boundary for the model that we are building. Our work is based on the industrial dynamics of Forrester so, our goal is to analyze the dynamic emerging from the PET value chain actors interactions and interconnections in order to assess environment, social and economic impacts. The variables of the model concern those that can allow us to measure a company's capacity of production in each WP, the inputs for production and end, the impacts from these activities. Then, the innermost circle that is the thoroughly modeled endogenous variables circle are some impact variables that we will try to assess in the whitecycle project, the superficially modeled endogenous variables concern the variables that determine PET recycling capacity and some inputs used in the waste treatment and recycling. The exogenous variables circle concerns the drivers which are essentials for the recycling process. And end, the deliberated omitted variables are those that could be impactful but we decide to exclude them in the model.

Figure 8: rPET value chain Bull Eye's Diagram



Source: the authors

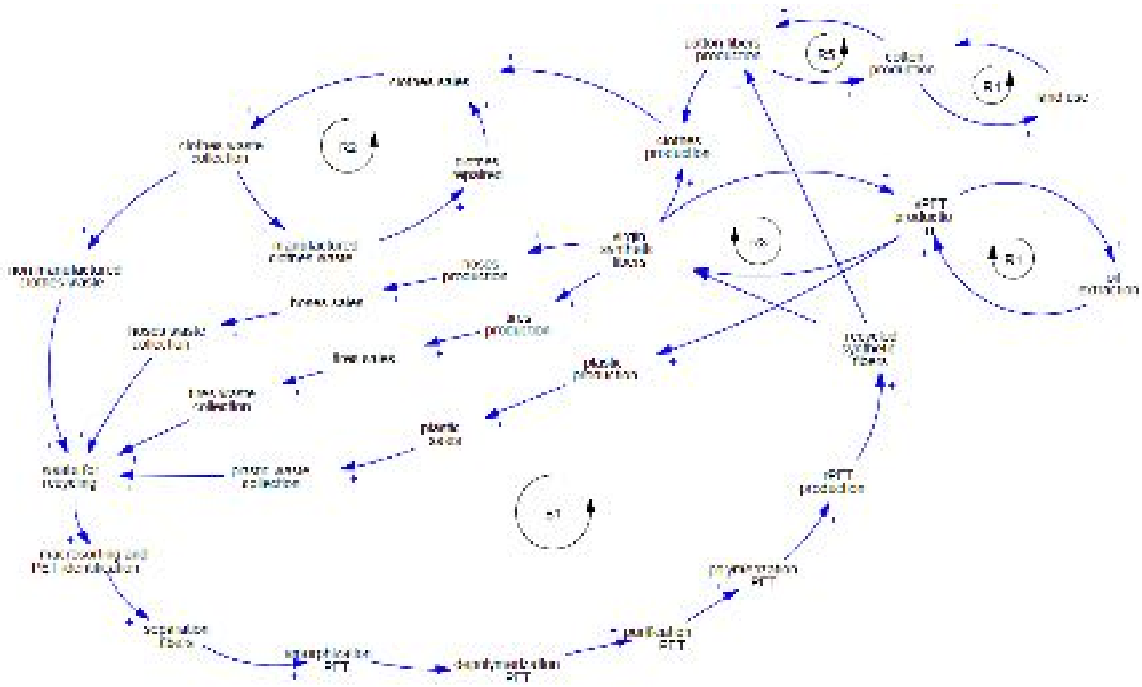
System Dynamics Model for PET (Textile, Hose and Tire)

The goals of the System Dynamics Model for PET are firstly to describe the functioning of the PET recycling process through the different steps and to get a shared knowledge about the interactions between the different parts of the supply chain. Secondly, it is to show the key elements of inputs and outputs that are relevant to shape the behavior of the recycling system by Work Package (WP) regrouping the partner's activities. Thirdly, we aim to use the different inputs and output to make a Life Cycle Assessment study for the purpose of determining the different impacts in environmental, social and economic areas generated by the Whitecycle project.

Causal Loop Diagrams of PET

The Causal Loop Diagram (CLD) of the figure 9 describes the structure of the PET supply chain starting with raw materials using via waste collection and recycling to PET recycling (rPET) to fibers and Yarn. The CLD structure is based on some main findings of some papers in the literature that provided some elements of thought in waste management with SD modeling (Das & Dutta, 2013; Pinha & Sagawa, 2020; Xiao et al., 2020). The first reinforcing feedback loop (R1) explains that we get Virgin PET (vPET) from oil processing and the more we produce vPET the more we use oil coming from the extraction process. The balancing feedback loop (B1) concerns the use of vPET in hoses, tires, clothes and plastic production by knowing that the main use of PET is the bottles market. So, after a certain time of use they become waste that we are going to collect and extract PET to be recycled (rPET) through many steps such as waste sorting, PET waste identification, fibers separation, PET amorphization, depolymerization, purification and polymerization. So, rPET obtained from waste could counterbalance vPET production with the reduction of virgin synthetic fibers produced from oil extraction (R3) and cotton production (R5) which has a positive impact on reducing oil consumption and land use. And end, the second reinforcing feedback loop (R2) refers to the part of clothes that could be remanufactured from waste collected and reintroduced in the value chain. This part of repaired clothes comes to increase stores' clothes inventory that will be sold to customers.

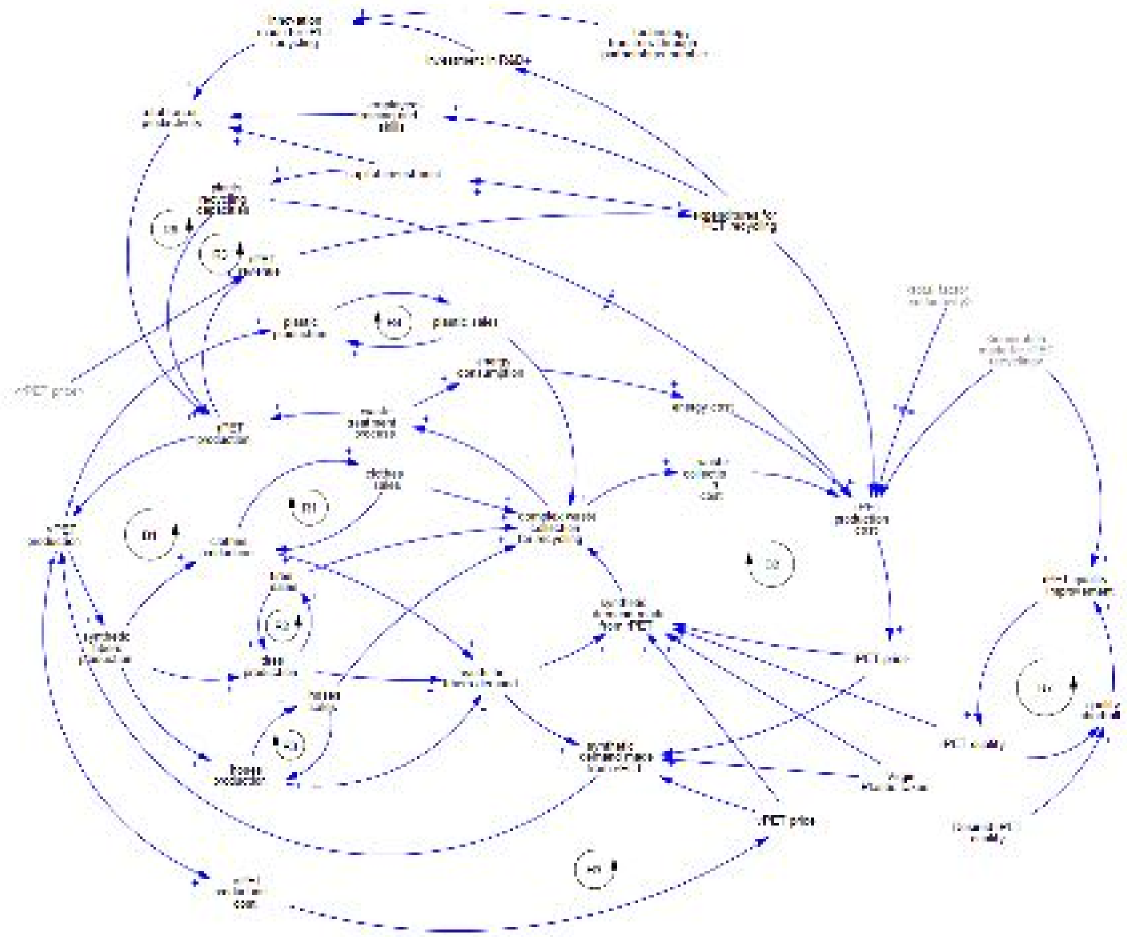
Figure 9: PET supply chain organization



Source: authors

After describing the PET valorization process, we decided to introduce the demand for rPET, vPET and also the prices for the two types of products to analyze the economic determinants of PET supply chain behavior. We see in the following CLD that the competitiveness of rPET to vPET is first linked to the difference of their prices. It means that if rPET price is higher than vPET, the plants that produce synthetic fibers will address their PET demand towards vPET producers. This situation could lead to a lower quantity of complex waste collected going into the PET recycling process. However, increasing expenditures towards investment in capital, R&D, technology transfers, employee skills improvement could in the long term be a leverage point to increase rPET competitiveness to vPET. The actual situation of the PET market in Europe is impacted by the non-competitiveness of rPET to vPET because rPET production cost is higher which leads to higher price. So the challenges for European countries are to find some strategies to reduce energy cost, storage cost and waste collection cost to lower the rPET production cost in order to match rPET production to demand (ICIS, 2022). That is one of the solutions to lower rPET prices in the EU. One more challenge for the European countries is to improve rPET quality which plays a key role in competitiveness. That quality improvement could be reached through a massive investment in equipment and technologies for a better treatment of waste. Another leverage point to enhance rPET value chain is to act on virgin plastic taxes. Because rising virgin plastic taxes discourages fiber demand made from vPET and shift it towards rPET fiber demand from rPET. It leads to reducing PET production from oil extraction.

