CLÁUDIO LUÍS DE MELO PEREIRA

The Circular Economy in Composite Materials Industry: A Parallel between European and Brazilian Contexts Applying System Dynamics Modeling Approach

Trabalho de formatura apresentado à Escola Politécnica da Universidade de São Paulo para a obtenção do diploma de Engenheiro de Produção.

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To my family, relatives, and beloved friends,
who always backed me regardless of how distant

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This work is the result of countless hours of commitment, only possible because of the contributions of different people and organizations to whom I would like to express my sincere appreciation.

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ABSTRACT

This work aims at investigating the influence of policies to encourage the transition towards a Circular Economy for composite materials. It seeks to develop a System Dynamics model to evaluate the effects of different policies in the adoption of composites produced by de-manufacturing processes. For this purpose, it investigates the current scenario of the specific industry both in Europe and Brazil. The model generated hosted the simulation of different regulatory scenarios for the European context, each containing experiments reproducing the effects that policies can generate. The work decouples the technical system from the regulatory scenario, translating policies' effects into model technical elements. The results suggest policies directed to the development of de-manufacturing and collection activities are more successful in promoting de-manufactured composites' use. Those focusing on increasing these materials' demand have limited benefits for their adoption under present circumstances. In addition, the work bridges the European and the Brazilian contexts, judging Brazil is in a favorable position to propel changes in its reverse activities' ecosystem. The study limited itself in offering suggestions for the industry, not predictions, since the assumptions made can reduce the precision of the findings, and it represents the industry at an aggregated level. Despite the limitations, the system dynamics model developed helps policymakers in their regulatory decisions, exploring the effects of policies for composites produced by de-manufacturing processes.

Keywords: Circular Economy; Composite Materials; System Dynamics;

RESUMO

O presente trabalho visa a investigação da influência de políticas promovendo a transição para uma Economia Circular relativa a materiais compósitos. O estudo busca desenvolver um modelo de Dinâmica de Sistemas para avaliar os efeitos de diferentes políticas na adoção de compósitos produzidos por processos de desmanufatura. Com esse intuito, o trabalho investiga o cenário atual da indústria em questão tanto na Europa como no Brasil. O modelo produzido simula diferentes cenários regulatórios para o contexto Europeu, cada um contendo experimentos que reproduziam os efeitos ocasionados pelas políticas analisadas. O trabalho separa o sistema técnico do ambiente regulatório, traduzindo os efeitos de políticas em elementos técnicos presentes no modelo. Os resultados sugerem que ações voltadas ao desenvolvimento das atividades de desmanufatura e coleta são mais bem sucedidas em promover o uso de compósitos desmanufaturados. Já aquelas focadas na promoção da demanda por esses materiais possuem poucos benefícios para sua adoção no atual contexto da indústria. Ademais, o trabalho aproxima os contextos Europeu e Brasileiro, e considera que o Brasil encontra-se em uma posição favorável para promover mudanças em seu ecossistema de atividades reversas. O estudo se limita em oferecer sugestões para a indústria e não previsões, uma vez que as hipóteses de modelagem adotadas podem reduzir a precisão das descobertas e a indústria é representada de forma altamente agregada. Apesar de suas limitações, o modelo de Dinâmica de Sistemas desenvolvido auxilia formuladores de políticas em suas decisões regulatórias, explorando os efeitos de políticas para compósitos produzidos por processos de desmanufatura.

Palavras-chave: Dinâmica de Sistemas; Economia Circular; Materiais Compósitos;

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LIST OF ABBREVIATIONS

ALMACO – *Associação Latino-Americana de Materiais Compósitos*
BM – Business Model
CBM – Circular Business Model
CE – Circular Economy
CFRP – Carbon Fiber-Reinforced Plastic
EoL – End-of-Life
EPR – Extended Producer Responsibility
EU – European Union
FRP – Fiber-Reinforced Plastic
GFRP – Glass Fiber-Reinforced Plastic
PNRS – *Política Nacional de Resíduos Sólidos*
R&D – Research and Development
rFRP – Recycled Fiber-Reinforced Plastic
SBM – Sustainable Business Model
SCW – Supercritical Water
SD – System Dynamics

SUMMARY

1. INTRODUCTION

The current chapter presents the motivation, the objectives, and the structure of this work. It also discloses a brief overview of the author's activities during his double-degree program, which first introduced him to the subject and allowed this study to occur.

1.1 Motivation

In recent years, climate change has progressively gained more attention worldwide and is currently considered one of the greatest threats faced by humanity. It is possible to observe mobilization on the topic in societies spread around all continents, led by the future generations, demanding concrete actions by the nations' leaders towards protecting the environment. The World Economic Forum's *The Global Risks Report 2020* lists climate change and other related environmental issues among the top five global risks in terms of both likelihood and impact and claims that the arrival of the problem's consequences anticipates expectations and causes damages more intense than what forecasts suggested (WORLD ECONOMIC FORUM, 2020).

To oppose climate change, the development standard underlying the global economy must incur a transformation. Several approaches are intending to guide this process, and one of the most prominent paradigms advocated is Circular Economy (CE), which supports the transition from the current model, referred to as linear, to a different one, the circular model. Under a circular standard, renewable energy would power the economy, and the design and use of products would occur in ways strategically conceived to allow the reduction of greenhouse gases emission, the conservation of the energy within products, and the sequestration of carbon. The approach has the support and approval of many stakeholders, as can be seen, for example, by the European Commission's plan *"Towards a Circular Economy: A zero waste programme for Europe"* presented in 2014, and the recent launch of the Latin American & Caribbean Circular Economy Coalition, in February 2021. According to the Ellen MacArthur Foundation, one of the actors leading the circular movement, Circular Economy can tackle the harder-to-reduce portion of global emissions, related to the production of goods and management of land, which current efforts neglect. For example, the institution claims the adoption of a Circular

Economy scenario would lead to a 40% reduction in CO2 emissions related to the production of four key materials, namely steel, aluminum, plastics, and cement (ELLEN MACARTHUR FOUNDATION, 2019).

A study by McKinsey&Company (2015) strengthens the plea for Europe to embrace a Circular Economy, since it concluded the net economic benefits of the introduction of Circular Economy principles for the region could represent €1.8 trillion, despite additional environmental and social gains. The analysis argues the European economy still operates on a wasteful value creation approach, and that emerging technologies and business models could help in improving resource productivity and achieving cost reductions to some extent. However, if these novelties were incorporated in the economy using Circular Economy rules, to achieve what they called Growth within – growth by extracting more value from the current stocks of material – their benefits would be strengthened and could result in gains in the trillions of euros. Whereas, in the case of Latin America and the Caribbean, participants of the mentioned coalition claim Circular Economy can help to tackle the "resource curse" faced by the regions' countries, typical exporters of raw natural resources with little value-added locally. In this way, a Circular Economy in the region can help to close this value-addition gap and deliver better growth for countries owning reserves of raw resources (ELLEN MACARTHUR FOUNDATION, 2021).

Within the movements featured earlier, the discussion about the environmental issues related to the manufacturing and use of plastics gained ground over the last decade. Plastics are responsible for a big part of waste generation and thus the pollution of many ecosystems around the globe. In consequence, these materials are the focus of several debates, and many are the actions promoting better ways to discard them or options for the reuse of plastic waste (WORLD ECONOMIC FORUM; ELLEN MACARTHUR FOUNDATION; MCKINSEY&COMPANY, 2016).

Nevertheless, despite the considerable attention received by plastics in general, fiber-reinforced plastics represent one of its types that remains barely unconsidered in discussions. Also called composites, these materials are made of a combination between plastics and fibers, and find multiple applications in many different economic sectors. Given their huge utilization and its increase, the number of composites discarded grows every year, but the majority of these waste flows do not follow the principles of Circular Economy, finishing in landfills instead.

The treatment of discarded composites presents some challenges, which may be behind their massive landfilling. Separating fibers from the plastic without impairing them can be difficult, and successful procedures might not pay off given the materials' relatively low prices.

However, the overarching circumstances can change to accommodate Circular Economy practices. For example, the mentioned European package foresees the establishment of an enabling policy framework. This possibility to alter the scenario can induce shifts in the model adopted for fiber-reinforced plastics after their use cycles.

1.2 Objectives

Standing on the motivations introduced, the present work seeks to develop a model of the composite industry that will allow the generation of insights for policies definition towards Circular Economy. Additionally, the study surveyed policies exploring a parallel between European and Brazilian contexts. Hence, this study aims to become a support tool for policymakers, which they can use to assist their decision-making process when discussing solutions for improving the current scenario regarding the end-of-life of fiber-reinforced plastics.

1.3 The Double Degree

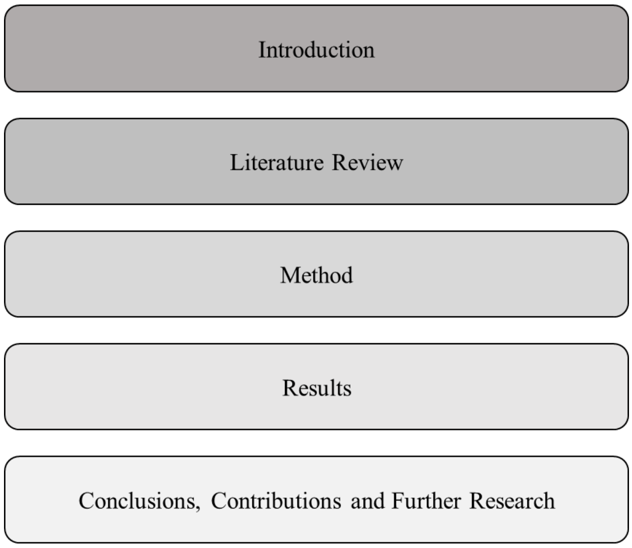
During his studies, the author was selected for a double-degree program in Management Engineering at *Politecnico di Milano*, owing to the agreement between the Italian university and *Escola Politécnica da Universidade de São Paulo*. The program lasted for two years, during which the student lived in Milan pursuing his degree.

Through *Politecnico di Milano*, the author had the opportunity to contribute to the FiberEUse consortium, a project within the European Commission's Horizon 2020 research and innovation program towards sustainable development. The project focused on composite materials and investigated the viability of Circular Economy business models for the sector. Therefore, this study started as part of *Politecnico di Milano*'s research effort in the consortium and continued following the author's return to *Escola Politécnica* in an attempt to bridge Italy and Brazil contexts.

1.4 Structure

The present work has five chapters, each responsible for one part of the process to reach its objectives, described in ***Figure 1***.

Figure 1 – Structure of the work



Source: Author's elaboration

Briefly, in Literature Review, the work analyses scientific literature about subjects necessary for the development of the study, namely Circular Economy, Composites, and System Dynamics. In Method, the stages followed during the research process and the activities executed within the investigation are disclosed in Research Stages, whilst Data Collection and Data Analysis present the procedures adopted for, respectively, collecting data and analyzing the results obtained by the work. The section Results presents the outputs of the work, covering a comparative analysis of composite industry's circular contexts both in Brazil and in Europe, the System Dynamics model developed and experimented and the cross-analysis of the model's results and the previous analysis, focusing on Brazil. At last, Conclusions, Contributions, and Further Research exhibits the study's outcomes and provides recommendations for future research efforts around the topics covered by the work.

2. LITERATURE REVIEW

This chapter introduces the theoretical background of the work and explores the literature regarding the subjects addressed. It contains three sections, one for each of the main pillars grounding the study, explicitly, Circular Economy, Composites, and System Dynamics, which further develop in subsections.