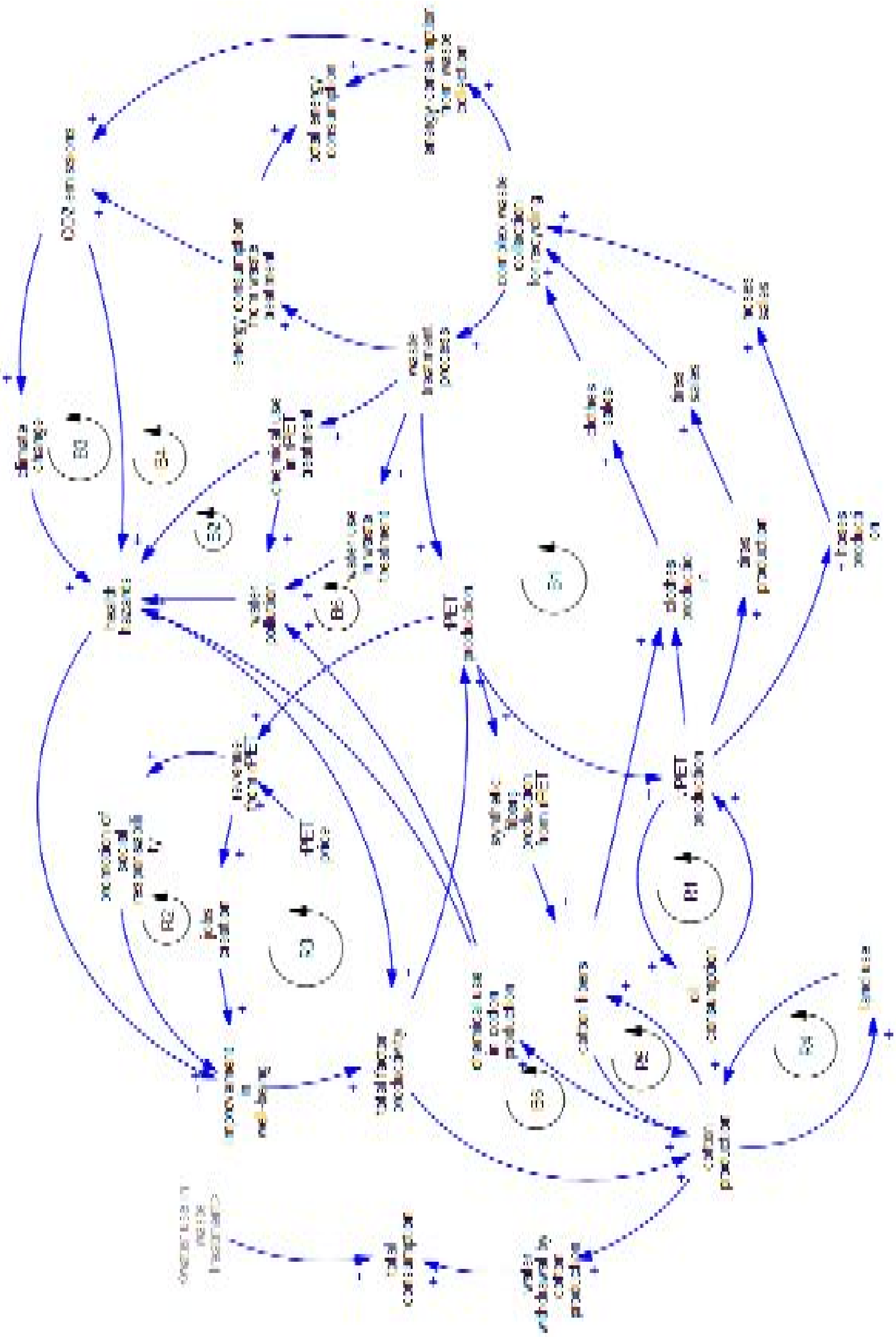
Figure 10: Economic value of rPET supply chain



Source: authors

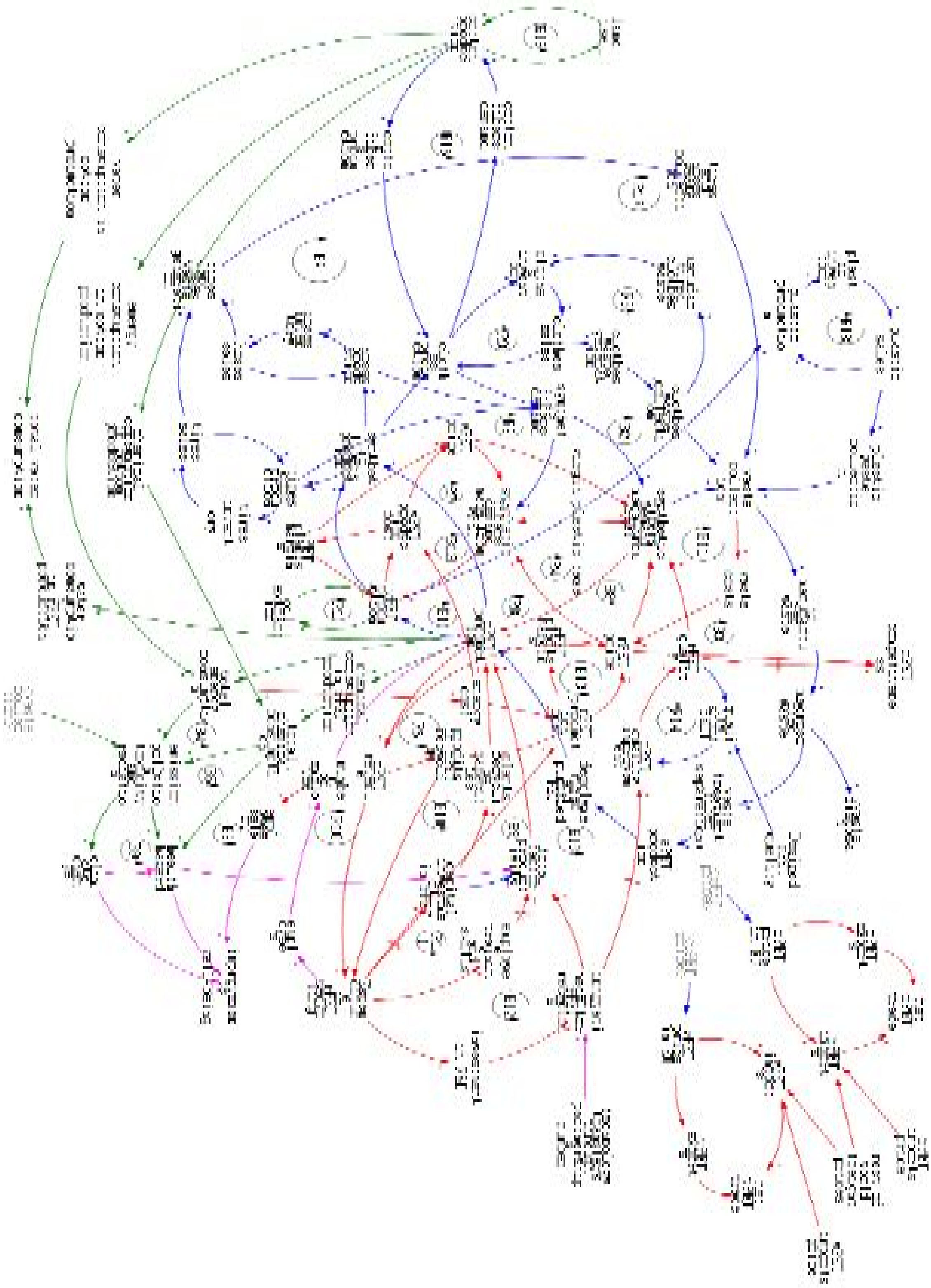
Beyond economic value production, the PET recycling activities are behind social and environmental impacts. Figure 10 shows that rPET treatment and waste collection necessitate energy use for machines and vehicles. The energy used by factors of production generate GreenHouse Gas (GHG) that contributes to climate change (B3) and health hazards (B4). Also, chemical substances are used in cotton production, PET purification and depolarization steps. These substances used have a negative impact on water quality and employees health status (B2 and B5). So, climate change, carbon dioxide emissions from energy consumption and chemical inputs have an adverse impact on employees health and we know that a bad health condition of employees will decrease their productivity which reduces rPET production (B6). But, the negative impact of total factor productivity reduction on rPET production due to the diminution of employee well-being is counterbalanced by the improvement in jobs creation and more social responsibilities promoted by industries (R2 and R3). The two reinforcing loops R2 and R3 describe first an improvement in employees well-being with high salary from new revenue generated by the supply chain. Secondly, by job creation and good working conditions due to more investments. These two levers show that enhancing employees well-being with high salary, good working conditions and training could create more employment engagement rate enabling to increase their productivity.