2.1. Circular Economy

2.1.1. Concept and Considerations

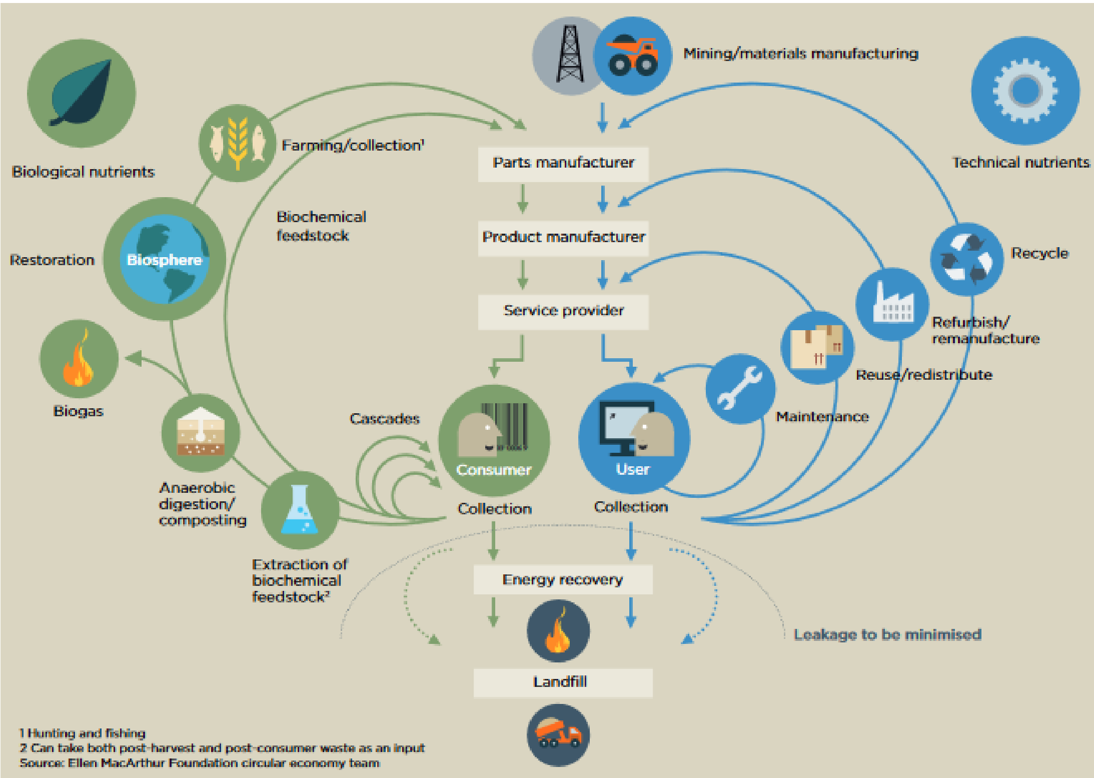
The concept of Circular Economy is one of the current perspectives shaping the transition to a more sustainable growth path towards the future. The Ellen MacArthur Foundation (2013) states that CE opposes the present linear consumption model, based on a “take-make-dispose” standard. Geissdoerfer et al. (2018) say Circular Economy has the potential to be a tangible alternative to conduce society and the economy towards the broad and abstract idea of Sustainable Development, among other existing possibilities.

A Circular Economy is defined as “[…] an industrial system that is restorative or regenerative by intention and design […]” (ELLEN MACARTHUR FOUNDATION, 2013, p. 7) and has as its building principles to design out waste and pollution, to keep products and materials in use, and to regenerate natural systems (ELLEN MACARTHUR FOUNDATION, 2019). It is a strategy against the established open system that tries to solve the issues of resource scarcity and waste disposal taking into consideration economic and value aspects (HOMRICH et al, 2018).

The Design out waste and pollution principle claims that if products are conceived within biological and technical materials cycles – biological material cycles referring to the regeneration of biologically based materials and technical material cycles to the recovery and restoration of products, materials, and components – considering disassembly and refurbishment, waste does not exist. In addition, the postulate Keep products and materials in use advocates that products should be designed with the aim of durability, reuse, remanufacturing, and recycling, to keep them in circulation for many distinct economic uses before their structural elements are returned to natural systems in proper and safe manners. At last, the proposition within Regenerate natural systems is that the economic system should refrain from using non-renewable sources of energy and resources, preserving the renewable ones and enhancing them by supporting natural regeneration when returning nutrients to the biological system (ELLEN MACARTHUR FOUNDATION, 2019).

The Butterfly Diagram of a Circular Economy is shown in ***Figure 2***, illustrating the flows of nutrients, separated in biological and technical, some of the actors involved in their processing, and the process options that can be used to reinsert them in the system. To clarify the distinction between nutrient types, according to Homrich et al. (2018) biological loops are usually closer to environmental and biological contexts, whilst the technical ones are connected to the economic and the industrial views.

Figure 2 – Butterfly Diagram of a Circular Economy



Source: Ellen MacArthur Foundation (2013)

2.1.2. Mechanisms of Value Creation

The principles of Circular Economy, in addition to establishing how such a system supposedly works, also define the mechanisms that create economic value. According to Ellen MacArthur Foundation (2013), the sources of value creation are Power of inner circle, Power of circling longer, Power of cascaded use and inbound material/product substitution, and Power of pure, non-toxic, or at least easier-to-separate inputs and designs.

The Power of inner circle consists of the idea that the tighter the circles/loops returning a used product to operation, the greater should be the savings in terms of costs and externalities related to the fabrication of items. Closing circles/loops at the earliest possible enables systems to reap the benefits arising from the effect of virgin material substitution and minimize material use in comparison to the linear production system. This mechanism of value creation relies on the difference between the linear and the circular setup, hence establishing circular systems is economically reasonable whenever the costs of collecting, reprocessing, and returning the item into the economy are inferior to those incurred in the linear approach (ELLEN MACARTHUR FOUNDATION, 2013).

Regarding the Power or circling longer, the value creation potential arises from maintaining items in use for longer periods, achieved either by making them undergo more consecutive use cycles or by increasing the duration of each cycle. The extension of the usage will reduce the disposal of materials out of the economic chain, also substituting the inflows of virgin materials (ELLEN MACARTHUR FOUNDATION, 2013).

Power of cascaded use and inbound material/product substitution refers to the opportunity to keep using the products, components, and materials across the value chain, in distinct product categories. The roots of this value creation mechanism lie on the lower marginal costs of the cascaded reuse of materials as substitutes for the inflow of virgin ones with its intrinsic costs and on the externalities versus the marginal costs of the recovery of the material aiming at a repurposed utilization (ELLEN MACARTHUR FOUNDATION, 2013).

Power of pure, non-toxic, or at least easier-to-separate inputs and designs is the value creation potential stemming from the amplification of the previous mechanisms generated by the increase in efficiency of collection and redistribution, whilst maintaining quality levels, given a higher purity and quality of reverse processes' inflows. These properties can be achieved if products are designed following the ease of separation, the identification of embedded components, and the material substitution standards, among others, as well as if the activities in reverse processes are also changed, tackling issues such as product damage rates during collection and transportation, scrap rates on reconditioning, and contamination of material streams during and after collection. Improvements on these levers can result in additional reductions in the comparative costs of the reverse activity, higher material lifespan, and productivity, and commercial uptake by current non-adopting sectors (TOLIO et al., 2017; ELLEN MACARTHUR FOUNDATION, 2013).

2.1.3. Evolution of the Concept

The concept of Circular Economy cannot be credited to a single author or date; instead, it arises from the efforts of a few academics, thought-leaders, and businesses that stimulated its practical uptake into modern economic systems and industrial processes. The schools of thought from which the notion has been developed and adapted are Regenerative Design, Performance Economy, Cradle-to-Cradle, Industrial Ecology, and Biomimicry (ELLEN MACARTHUR FOUNDATION, 2013).

In their work, Tolio et al. (2017) pointed out the first four schools' contributions to the concept. Regenerative Design, introduced by John T. Lyle in the late 1970s, presented the idea of connecting resource regeneration to sustainable development (LYLE, 1996). Performance Economy, presented by Stahel and Reday (1981), offered the economic basis for migration towards non-linear industrial models, later adapted to include the notion of Cradle-to-Cradle design, a framework aiming at the creation of waste-free by essence, efficient systems (MCDONOUGH; BRAUNGART, 2002). Finally, the Industrial Ecology idea studies the material and energy flows through industrial systems, paying specific attention to people's connections within the system in an attempt to have closed-loop chains using waste as possible input (FROSCH; GALLLOUPOLOS, 1989). They also add as a precursor the work by Pauli (2010) entitled Blue Economy, which collected a series of practical examples in which resources are linked in cascaded systems enabling waste flows from one product to become by-products, used as inputs in the creation of new cash flows. For what concerns Biomimicry, Ellen MacArthur Foundation (2013) presents it as a notion developed by Benyus (2002) that studies natural designs, trying to imitate, transform and apply them to create innovations having nature as their primary inspiration and to eradicate human problems as their goal.

There are several examples of the successful use of the concept and principles of CE by different companies in distinct sectors, such as Michelin, Caterpillar, Renault, Ricoh and Desso,

as well as Komatsu Ltd., Knorr Bremse, Bosch, Airbus, and Mitsubishi Electric Corporation to mention some (ELLEN MACARTHUR FOUNDATION, 2013; TOLIO et al., 2017). This application of CE at the enterprise level is the result of CE's consolidation, appearing since 2010 as a consequence of theoretical integration and application given combined efforts from academia and entrepreneurs (GAO et al., 2019). The Ellen MacArthur Foundation can be highlighted as one of the players in the vanguard of this process (HOMRICH et al., 2018).
Galvão et al. (2020) conducted vast research over current scientific literature around Circular Economy and revealed there are eight main clusters of studies regarding the subject. The trending topics of actual CE literature are theoretical knowledge; empirical research; circular business models; value creation; major guidelines; integration and conflicts; innovation; and public policy.

Sustainably shifting towards a Circular Economy is presumed to be beneficial in terms of the environment, the economy, and society. Regarding the environmental aspects, it can bring significant savings in raw materials and energy consumption comparing to the traditional linear production of goods, impacting CO_2 emissions and sustaining the fight against climate change. As for the economy, it brings producers cost savings in energy and material, in addition to those related to end-of-life (EoL) items' disposal. In the social sphere, CE businesses are supposed to create new job vacancies given a rise in consumption of sustainable products due to their more affordable prices (TOLIO et al., 2017).

2.1.4. De- and Remanufacturing

The establishment of a Circular Economy, if to attain its goals, requires a group of activities entitled to closing the loop/circle of the system. Their function should be to collect products, components, and materials after their use phase and reinsert them into the economic value chain. It is within this context that the activities related to the De-manufacturing of products, components, and materials are found.

According to Duflou et al. (2008, p. 2)

> Demanufacturing can be defined as the breakdown of a product into its individual parts with the goal of reusing parts, remanufacturing and recycling the remainder of the components. It is a recovery strategy that focuses on retrieval of product assets as a tactic minimum disposal approach.

The previous definition mentions some key processes supporting the implementation of a De-manufacturing strategy. Reuse is a term used to characterize the process in which items are put in operation again without the need to perform repair activities, while the term Refurbishment is used for cases in which these tasks are required. Remanufacturing aims to return the product to its initial condition by submitting it to industrial processes, without modifying its identity. The Recycling activity is a process targeting material recovery through the collection and reprocessing of material flows, whose origins can be industrial residues or actual products. In general, this task downgrades materials' characteristics, although it is possible to preserve the material quality even after recycling in specific cases (DUFLOU et al., 2008).

Tolio et al. (2017) propose a second definition for the concepts of De- and Remanufacturing, claiming that they encompass the technologies and systems, tools, and knowledge-based methods applied to systematically recover, reuse, and upgrade features and materials from industrial waste and post-consumer goods, aiding the sustainable implementation of Circular Economy businesses in a manufacturer-centric approach.

Furthermore, they point out there are additional options and business models which are implemented and go beyond the aforementioned alternatives. They suggest that in industrial practice, Remanufacturing can be further specified, being either for function restore or for function upgrade. In the first case, products are returned to at least their original performance and are warranted equivalently or better than when they were new. It is also stated that remanufactured products fulfill functions similar to the original's applications, and are subject to a standardized industrial process compliant with technical specifications in their making. In the second case, Remanufacturing grants the items fresh functionalities, intending to extend their value life by the introduction of technological innovation, which enables the fulfillment of evolving customers' preferences and preserves the physical resources that have been employed in the process at the same time. Moreover, they present Repair, which can be considered a synonym for Refurbishment, and differentiation for Recycling, either open-loop or closed-loop. Closed-loop recycling characterizes the processes in which there is no property downgrading, implying it is possible to submit gears to the activity indefinitely, whereas Open-loop recycling refers to cases in which there is property degradation because of the process. In the latter, the recycled material cannot be used as a perfect substitute for the virgin one given the difference in their attributes, which results in its use for distinct applications, in replacement of other materials.

To attain its objectives, De-manufacturing systems rely on a set of activities that conduct specific operations on goods, in the end enabling their reintroduction to the value chain. Therefore, those systems frequently combine different stages, and in each stage, certain activities with specific goals are executed. These processes constitute the main components of the system, thus require a proper integration so they can offer to the value chain their joint capabilities. The process stages are Materials and functions liberation; Sorting and Separation; End-recovery; Inspection; Reconditioning; and Logistics (TOLIO et al., 2017).