Figure 11: social and environmental impacts of the rPET supply chain



Source : The authors

Figure 12: Integration of all CLDs



Source: the authors

Stocks and Flows Diagram (SFD) of PET

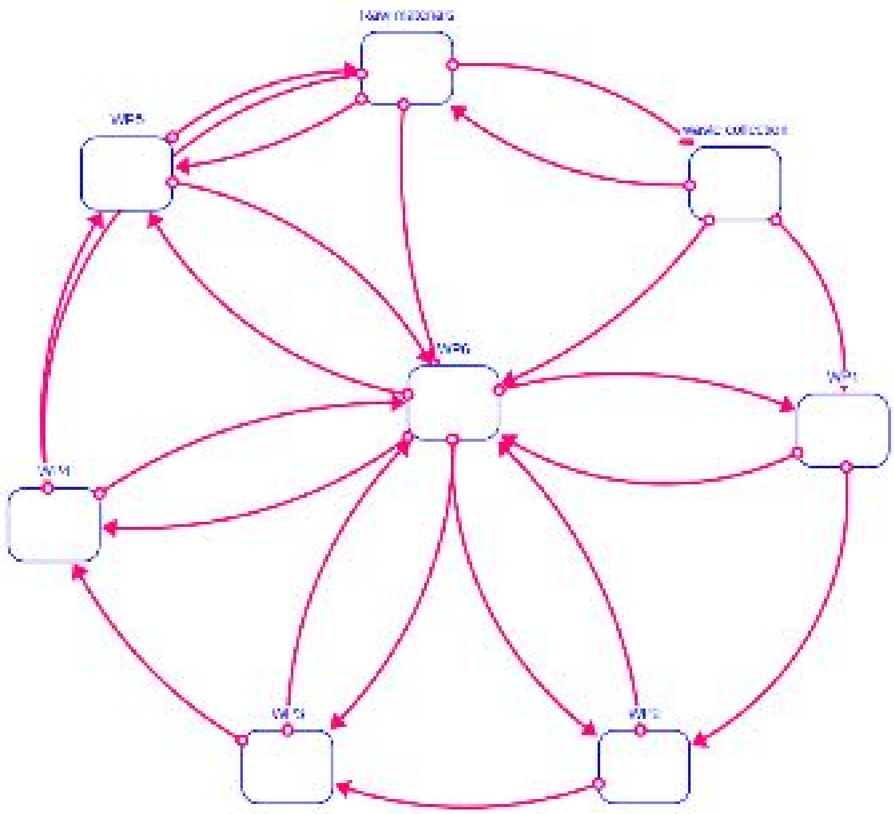
This stage of the modeling concerns the use of Stock and Flow Diagrams (SFD) which is one tool of SD that allows us to quantify the flows of materials and information across the PET system. We use Stella Software which enables us to create and simulate SD models by using variable data values. The model focuses on PET industry recycling activities and our goal is to analyze the behavior of the PET value chain to recommend the implementation of some strong actions and policy towards a sustainable value chain. So, we organize the modeling process by modules that allow us to regroup the flow of information and materials per step of the PET recycling activities. Each step is defined by a work package that we encapsulate into a module. The advantage of the module is to get the structure of the system elements (informations and materials variables) by type of activity, to use connectors[2] to draw the relationship between actors regrouped by work packages through the interconnections between variables in modules. That organization is helpful to identify the inputs and outputs for each module which is important to determine the nature and the quantity of resources going from one actor towards other actors. The inputs are the information or the materials need a WP meaning another actor to use in its production. The output variables contain information generated by WP and that can supply a value to other connected WP. Then the model below shows the interconnection between the different Work Packages (WP) that are related to each other by the module inputs and outputs. The firsts modules (respectively raw material and waste collection) concern the processing of oil and cotton to fibers which are used in the clothes, tires and hoses production. In the raw material (RM) module, it is to measure first, how much of vPET companies could produce with 1 barrel or kilogram (kg) of oil. Secondly in the module, it is a question to calculate the quantity of cotton and synthetic fibers that are used to produce 1 meter of cloth, 1 tire and 1 meter of hose. Measuring these quantities allows us to know how much waste could be collected by considering the product's lifetime of use. The quantity of waste collected is an input for the WP1 and used as raw material for the PET recycling process. So, the WP1 concerns sorting and separating PET from multilayer waste feedstocks of tires, hoses and clothes collected for recycling. In this step, our purpose is to calculate the quantity of PET that the Synergies company can identify and separate per year. We use the machine's production capacity, which is the number of tons of kg of complex waste sorted per year and the ton of PET separated per year from the complex waste. However, in the project, the idea is to constitute 80% PET content waste, so our purpose is to know the part of 80% PET content waste collected for recycling. When the 80% PET content waste is separated from complex waste, it is sent into the WP2 to be amorphized. Here, the PET amorphization is a pre-treatment process to decrease PET crystallinity and increase its surface area. We need here to measure the quantity of PET that can be shaped per year by using the unit capacity of amorphization. The WP3 concerns the depolymerization and the purification of the amorphized PET of the WP2. In this module, the actor's role is reducing the impurities through water use and additives. The goal in the WP3 is to know the part of impurities contained in the amorphized PET through the units depolymerization capacity and purification. After that, the purified PET is transferred to the actors working in the WP4. Here, the purpose is to reinforce the PET quality to achieve the desired technical yarn, and further adequate twisted, dipped cord. Then, they will use some technical (Esterification and polycondensation) in this step of PET recycling, to reduce the remained impurities in the purified PET, they also apply new additives to increase the PET molecular weight in order to obtain an r-PET resin featuring equivalent properties to those of virgin PET. In the WP4 we calculate the PET polymerization capacity of the unit for the purpose to know how much r-PET actors can produce per year in this project. And end, the r-PET produced is processed in yarn that is used as input in the WP5. In the WP5, the yarn obtained from the r-PET in the WP4 is used here as a relevant raw materials to produce

[2] https://www.iseesystems.com/resources/help/v3/Content/08-Reference/01-ObjectsAndProperties/01-Building Blocks/Connectors.htm

new clothes, tires and hoses by Inditex, Michelin and Mandals respectively. These new products will be reinjected in their value chains to create a more circular economy.

Firstly, the WP6 consists of identifying and measuring the use of factors of production such as workers, capital, technology, energy, water, … used in the waste collection to their treatment. Secondly, the WP6 also tries to assess the different impacts of the project in terms of environmental, social and economic impacts by using some SDGs indicators that could be calibrated at the company level (table in the SDGs Reporting in White cycle project section). Thirdly, the WP6 (module) is used to analyze the behavior of the whole system, to identify the adverse impacts of the project which is helpful to minimize them through the implementation of some leverage points.

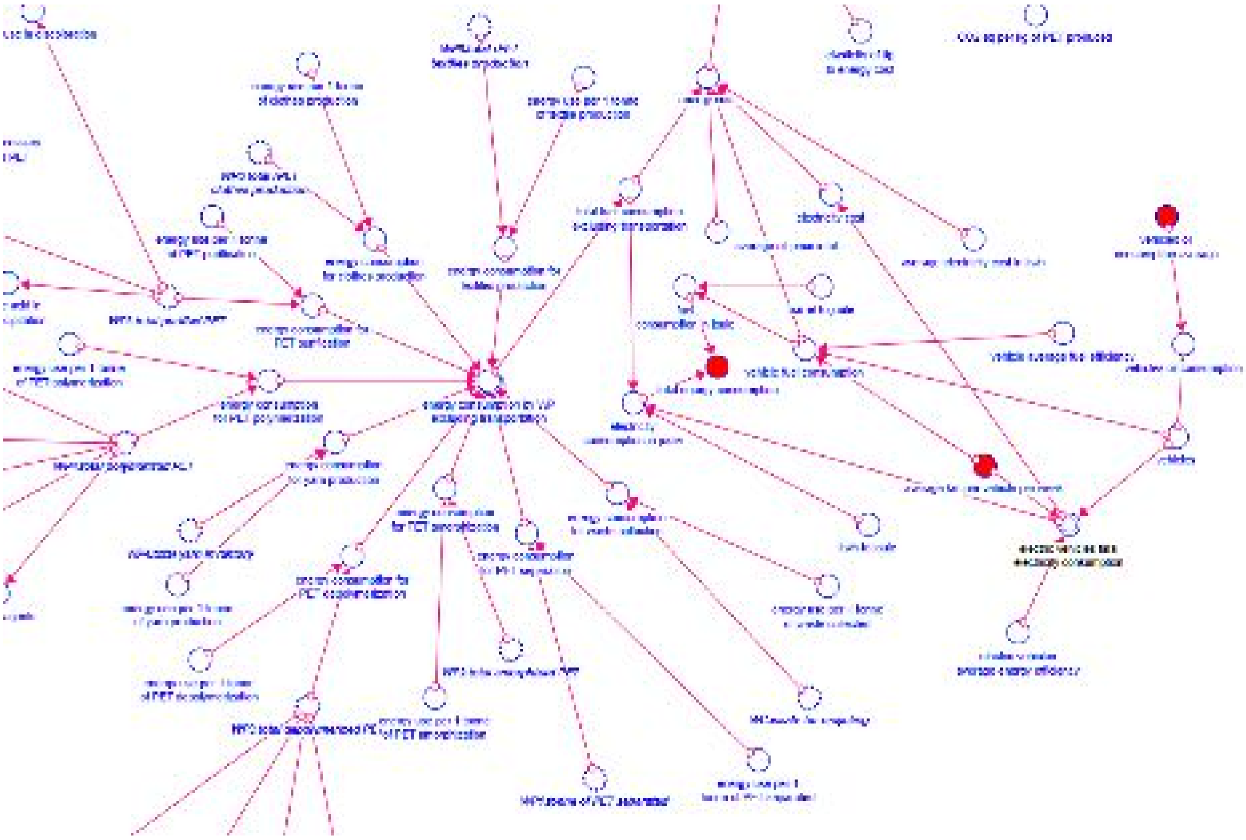
Figure 13: System Dynamics Model for PET supply chain



Source: the authors

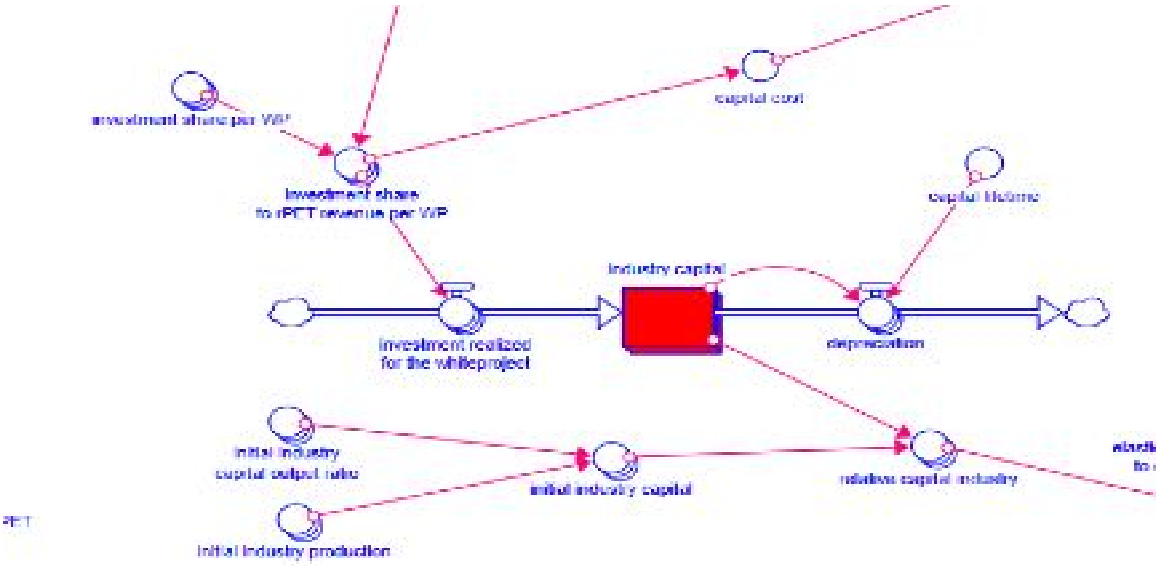
The following SFDs describe some elements that we are trying to calculate in the WP6. In the figure 14, the purpose is to estimate the total energy (oil and electricity) used in the PET recycling from waste collection to rPET products production (cloth, tire and hose). To calculate the amount of energy used in the project, we use a parameter that is the quantity of energy necessary to collect and treat 1 kilogram or one ton of waste and PET. So the multiplication of this parameter to the amount waste collected and treated allows us to get the total energy consumption. After that, by using the total energy consumption we will be able to estimate the quantity of CO_2 emissions per WP and the project by applying some converters.

Figure 14: Energy consumption in each step of PET recycling by WP



Source: the authors

Figure 15: Capital by WP

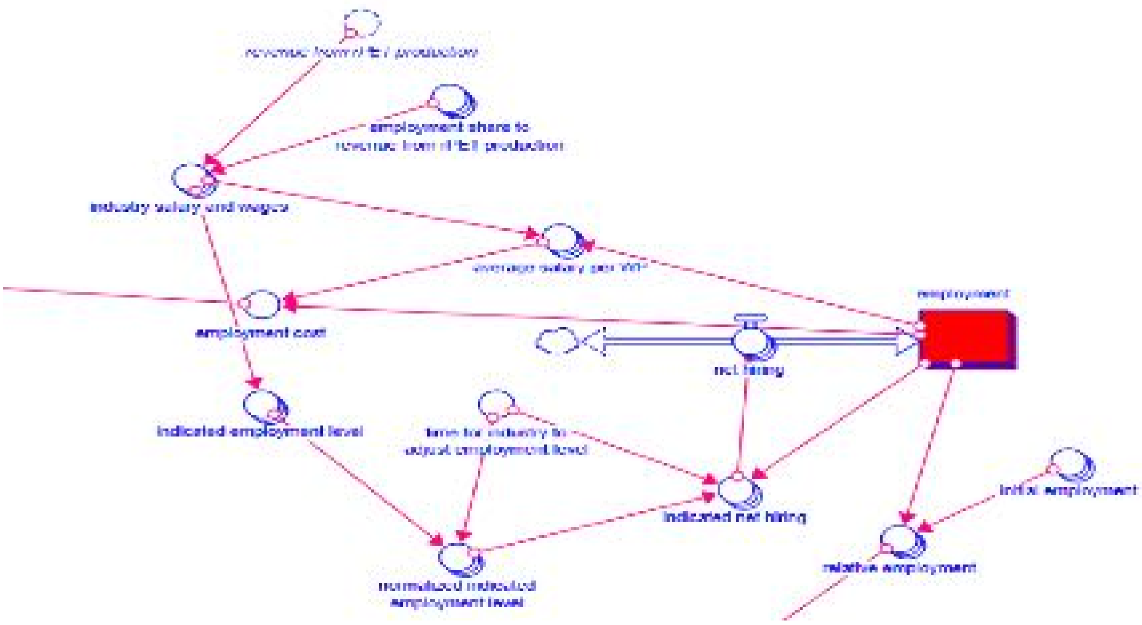


Source: the authors

In figure 15, we attempt to assess the accumulation of capital of partners in each WP that is increased by new investments and decreased by capital depreciation. The over time capital accumulation in relation to the initial capital gives us the relative capital output ratio that is relevant to impact the total factor productivity and further companies production performance.

With the employment SFD represented by the figure 16, we try to calculate the number of workers employed in the project, by considering the companies hiring capacity that is scaled to the revenue generated by their activities. Then, the number of workers hired per year by companies depends on the average salary and the revenue disposal for companies to recruit. Here also, we calculate the employment relative that we use to assess the impact of employment on the total factors productivity and the companies production. However, as data collection is ongoing, the simulation of the model is not possible yet and will be done when we get feedback from partners about data. So, some of the data that we request to partners will be used as inputs to solve the equations formulated in the Stella Software to measure the flow of waste treated across each step of the recycling chain, the quantity of resources used in waste processing. And other data notably those coming from experience results will be considered as historical data for a comparison purpose with the simulation results. The comparison of simulated results to the historical data is helpful to analyze the ability of the model to replicate the historical trend. This process is important for us to revise the mathematical equations formulated to calculate the flow and stocks in the model, to adjust the values of our parameters used, and also to verify data quality from partners.