Materials and functions liberation normally are processes at the beginning of a De-manufacturing system and can be divided into Disassembly and Size-reduction activities. In Disassembly, the objective is to isolate hazardous components, not to let them enter the process flow, as well as reusable parts with great residual value and parts that require dedicated processing. It can be further distinguished between destructive, semi-destructive, and non-destructive disassembly. This option enables the recovery of product functions, the obtainment of high material-return rate, and the pre-concentration of waste, but it frequently entangles higher costs because of the tasks' complexity and the requirements of manual labor, a consequence of the intricacy. In Size reduction, also called Comminution, the goal is to make the constituents of a mixture smaller by breaking, incurring in the liberation of heterogeneous material particles, hence it is always a destructive process. Normally, it is used to benefit the quality and feasibility of separation stages downstream (TOLIO et al., 2017).

For what concerns Sorting and Separation, the aim is to divide a flow of input into two or more streams of output to which the materials composing the inflow are directed based on their intrinsic properties. That specific direction grants one of the outflows with a higher concentration of a certain product, component, or material relative to the input stream, therefore, denominated as the target. This process usually occurs over multiple stages, as this allows to lever on different properties for the sequential separation of different materials at high grade and to submit the targeted flows to the same operation as many times as required for the achievement of the level of recovery or grade desired. In their functioning, sorting processes generate an environment that induces different trajectories in particles according to the value of a property they display; hence, the separation happens through a selected characteristic, chosen by design. However, this stage's outcome is subject to inaccuracy and errors because of random disturbances, leaving a possibility that output flows are contaminated with particles incorrectly classified (TOLIO et al., 2017).

End-recovery activities pursue the obtainment of a separated target material likewise, although for this purpose they employ chemical-thermal rather than mechanical processes, thus being able to achieve superior grade levels. Normally, they are batch processes, which take as inputs mixtures previously sorted (TOLIO et al., 2017).

Inspection stages are inserted in De-manufacturing systems in multiple levels with varying motivations. This process can be used in recovery stages, aiming at gathering information about the mixture and its constituents, which can, in turn, be used to adapt the system to the inflow's condition, raising its efficiency, and in remanufacturing stages, for the acceptance of post-consumer goods, the identification of failures in part and the testing of final products. Depending on the application, the objectives of the inspection processes and the technologies that should be adopted to reach them will vary (TOLIO et al., 2017).

Cleaning processes are essential, since surface cleanliness strongly influences the capability to execute surface treatments such as inspection, reconditioning, reassembly, painting, and finishing, and are some of the most demanding activities in the context of De-manufacturing. In this scenario, cleaning happens in the whole piece so the quality requirements to which it will be subject after remanufacturing can be met. Additionally, the treated parts are characterized by high variability in aspects such as size, shape, material, surface condition, and contaminant, amongst many others. Equally to Inspection, cleaning activities can be positioned at different levels of the De-manufacturing process chain, and according to the placement, it will have distinct goals, methods, and results (TOLIO et al., 2017).

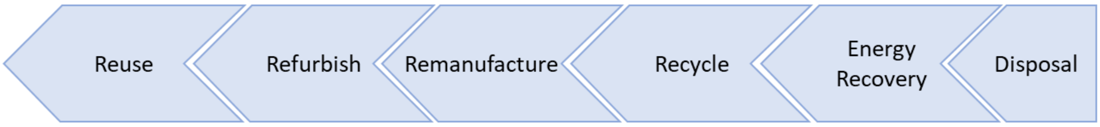
Reconditioning activities restore the features of products, parts, and components after the previous stages were executed, and the choice of process depends on the feature to be reconditioned and on the defect type the part exhibits. Although the possible differences in process, they might contain the standard activities of surface and shape defects removal; material addition and deposition; material properties restoration; and surface finishing (TOLIO et al., 2017).

Logistics processes perform spatial transformations on the elements treated by De-manufacturing systems, necessary given the coexistence of discrete and continuous flows inside and across its multiple stages. The internal logistics processes present in this context are marked by high rigidity, which inhibits route flexibility during the operation (TOLIO et al., 2017).

In their work, Tolio et al. (2017) present a collection of activities constituting the many De-manufacturing process' stages, the most common technologies used to perform them nowadays, as well as promising solutions and techniques available that may be introduced shortly to enhance the system's performance.

The selection of the appropriate EoL treatment to employ occurs after the screening and assessment of waste flows, which distinguish used goods among different categories. After their classification, the hierarchy presented in ***Figure 3*** should be used to determine the process they shall undergo, respectively (*from left to right*), from the most to the least desirable, assuming the waste flow generation cannot be avoided (SELIGER, 2012).

Figure 3 – Hierarchy of EoL alternatives



Source: Adapted from Seliger (2012)

Further information about the EoL pathways is valuable. The Reuse activity must aim initially at products, then at components. The Energy Recovery alternative frequently is implemented using incineration processes, which are also the first solution in Disposal when energy recovery is unavailable, a practice preferable to sending goods to landfills, which represents the last remaining option (DUFLOU et al., 2008).

The adoption of a De-manufacturing strategy has several implications for companies concerning their operations and business models, and current global trends convey challenges that have consequences on the requirements for De-manufacturing systems. These include high adaptability both to the product and to the market conditions; high degree of automation; availability and traceability of information; environments conceptualized with the human being at the center, displaying high levels of ergonomics and safety; and sophisticated decision support tools embracing cutting-edge data processing methods (TOLIO et al., 2017).

Tolio et al (2017) argue that modern examples of established Circular Economy business models leverage on the strong participation of the product manufacturer, which brings crucial information to the De-manufacturing process, and that current models addressing the topic focus only on the product perspective, lacking stakeholders, especially manufacturers, issues and information flows over the value chain. They come up with a new framework to represent the CE context, which calls attention to relevant aspects, as that manufacturing and de-manufacturing systems should be assessed in an integrated approach, focusing on the exploitation of the synergies existing between them; and that there is an increase in variability and uncertainty in the inputs of de-manufacturing processes, following the goods' use phases, if compared to the inputs of the manufacturing activity, which must be tackled and successfully tendered by the system. These aspects include information flows' paramount importance in this context, especially those that share design content with the systems and/or offer data on the post-use products' conditions; and that both manufacturing and de-manufacturing activities must be comprised in the company's value chain and business model, subject to the defined targets and allocation of activities that take into account the whole value chain with the ultimate goal of delivering added-value functions to consumers.

Likewise, Poles (2013) claims companies' objectives within the context of the introduction of remanufacturing systems should be to optimize the integrated reverse and forward supply chain system to attain the levels of minimum total costs and maximum benefits. Fleischmann et al. (1997) also highlight the inferior homogeneity and standardization of used goods when observed as inputs, and state that handling this uncertainty in the planning of the reuse activity is of paramount importance. They also describe the context in more detail, deepening on the topic of reverse logistics, characterizing its scope, noticing there was yet no general framework for it, and pointing out research regarding the subject was restricted to narrow views on single issues, offering isolated results and few comprehensive approaches, to conclude that the theme required additional research efforts.

The previous challenges and requirements for a De-manufacturing system make its establishment a difficult task, and the manner and comprehensiveness in which such systems will be implemented are determined by the forecasted profits they can bring to companies. Nonetheless, actions encouraging producers to take care of their products after the use phase can be put in force by regulators, such as economic incentives or recycling quotas, hopefully stimulating firms to establish their reverse supply chains as a move in the pursuit of economic returns (INDERFURTH, 2005).

In alignment, Galvão et al. (2020) also stress the fundamental role of policies for CE to gain traction in the real world. They suggest that governments, as primary policymakers, have the opportunity to catalyze the establishment of Circular Economies worldwide. The enforcement of new regulations can act as present-lacking governmental support that initiates the transition towards CE, leapfrogging the existing inertia arising from the complexity of integration, the apparent conflict of interests, the concerns around economic viability, the innovation-related uncertainty, the long-term returns, etc., what turns policy-making one main topic inside Circular Economy that acts as a top-down direction for the transition (GALVÃO et al., 2020; HOMRICH et al., 2018; GUZZO, 2020). Homrich et al. (2018) disclose an extensive coverage of examples in the scientific literature showing the fundamental role of policies in leveraging the establishment of CE. It can be also seen that the actions of public authorities must concentrate on the supply chain and also on the public. It is important to raise awareness in society to create a market that is willing to consume the recovered goods, which, currently, are perceived as part of an inferior-quality tier of products that caps their realizable price regardless of the quality standards followed during production activities (HOMRICH et al., 2018; GEISSDOERFER et al., 2018). A crucial point after policy establishment is to make the regulation process systematic and periodically reviewed, fostering emerging state-of-the-art practices and further innovation (ALAMEREW; BRISSAUD, 2020).

The emphasis on regulation has been recently increased in a new report published by Ellen MacArthur Foundation (2021). The document presents five complementary policy goals: Stimulate design for the circular economy; Manage resources to preserve value; Make the economics work; Invest in innovation, infrastructure, and skills; and Collaborate for system change; in an attempt to align action for accelerating the transition towards CE. The report stresses that the change requires comprehensive policy frameworks to happen since the needed scale cannot be achieved by current leading businesses alone. Therefore, these goals represent standards around which public and private agents must operate in coordination for their common objectives. It also highlights the timing is opportune, as the role governments have in the economic recovery following the depression caused by the Covid-19 pandemic offers the chance to restart the economy already pushing for the circular model (ELLEN MACARTHUR FOUNDATION, 2021).

2.1.5. Circular Business Models

The Business Model (BM) of a company describes its value architecture. It contains the value elements inside the business that once combined guarantee its perpetuation. These elements are clustered in categories, namely Value creation, Value delivery, and Value capture. The components in Value creation define how the company's activities generate value for its target customers. Moreover, those within Value delivery explain the ways the value created is transferred to the end consumers. At last, Value capture fits the elements that enable the firm to convert this delivery into profit, capturing money from its customers in exchange for the value provided.

As already described, the transition towards more sustainable or circular systems requires many changes in companies. More specifically, the operational routines' management, manufacturing processes, and supply chain management activities must be rethought, and the needed modifications to adhere to CE principles may force the firm to redesign its Business

Model (HOMRICH et al., 2018). Accordingly, Galvão et al. (2020) manifest that these necessary changes can be profound if managers desire to pursue the strategy consistently, systematically, coherently, and continuously. They continue their argument claiming the BM might call for additional development to englobe circular values left uncaptured and to deal with the possibly paradoxical seeking for both business objectives and sustainability goals in parallel (GALVÃO et al., 2020).

Thereupon, given the specificities in a BM for its compliance with CE principles, those that fulfill the criteria may be referred to as Circular Business Model (CBM). CBMs are viewed as the means to operationalize CE strategies, or else, a sustainable business model (SBM) strategy or subcategory that enables the proper functioning of the Circular Economy's value creation mechanisms (GALVÃO et al., 2020). As it happens, Franco (2019) calls CBMs the labels for BM under the CE context, whose strategies targeting resource loops increase the efficiency of resource utilization.

In greater detail, Galvão et al. (2020) bring Linder and Willander's (2017, p.2) definition of CBM as "a business model in which the conceptual logic for value creation is based on using the economic value retained in products after use in the production of new offerings". Additionally, Geissdoerfer et al. (2018) present CBMs also as SBMs, which they define as BMs that focus on solutions for sustainable development, bringing extra monetary and non-monetary value by the way they manage stakeholders and consider the problem's big picture and time length. They add CBMs specifically target alternatives for the CE using circular value chains and stakeholder incentive alignment, which helps in their definition of Circular Supply Chain Management (GEISSDOERFER et al., 2018).

In practice, it is possible to find a variety of CBMs being used by companies. For instance, there are sharing platforms; product as a service; circular supply chains; resource recovery; product life extension, and more (GALVÃO et al., 2020). Moreover, there are also ways of trying to transition towards CE with different arrangements to current BMs, as in the example brought by Alamerew and Brissaud (2020), in which the company maintains its ownership of the battery over its lifecycle to ensure circularity occurs. As a guideline, Franco (2019) says that for CE to evolve at the firm level, corporations should center their strategies both on product design and business model innovation.

Consequently, companies that try to implement De-manufacturing strategies and incorporate reverse flows in their operations are converting their actual Business Models into CBMs.