Figure 16: Employment by WP



Source: the authors

SDSs Reporting (links between PET Innovation and SDGs with indicators)

Architecture of SDGs

The United Nations Sustainable Development Goals (SDGs) have become a reference point for policy-making processes worldwide. The goal of SDGs was first published in 1987, where the main goal was to meet the needs of present and future generations in full compliance with the natural environment (WCED, 1987). The concept of sustainable development has evolved over time to the Millennium Sustainable Development Goals (MDGs) in 1992 and to the current version named 2030 Agenda goals which was drawn up in 2015 with a 15 year period of implementation planned. It outlined 17 Sustainable Development goals (SDGs), 169 associated targets and 231 unique indicators.

Table 2 : SDGs, Targets and Indicators

Goals and targets (from the 2030 Agenda for Sustainable Development)	Number of targets	Number of indicators
Goal 1. End poverty in all its forms everywhere	7	13
Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture	8	14
Goal 3. Ensure healthy lives and promote well-being for all at all ages	13	28
Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	10	12
Goal 5. Achieve gender equality and empower all women and girls	9	14
Goal 6. Ensure availability and sustainable management of water and sanitation for all	8	11
Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all	5	6
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	12	16
Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	8	12
Goal 10. Reduce inequality within and among countries	10	14
Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable	10	15
Goal 12. Ensure sustainable consumption and production patterns	11	13
Goal 13. Take urgent action to combat climate change and its impacts	5	8
Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development	10	10
Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	12	14
Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels	12	24
Goal 17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development/	19	24
Total	169	248

Source: https://unstats.un.org/sdgs/indicators/indicators-list/

Traditionally developed with national governing organisations for applications on a policy level, SDGs became a great challenge for companies, especially for those who wanted to contribute to these goals. SDGs provide a shared vision for sustainable development which essentially indicate the need to protect the social and environmental equilibrium in the process of economic development. Their implementation is possible due to the global goals set, which in a more or less precise manner indicate the directions in which organisations and people should follow to care for both the environment and each other. According to the UN Global Compact Strategy 2024–2025, the strategy for business practice on the SDGs can be divided into three groups. (1) 'Lead and shape', (2) 'Cooperate with others', and (3) 'Follow and amplify'.

Figure 17 : Summarises SDGs priorities in three general categories

Source: UN Global Compact Strategy 2024–2025

There are several studies researching SDGs in business practice. KPMG (2022) investigated the world's 250 largest companies across all sectors. The result reveals that Three SDGs remain the most popular for companies: 8: Decent Work and Economic Growth; 12: Responsible Consumption and Production; and 13: Climate Action. Table 3 presents the three goals addressed (8, 12 and 13) with their targets and respective indicators to monitor their achievement.

Table 3 : Example of the most popular three SDGs with their Targets and Indicators

SDGs	Targets	Indicators
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	8.1 Sustain per capita economic growth in accordance with national circumstances and, in particular, at least 7 per cent gross domestic product growth per annum in the least developed countries	8.1.1 Annual growth rate of real GDP per capita
	8.2 Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors	8.2.1 Annual growth rate of real GDP per employed person
	8.3 Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises, including through	8.3.1 Proportion of informal employment in total employment, by sector and sex

	access to financial services	
	8.4 Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-Year Framework of Programmes on Sustainable Consumption and Production, with developed countries taking the lead	8.4.1 Material footprint, material footprint per capita, and material footprint per GDP
		8.4.2 Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP
	8.5 By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value	8.5.1 Average hourly earnings of employees, by sex, age, occupation and persons with disabilities
		8.5.2 Unemployment rate, by sex, age and persons with disabilities
	8.6 By 2020, substantially reduce the proportion of youth not in employment, education or training	8.6.1 Proportion of youth (aged 15–24 years) not in education, employment or training
	8.7 Take immediate and effective measures to eradicate forced labour, end modern slavery and human trafficking and secure the prohibition and elimination of the worst forms of child labour, including recruitment and use of child soldiers, and by 2025 end child labour in all its forms	8.7.1 Proportion and number of children aged 5–17 years engaged in child labour, by sex and age
	8.8 Protect labour rights and promote safe and secure working environments for all workers, including migrant workers, in particular women migrants, and those in precarious employment	8.8.1 Fatal and non-fatal occupational injuries per 100,000 workers, by sex and migrant status
		8.8.2 Level of national compliance with labour rights (freedom of association and collective bargaining) based on International Labour Organization (ILO) textual sources and national legislation, by sex and migrant status
	8.9 By 2030, devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products	8.9.1 Tourism direct GDP as a proportion of total GDP and in growth rate
	8.10 Strengthen the capacity of domestic financial institutions to encourage and expand access to banking, insurance and financial services for all	8.10.1 (a) Number of commercial bank branches per 100,000 adults and (b) number of automated teller machines (ATMs) per 100,000 adults
		8.10.2 Proportion of adults (15 years and older) with an account at a bank or other financial institution or with a mobile-money-service provider
	8.a Increase Aid for Trade support for developing countries, in particular least developed countries, including through the Enhanced Integrated Framework for	8.a.1 Aid for Trade commitments and disbursements

	Trade-related Technical Assistance to Least Developed Countries	
	8.b By 2020, develop and operationalize a global strategy for youth employment and implement the Global Jobs Pact of the International Labour Organization	8.b.1 Existence of a developed and operationalized national strategy for youth employment, as a distinct strategy or as part of a national employment strategy
Goal 12. Ensure sustainable consumption and production patterns	12.1 Implement the 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries	12.1.1 Number of countries developing, adopting or implementing policy instruments aimed at supporting the shift to sustainable consumption and production
	12.2 By 2030, achieve the sustainable management and efficient use of natural resources	12.2.1 Material footprint, material footprint per capita, and material footprint per GDP
		12.2.2 Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP
	12.3 By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses	12.3.1 (a) Food loss index and (b) food waste index
	12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment	12.4.1 Number of parties to international multilateral environmental agreements on hazardous waste, and other chemicals that meet their commitments and obligations in transmitting information as required by each relevant agreement
		12.4.2 (a) Hazardous waste generated per capita; and (b) proportion of hazardous waste treated, by type of treatment
	12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse	12.5.1 National recycling rate, tons of material recycled
	12.6 Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle	12.6.1 Number of companies publishing sustainability reports
	12.7 Promote public procurement practices that are sustainable, in accordance with national policies and priorities	12.7.1 Number of countries implementing sustainable public procurement policies and action plans
	12.8 By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature	12.8.1 Extent to which (i) global citizenship education and (ii) education for sustainable development are mainstreamed in (a) national education

		policies; (b) curricula; (c) teacher education; and (d) student assessment
	12.a Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production	12.a.1 Installed renewable energy-generating capacity in developing and developed countries (in watts per capita)
	12.b Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products	12.b.1 Implementation of standard accounting tools to monitor the economic and environmental aspects of tourism sustainability
	12.c Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities	12.c.1 Amount of fossil-fuel subsidies (production and consumption) per unit of GDP
Goal 13. Take urgent action to combat climate change and its impacts3	13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries	13.1.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population
		13.1.2 Number of countries that adopt and implement national disaster risk reduction strategies in line with the Sendai Framework for Disaster Risk Reduction 2015–2030
		13.1.3 Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies
	13.2 Integrate climate change measures into national policies, strategies and planning	13.2.1 Number of countries with nationally determined contributions, long-term strategies, national adaptation plans and adaptation communications, as reported to the secretariat of the United Nations Framework Convention on Climate Change
		13.2.2 Total greenhouse gas emissions per year
	13.3 Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning	13.3.1 Extent to which (i) global citizenship education and (ii) education for sustainable development are mainstreamed in (a) national education

		policies; (b) curricula; (c) teacher education; and (d) student assessment
	13.a Implement the commitment undertaken by developed-country parties to the United Nations Framework Convention on Climate Change to a goal of mobilizing jointly $100 billion annually by 2020 from all sources to address the needs of developing countries in the context of meaningful mitigation actions and transparency on implementation and fully operationalize the Green Climate Fund through its capitalization as soon as possible	13.a.1 Amounts provided and mobilized in United States dollars per year in relation to the continued existing collective mobilization goal of the $100 billion commitment through to 2025
	13.b Promote mechanisms for raising capacity for effective climate change-related planning and management in least developed countries and small island developing States, including focusing on women, youth and local and marginalized communities	13.b.1 Number of least developed countries and small island developing States with nationally determined contributions, long-term strategies, national adaptation plans and adaptation communications, as reported to the secretariat of the United Nations Framework Convention on Climate Change

Several guidelines of steps to define SDGs in company strategies and sustainable reporting can be observed from the Business reporting on the SDGs as shown in Figure 18 (https://www.unglobalcompact.org) and Figure 19 (Ana et al., 2002) proposed steps to implement SDGs from impact areas analysis.

Figure 18 : The steps outlined to embed the SDGs in existing business and reporting processes

Source: UN Business reporting on the SDGs (2018)

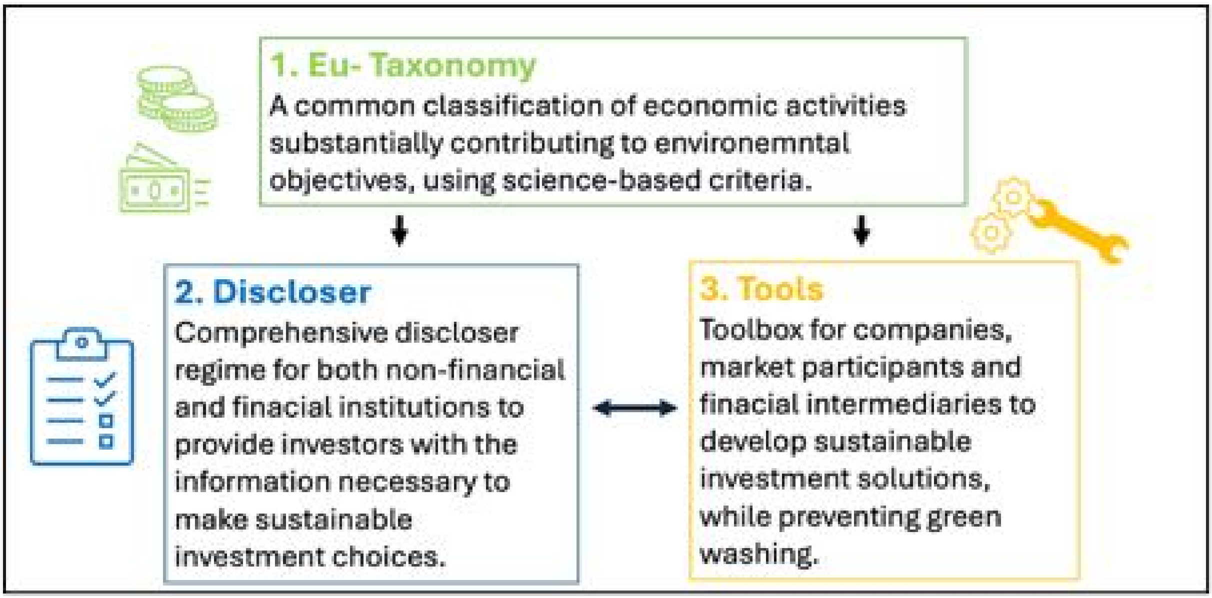
Figure 19 : The steps outlined to embed the SDGs from impact areas analysis

SDGs Reporting at the company Level

The EU Sustainable Finance Strategy Construct - An Overview

The Corporate Sustainability Reporting Directive (CSRD) is one of the three pillars of the EU's Sustainable Finance Strategy, alongside the Disclosure Regulation (SFRD) and the EU Taxonomy Regulation (EU Tax-VO). They all contribute to channeling financial flows on the European capital markets into sustainable investments, i.e. companies with "green economic activities".

Figure 20 : Overview of the foundations of the EU Sustainable Finance Framework



Source : The Authors

The Corporate Sustainability Reporting Directive (CSRD) further develops the original Non-Financial Reporting Directive (NFRD) from 2014. The aim was to harmonize non-financial reporting with financial reporting, focussing on sustainability aspects and metrics. The NFRD obliges large companies to report from 2024 and medium-sized companies from 2026. The CSRD specifies what information companies must report on their sustainability performance.

The Sustainable Finance Disclosure Regulation (SFRD), also known as the Regulation on Sustainability-related Disclosure Obligations, is a European Union regulation that came into force on 10 March 2021. It aims to improve the transparency and comparability of sustainability-related information for financial market participants and investors. The SFRD regulates how financial market participants must disclose the information required to report as per CSRD.

The **EU Taxonomy Regulation (EU Tax-VO)** defines standardized criteria for sustainable economic activities and enables the identification and classification of "green" investments and has been in force since 2022. The EU Taxonomy Regulation defines which economic activities are considered sustainable.

The Table 4 below outlines the relationship between the EU Taxonomy, CSRD, and SFDR.

Table 4 : Relationship between the EU Taxonomy, CSRD, and SFDR

Framework	Purpose	Relationship with other regulations	Role in Sustainability Practices
EU Taxonomy	Serves as a classification system for sustainable economic activities. Applied within the frameworks of CSRD and SFDR.	Provides the foundational criteria for identifying sustainable activities required for reporting under CSRD and SFDR.	Facilitates alignment of investments with activities that are Taxonomy-aligned.
CSRD (Corporate Sustainability Reporting Directive)	Aims at enhancing the quality and scope of corporate sustainability reporting.	Complements SFDR by supplying crucial data for SFDR reporting.	Mandates companies to report ESG (Environmental, Social, Governance) metrics that are aligned with EU Taxonomy. Incorporates these metrics into SFDR reporting.
SFDR Sustainable Finance Disclosure Regulation	Focuses on enhancing transparency in ESG disclosures and sustainable investment practices.	Utilises data from CSRD to enrich its own reporting and integrates it to provide a more comprehensive view.	SFDR reports integrate metrics from CSRD. Places emphasis on ESG disclosures to promote sustainable investment practices.

To summarize, the CSRD, SFRD, and EU Taxonomy Regulation are important instruments for promoting sustainable investment in Europe. The three pillars are interlinked and ensure that companies report comprehensively on their sustainability performance, that financial market participants disclose this information transparently, and that "green" investments can be identified.

The European Sustainability Reporting Standards (ESRS)

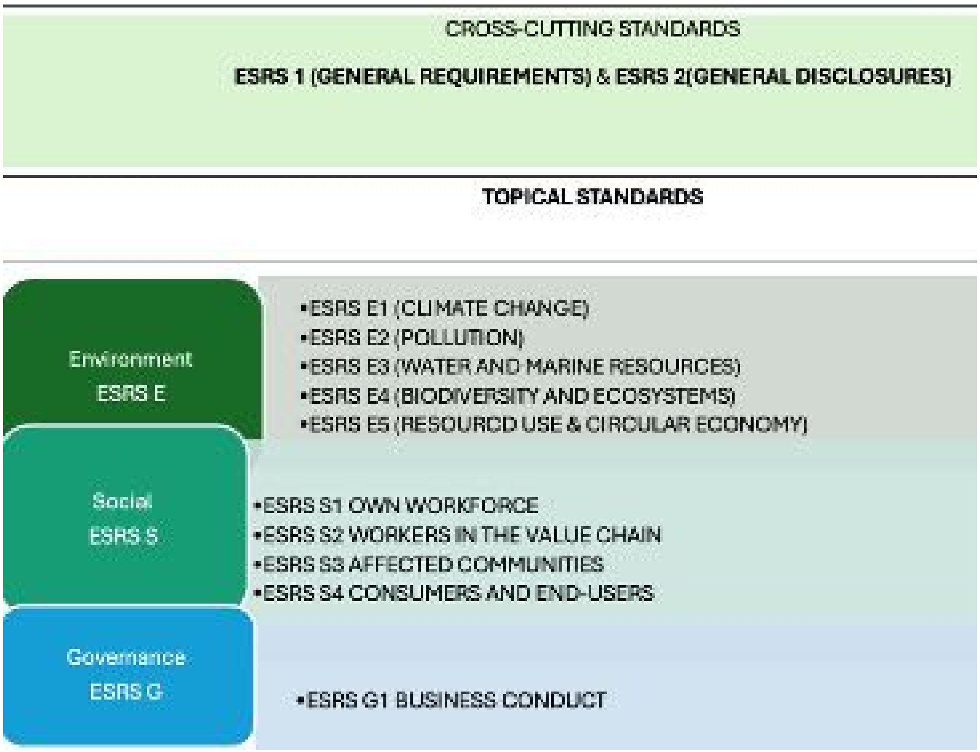
The European Sustainability Reporting Standards (ESRS) play a central role in the harmonization and standardization of sustainability reporting in Europe. They concretize the content requirements of the Corporate Sustainability Reporting Directive (CSRD) and provide companies with guidelines for comprehensive reporting on their sustainability performance. They contribute to more transparent, comparable and comprehensive reporting and thus promote sustainable investments and sustainable development. The most important functions of the ESRS:

- **Creation of a standardized framework:** The ESRS define standardized criteria and indicators for sustainability reporting. This makes it easier for companies to report and for stakeholders to compare corporate performance.