2.2. <u>Composites</u>

2.2.1. Definition and Considerations

The term Composite is used to refer to material structures "[…] that consist of at least two macroscopically identifiable materials that work together to achieve a better result." (NIJSSEN, 2015, p. 13). The report from FiberEUse (2017b) add they are also known as fiber-reinforced plastics (FRP), if containing plastics, and englobe many different material types in terms of mechanical properties, composition, and fields of application. The main components of these materials are fibers, mainly glass and carbon, and matrices or resins, which are usually plastics/polymers, also containing additives and fillers if required. Although the two main elements – fibers and matrix/resin – are used in combination, they do not blend to become one mixed final substance. Instead, they keep visible as different constituents of the final heterogeneous material, working in unison during its utilization. The goal of this mixture is to achieve better performance of the resulting material in comparison to the single performances of its components, which are combined in a way that enhances some desired characteristics while smoothing unfavorable others (FIBEREUSE, 2017b; NIJSSEN, 2015).

Not differently from other materials, composites have benefits and drawbacks, which are summarized in ***Table 1***. It is important to mention that the perspective used to define characteristics as positive or negative is that of a non-specific material, and careful distinctions are necessary for each design. Moreover, costs and the sustainability of each creation should be analyzed with the entire life cycle as the perspective instead of single activities viewed in isolation (NIJSSEN, 2015).

Table 1 – Benefits and Drawbacks of Composite Materials

Benefits	Drawbacks
Weight reduction	High raw material costs
Flexibility in shape, material, and fabrication process	Need of sophisticated computational methods in some cases
Easy to color	Unpredictability in color and gloss preservation in some cases
Translucent	Relatively limited knowledge on structural behavior of details and connection methods
Enable high degree of integration of functions	Not well-developed finishing processes
Strength, stiffness, thermal and electrical resistance oriented by design choices	Possibly undesirable stiffness and failure behavior;
Low total maintenance costs	Sensitivity to temperature, fire and lightning strikes
Resistant to water and chemically resistant	UV light sensitive
Possibility to use durable materials	Not yet well developed recycling methods
Possibility of automated manufacturing	Capital intensive production methods can be required in some cases

Source: Adapted from Nijssen (2015)

2.2.2. Components

Fibers are applied in composites to alter the material's strength and stiffness, normally to superior levels, especially in the direction they are positioned inside the structure; consequently, in practice, they are introduced in different directions. The classification of fibers depends on the composition, the length, and the type of semi-finished product or bundling of fibers (FIBEREUSE, 2017b; NIJSSEN, 2015).

The most used fibers in the market are made of glass, carbon, natural materials, aramid, and basalt, among others, which are used in more specific applications and niche products. There is further differentiation of fibers fabricated with the same material according to their chemical composition, which changes the properties displayed such as strength, stiffness, density, and chemical resistance. Regarding the length, the main variations are short, long, and endless fibers. The main influence of this aspect is on the composite's mechanical characteristics. Typically, fibers are not only used in isolation but also in assortments seen as semi-finished products. Each bundling arrangement offers different characteristics, thus suits disparate applications (FIBEREUSE, 2017b; NIJSSEN, 2015).

The resin, which is also referred to as matrix, is the substrate material in which fibers are embedded, often a polymer. The matrix operates as an adhesive that keeps fibers together and transfers loads between them through shear stresses, resulting in a better distribution of external loads in composites in comparison to fiber bundles and higher compression resistance granted by the resin. Composite characteristics, for instance, color, surface aspects, opacity, and performance in the presence of external factors such as heat, fire, UV radiation, moisture, and chemicals are strongly influenced by the matrix's choice, highlighting the importance of the resin for the composite's properties. As main groups of matrices, there are Thermoset and Thermoplastic materials (NIJSSEN, 2015).

2.2.3. Fabrication and Utilization

The method employed for the composite's fabrication depends on the type of resin used, hence, the routes for thermoplastic and thermoset materials are distinct. Thermoplastic composites are produced mainly by the use of injection and compression molding processes such as injection, injection molding compounder, water injection technology, and blanks compression. In the case of thermoset resins, some of the methods employed are resin transfer molding, infusion, continuous lamination, and hand layup (FIBEREUSE, 2018b).

Fiber-reinforced plastics find several fields of application. They are used in airplane's structural and interior parts; wind blades; car bodies, chassis structures, powertrains and interior parts of cars; roofing and ceiling panels and sheets; inks and bathtubs; skis and helmets, etc. (FIBEREUSE, 2017b).

2.2.4. Reverse Operations

An important issue that arises when observing the use of composites within the Circular Economy's perspective is their recycling and remanufacturing. As made explicit in

, these materials pose challenges regarding their reverse processing, especially considering collection, transportation, both affected by the regulatory context, and remanufacturing or recycling activities, which influence the recycled material's properties, thus performance. However, the crucial factor is not the method availability, which exists for all kinds of material, but the economic feasibility of the de-manufacturing process given the low commercial value of recycled composites and even of certain virgin FRP. The most popular strategies for the treatment of EoL composite waste, namely glass-fiber-reinforced plastics (GFRP) and carbon-fiber-reinforced plastics (CFRP), can be segmented into the categories: landfilling; incineration and co-incineration; thermal or chemical recycling; and mechanical recycling (FIBEREUSE, 2017b).

In Landfilling, products are sent to landfills, in which they are properly buried. Incineration allows the partial or complete recovery of the energy embedded in the waste material, while Co-incineration, usually in cement kilns, introduces the additional benefit of the incorporation of the mineral constituents of composites into the cement clinker. Nonetheless, major drawbacks are air pollution and the following landfilling of fibers and filler contents. Thermal or chemical recycling routes have as objective the separation of the fiber from the polymeric matrix in which it is inserted and include the processes of pyrolysis and solvolysis. Mechanical recycling aims at the incorporation of powdered material as filler or reinforcement in new composites after submitting waste FRP to size-reduction processes such as shredding, crushing, and milling. A relevant aspect in the reverse processing of composites is properties' downgrading since it is difficult not to compromise the material's characteristics, mechanical properties in special, during recycling activities (FIBEREUSE, 2017b).

Some studies tackle the recycling problem. La Rosa et al. (2016) use Life Cycle Assessment and Life Cycle Costs analysis to study the recycling of carbon fibers and conclude there are resource savings and avoided impacts if the use of polyacrylonitrile fibers is avoided. Longana et al. (2016) apply the High-Performance Discontinuous Fiber method to investigate CFRP multi-closed loop recycling – when there is more than one recycling operation in the material's life – finding out that after the second loop of recycling there is a great decline in properties. Therefore, they state there is a need for fiber reclaiming process optimization to avoid contamination on the fiber surface and damage to fibers, thus the loss of their properties. Higher-level approaches are also found, although less numerous, in which there is no specific focus on the properties of the material, but rather on the supply chain. Vo Dong et al. (2018) analyze the recovery and disposal pathways for CFRP management and reach interesting conclusions. They claim without regulation, landfilling and incineration will continue to be dominant economic choices in CFRP waste management, and suggest there is an economic and environmental conflict in CFRP recycling when techniques with a high yield of recovery are applied. Additionally, they present price figures for many other possible routes, which may be selected in scenarios that consider regulatory measures in place.