- **Improving transparency:** The ESRS contributes to more transparent and comprehensive sustainability reporting. This enables stakeholders to better assess a company's sustainability risks and opportunities.

- **Promotion of sustainable investments:** The ESRS can help promote sustainable investment by providing investors with information on companies' sustainability performance.

Figure 21 : Cross-cutting issues in European Sustainability Reporting Standards (ESRS)



On 31 July 2023, the EU Commission adopted the first twelve ESRS. These comprise two overarching standards and 10 specific standards for the areas of environment (E), social (S), and governance (G).

ESRS overarching standards:

- ESRS 1: General requirements
- ESRS 2: Materiality assessment and reporting process

Specific standards:

- ESRS E1: Environmental objectives and risks
- ESRS E2: Water and Marine Resources
- ESRS E3: Circular Economy
- ESRS E4: Environmental Pollution
- ESRS E5: Biodiversity
- ESRS S1: Labour Relations and Working Conditions
- ESRS S2: Human Rights and Social Inclusion
- ESRS S3: Product Safety and Consumer Information
- ESRS G1: Corporate Governance
- ESRS G2: Bribery and Corruption

Outlook: The development of the ESRS is an ongoing process. Further standards for various industries and sectors are to be adopted over the next few years.

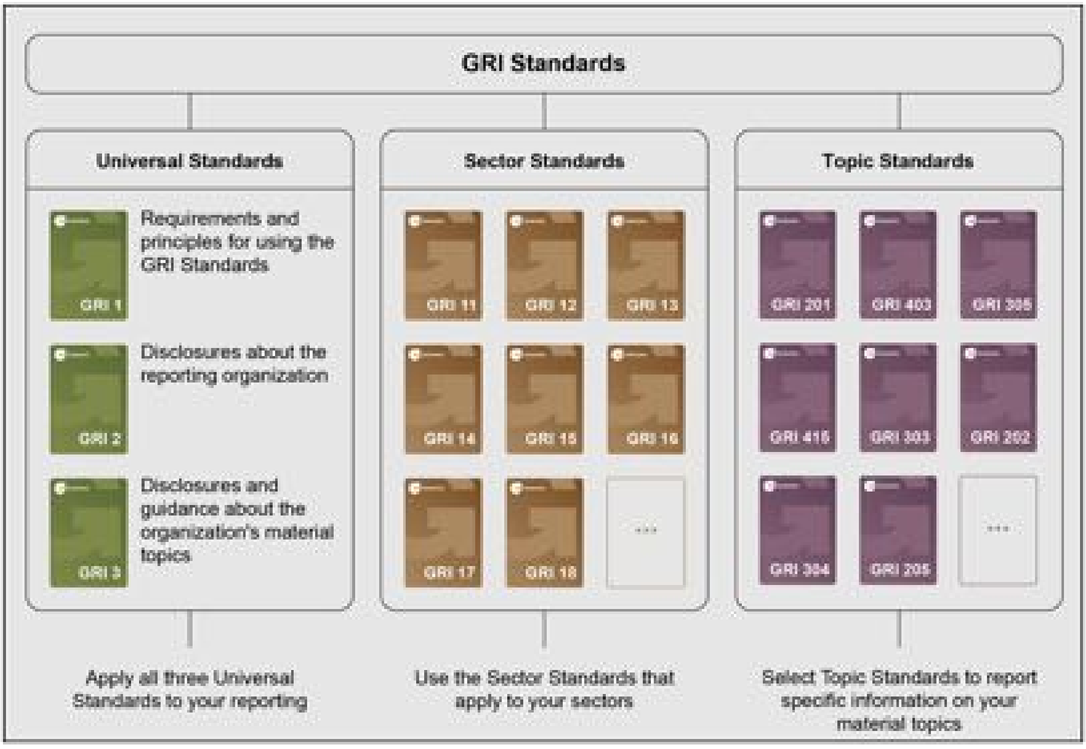
Standards used by various industries and sectors

The ESRS (mandatory): The ESRS provides a specific catalog of requirements, including mandatory disclosures on certain environmental and social aspects. of double materiality, i.e. both the impact of sustainability on the company (outside-in) and the impact of the company's activities on society and the environment (inside-out) are accounted for. They are prescribed by the EU Directive on Corporate Sustainability Reporting (CSRD).

The GRIs (voluntary): Offer a more flexible and comprehensive framework with different reporting levels, allowing companies to customize their reports to their specific needs and stakeholders. Although not mandatory, they are widely recognized as the leading standard for sustainability reporting.

The organization's guidelines are internationally recognized, providing a detailed roadmap for preparing CSR reports. 80% of the world's largest companies that prepare CSR reports do so by applying GRI criteria. The core of the GRI report is organized around three chapters - economic, environmental, and social - and thus covers all ESRS.

Figure 22 : GRI Standards is a modular system of interconnected standards



Source: globalreporting.org.

Other standards for sustainability reports and tools used

→ **General quality characteristics of a sustainability report**

● *Balance*: The information provided should highlight both the positive and negative aspects.

● *Comprehensibility*: An understandable and accessible way of reporting is pivotal, for example through graphical representations.

● *Comparability*: Reporting should be standardised so that changes in performance over time are visible and can also be compared with other companies.

● *Reliability:* The information used should be reliable so that it can be checked for quality and materiality.

● *Timeliness*: Timely reporting is important for acute assessments of stakeholders.

● *Accuracy*: The information contained in the report should be sufficiently accurate and detailed for an assessment.

In addition to the Global Reporting Initiative (GRI) Standard, the best-known and most internationally established standard for sustainability reports, some other standards and frameworks provide companies with support and guidelines when preparing their sustainability reports. The choice of the appropriate standard depends on various factors, such as the size and sector of the company, its stakeholders and the specific sustainability goals and performance to be reported.

→ Description of GRI Standard

GRI Standards, short for Global Reporting Initiative Standards, were developed to help companies, governments and other organisations understand and transparently communicate the impact of their activities on critical sustainability issues. These are coherent standards, covering both general and topic-specific aspects. The GRI Standards are an international guideline for sustainability reporting that focuses on material issues and provides customers and stakeholders with overviews of a company's non-financial activities. Transparency is the main intention of reporting, offering readers insights into the interaction between the company and the environment. A GRI Report is structured into topic-specific chapters that examine the company from different perspectives:

- General disclosures about the company and management approach (GRI100)
- Economic disclosures (GRI200)
- Environmental information (GRI 300)
- Social disclosures (GRI 400).

Ideally, the sustainability report should be helpful for customers, stakeholders, and the company alike. By applying these standards, companies can not only keep an eye on their performance but also present their efforts to promote sustainability in a comprehensible manner. The quality criteria of the GRI standard are based on the motivation of making a company transparent to the outside world. The reporting quality follows the principle of accuracy and comparability, while the report content focuses on the aspects of materiality, stakeholder involvement and sustainability.

The GRI[3] standard provides a valuable basis for comprehensive and authentic sustainability reporting. The sustainability report aims to maintain the trust of stakeholders to fulfill the global responsibility of sustainable action and to document it transparently in the report. To summarise, the GRI standards provide an essential resource for paving the way to a more sustainable future. By reporting to the GRI standard, companies can enhance their transparency, accountability, and overall sustainability impact, aligning their strategies with global best practices and stakeholder expectations.

DNK (German Sustainability Code): For small and medium-sized companies in Germany, the DNK is a national standard developed specifically for companies in German-speaking countries.

[3] A critical review of the GRI standards is provided in Inês et al. (2023), A review of greenwashing and supply chain management: Challenges ahead, *Cleaner Environmental Systems*, 11.

It is characterized by its high practical orientation and its focus on the German SME landscape. https://www.deutscher-nachhaltigkeitskodex.de/en/

SASB (Sustainability Accounting Standards Board): internationally recognized. The SASB standard focusses on industry-specific sustainability aspects relevant to financial market stability. It is particularly suitable for companies orientated towards capital markets. https://sasb.ifrs.org/

CRS (Corporate Reporting Standards): The CRS are sustainability reporting standards developed by the European Financial Reporting Advisory Group (EFRAG). They are still in the development phase but are intended to represent future European standards for sustainability reporting. https://www.efrag.org/

→ Tools and Guidelines

ISO 26000: Although ISO 26000 does not provide an explicit framework for sustainability reports, it defines guiding principles for corporate social responsibility and can thus be used as a basis for sustainability reporting. https://www.iso.org/iso-26000-social-responsibility.html

The UN's 17 Sustainable Development Goals (SDGs) are a good tool for creating a sustainability report and defining individual sustainability goals for the company. Although the SDGs do not constitute an independent reporting standard, they can be used as an orientation framework for sustainability reporting. Companies can measure and report their sustainability performance based on the 17 SDGs and the associated targets. They offer companies a good opportunity to position themselves on individual goals and agree internally on the goals best being implemented through their activities.

Figure 23 : Sustainable Development Goals of the United Nations

Combining several standards is possible and often very useful if it supports coverage of all aspects of the ESRS in the sustainability report.

Overview of sustainability reporting at the company level

→ Who has to report ?

● *Large companies*: with a balance sheet total of > 20 million EUR, sales > 40 million EUR, as well as companies with over 250 million EUR balances regardless of capital market orientation.

● Small and medium-sized enterprises with a capital market orientation.

● Non-European companies: that generate a net turnover of more than 150 million € in the EU and have at least one subsidiary or branch in the EU (from 2028)

The EU Commission expects around 50,000 companies in the EU to be required to report under the CSRD.

→ Aim and purpose

Companies must report comprehensively on their sustainability performance as part of the CSRD. The aim and purpose of the sustainability report are to provide investors and stakeholders with comprehensive information about the company's sustainability goals, risks, and the business strategy derived from them and also to make the company comparable with other companies in terms of sustainability. The sustainability report serves as a central instrument for transparency and stakeholder communication. Companies are responsible for their actions and their impact on the environment, society, and the economy. To make this responsibility transparent and to inform stakeholders about their sustainability performance. The EU Taxonomy Regulation can help companies classify their economic activities as sustainable and thus gain access to sustainable financing. A common reporting standard is the GRI Standard, which covers all important aspects at the international level. Although the GRI accounts for the relevant aspects of the ESRS, the sustainability report should still be checked to ensure that it complies with the ESRS standard and the binding EU regulations.

→ Report Content and organisation

From a sustainability perspective, sustainability reporting should describe the course of business, the business results, the situation of the company, and the impact of the company's activities on the environment, taking into account the principle of "double materiality". As shown below is the CSRD reporting framework, concretized in terms of content by the European Sustainability Reporting Standards (ESRS). Consisting of a part with general and specific reporting.

General report content
● **Information on the business model and corporate strategy**, including opportunities and risks in connection with sustainability aspects and resilience to these risks. ● **Information on sustainability goals** set by the company and progress made. ● **Information on the company's policies** concerning sustainability aspects. ● **A description of the principal actual or potential adverse impacts** associated with the company's value chain and actions taken to prevent, mitigate, or remediate them.

Specific report content		
Environmental ● Information on the six environmental goals of the European Union ● Climate protection ● Adaptation to climate change ● Protection of water and marine resources ● Strengthening the circular economy ● Reducing environmental pollution ● Protecting biodiversity	**Social** ● Information on social aspects ● Equal opportunities, including gender equality and equal pay ● Working conditions, such as safe workplaces, healthy working environments, wages, employee participation, work-life balance ● Respect for human rights, fundamental freedoms, democratic principles and international standards	**Governance** ● Disclosures on governance aspects ● Role of the administrative, management, and supervisory bodies concerning sustainability aspects ● Corporate ethics and culture, including the fight against corruption ● Political engagement of the company, including lobbying activities ● Relationships with business partners ● Internal control and management systems

There are various **editing options** for the sustainability report

- Collaborative processing across the company: implies that the whole company is involved in the sustainability report process and that individual employees know what information they need to add to the report to be completed over the year. Hence, the report is edited as a collaborative, living document. The sustainability manager acts as a coordinator.
- Single responsibility: The sustainability report is written by a responsible person (e.g., an employee tasked, a part-time working student, or a sustainability manager). Hence, the report becomes one-sided, yet offering a convenient way for the company. Often the sustainability manager acts only as a supervisor. This mode of reporting comes at the expense of transparency.
- Dedicated team work: The team can consist of employees from different business levels having a particular interest in sustainability. This adds diversity to the reporting, as managers and perspectives from different areas contribute their influence and opportunities for action concerning sustainability.

The person who writes the sustainability report collects the necessary data and answers the extensive questionnaire of the GRI standard. Analyzing and calculating the carbon footprint stands out in terms of work effort (e.g., collecting data). The range of data is diverse, including company-level data, data about waste handling, and business trips. A challenge for the re-use of data is to interpret existing ones and document data for third parties.

The importance of stakeholders

Stakeholders are part of sustainability reporting. Their involvement increases the transparency, relevance, and effectiveness of reports, aligns company practices with broader societal expectations, and helps to build trust and stronger relationships. Direct stakeholder engagement can be achieved through dialogue and feedback. The sustainability report itself is also part of the stakeholder dialogue.

Figure 24: Overview of stakeholders in sustainability reporting

Source : the authors

SDGs Reporting in Whitecycle project

Concerned with plastic production, the adoption of SDGs is observed in many researches (Fabiula D., 2021), (Navarro et al., 2023). For the Whitecycle project, the implementation of SDGs in rPET is investigated and results from Table show SDGs concerned with explanation.

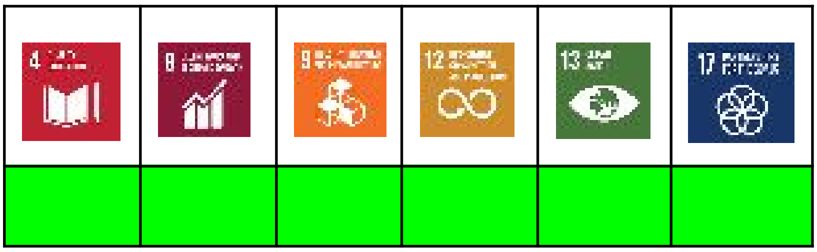


Table 5: Whitecycle SDG indicators

SDG concerned	SDG target concerned	Example of indicator name
4	T4.7:By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture's contribution to sustainable development	-Company investment for training staff -Ratio of female staff
8	T8.5:Achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value 8.8:Protect labor rights and promote safe and secure working environments for all workers, including migrant workers, particularly women migrants, and those in precarious employment	-Hours of work -Fair salary -Equal opportunity -Health&Safety
9	T9.4: By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes	-Investment or expenditure of infrastructure -Transportation cost -CO2 emission per year from the activity

12	T12.5:Substantially reduce waste generation through prevention, reduction, recycling, and reuse T12.6:Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle	-Quantity of waste material consumption in project (tires, hoses, cloth) -Quantity of Hazardous waste generated in project -Number of companies publishing sustainability reports -Company recycling rate -Number of Workshop organized to developing company
13	T13.2 Integrate climate change measures into national policies, strategies and planning	-Total greenhouse gas emission per year (tCO2e)
17	T17.6:Enhance the global partnership for sustainable development, complemented by multi-stakeholder partnerships that mobilize and share knowledge, expertise, technology, and financial resources, to support the achievement of the sustainable development goals in all countries, in particular developing countries	-Number of deliverable or technology transfer between the project and to developing country partner -Dollar value of financial and technical assistance committed to developing country -Total amount of funding for developing countries to promote the development, transfer, dissemination and diffusion of environmentally sound technologies

Source: the authors

Conclusion

This chapter analyzed the environmental, social and economic impacts of PET recycling. We used System Dynamics tool to describe the structure of the PET supply chain with some Causal Loop Diagrams (CLDs) and the dynamics of the interactions within the supply chain with the Stock and Flow Diagram (SFD). On the one hand, the CLDs allowed us to explain the dynamics of industrial operations, the interconnections in the supply chain and the potential consequences that could arise from the activities and operations of 17 partners of the Whitecycle project. On the other hand, the use of the SFD helped to write some equations that will allow us to assess the global behavior of the PET recycling system, the behavior of some key variables in the system and the level of resources (inputs) used in the PET recycling process. This part of the modelling is still in progress, as we are waiting to hear back from partners about the data to be imported into Stella software. In addition, some of the equations and indicators of the model are still to be defined and we are working to achieve conclusive results. The development of these SFDS and CLDs has followed the various steps and hypotheses recommended by Forrester in "*Industrial Dynamics*" and Randers in "*Conceptualising Dynamic Models of Social Systems*": *Lessons from a study of social change*" for a better modelling process. The last part of the chapter consisted of the presentation of SDG indicators, which companies can use to demonstrate their commitment to social, economic and environmental responsibility through three processes: Identifying SDG targets, measuring and analyzing them, and reporting on the impact of companies' activities on the three dimensions of sustainable development. In the EU, corporate engagement with the SDGs is overseen by the EU Sustainable Finance Strategy Construct, which brings together a number of regulations and directives to channel financial flows in European capital markets towards sustainable investments. The European Sustainability Reporting Standards (ESRS) also play a central role in harmonizing and standardizing sustainability reporting in Europe, contributing to more transparent, comparable and comprehensive reporting on corporate activities. Then, we will use all this information to guide and engage companies in greener economic activities by building SDG indicators for the Whitecycle project.

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