Another interesting research lies in the scope of *FiberEUse – Large scale demonstration of new circular economy value-chains based on the reuse of end-of-life fiber reinforced composites* (2017-2021), which is an initiative funded by the European Commission. It focuses on providing proof of economically and technically viable pathways for EoL composite waste with origins in different industrial sectors, as well as on identifying new business opportunities for recycled FRP (rFRP) making use of a comprehensive approach that considers cross-sectorial open-loop recycling possibilities.

2.3. System Dynamics

2.3.1. Introduction

System Dynamics (SD) is a field of study initially developed by Jay W. Forrester during the 1950s at the Massachusetts Institute of Technology, addressing the investigation of complex, non-linear, dynamic systems using formal mathematical modeling and computer simulations (FORRESTER, 1961). In Franco (2019), SD is defined by its focus on increasing the comprehension of complex feedback systems at the same time it assists decision-making within policy formulation processes. It acknowledges that real-world problems arise in consequence of the dynamics of the system in which they are embedded, and when trying to solve them people are often misled by their mental models to wrong inferences about these dynamics, regardless of the simplicity of the system (STERMAN, 2002).

Because of the limitations in their mental models, people's actions do not take into consideration all their possible outcomes, and the efforts applied to solve specific problems frequently create unpredicted side effects. In turn, those side effects generate new problems shortly. Hence, the instruments applied as a response to an issue can be the cause of new issues ahead. System Dynamics is presented as a methodology to overcome these limitations and enhance the comprehension of the system and its dynamics before decision-making (STERMAN, 2002).

Sterman (2002) points that complex systems' behavior in which the systems' response to an intervention prevails over the interference, denoted policy resistance, is caused by dynamic complexity, described as the counterintuitive response of such systems in reaction to the agents' interactions. Additionally, he presents the characteristics of systems culminating in dynamic complexity, which are: constantly changing; tightly coupled; governed by feedback; non-linear; history-dependent; self-organized; adaptive; trade-off characterized; counterintuitive; and policy resistant.

The reason behind erroneous decision-making in complex dynamic systems is the misinterpretation of causal relations. Commonly, these are built from heuristics incapable of coping with main sources of dynamic complexity, namely feedbacks, stocks and flows, and time delays, the primary components of SD thinking (STERMAN, 2002).

2.3.2. Components

The henceforth presentation of System Dynamics' key components is mainly based on the work by Sterman (2000) unless stated otherwise.

2.3.2.1. Feedbacks

When approaching real-world problems, people tend to use an event-oriented perspective in a never-ending, linear, open-loop view of the world. Nonetheless, the previous notion assumes the system's state remains static after agents' interferences; however, it reacts to the interventions. The system responds to the actions taken, and the results obtained shape its future state, to which agents will be exposed. This latter will then serve as the basis for future decisions, in a behavior that constitutes the systems' feedbacks. These responses can go as predicted but also give rise to unexpected side effects of the measures in place. Moreover, one agent's actions trigger actions from other agents that will feedback on the state of the system. Ultimately, there is a risk of rendering policies ineffective and producing unpredicted results. This view of the world, in which events originate from the feedback loops arising as interactions of the agents, can foster the understanding of systems' behavior, changing its perception of being unpredictable and uncontrollable.

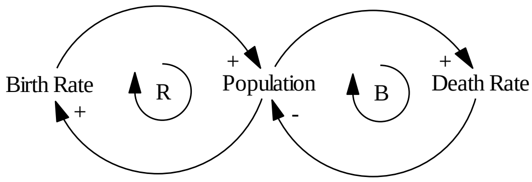
There are only two types of feedback loops that can shape the dynamics of any existing system: positive (or self-reinforcing) and negative (or self-correcting) loops. Positive loops enhance and reinforce every system's observed behavior, and are responsible for nurturing their growth, whilst negative loops halt and oppose this behavior, seeking balance and steady states for the system. All systems are a network of positive and negative feedbacks, and every dynamic arises from the interactions between them.

The representation of a system's feedback structure in System Dynamics employs a tool labeled Causal Loop diagram, which enables its users to capture their hypothesis for the dynamics' causes, understand the mental models of individuals and groups of people, and communicate the main feedbacks thought to be responsible for a certain issue.

Causal loop diagrams are composed of variables that are interconnected by arrows with defined polarities, either positive or negative. The arrows represent the causal links between the variables, while their polarity displays if they vary in the same direction, defined by the positive sign, or on the contrary, shown by the negative sign. The first variable is called the independent variable, whilst the second is referred to as the dependent variable.

If following a sequence of causal links the variable of origin can be reached as a destination, a loop is established. The important loops are emphasized using loop identifiers that display whether it is a reinforcing/positive or balancing/negative feedback. Causal links that involve significant time delays should disclose this aspect explicitly in the diagram. In ***Figure 4*** it is possible to observe a simple example of a Causal Loop diagram representing the dynamics of population, birth and death rates, which contains both reinforcing and balancing feedbacks. Georgiadis and Vlachos (2004) state causal loop diagrams play two main roles in SD: they serve as preliminary drafts of causal hypotheses and allow the simplified representation of a model.

Figure 4 – Example of a Causal Loop diagram



Source: Adapted from Sterman (2000)

Behind the graphical representations of polarity, there is a mathematical background. Equations ***(1)*** and ***(2)*** show the mathematics behind positive and negative link polarity, respectively, in which the independent variable is denoted by *x* and the dependent by *y*.

$$\frac{\partial y}{\partial x} > 0 \; or \; y = \int_{t_0}^{t} (x + \cdots) ds + y_{t_0} \quad \textbf{(1)}$$

$$\frac{\partial y}{\partial x} < 0 \; or \; y = \int_{t_0}^{t} (-x + \cdots) ds + y_{t_0} \quad \textbf{(2)}$$

The interplay of positive and negative feedbacks can give rise to specific dynamics, being the main modes of them Exponential growth, Goal seeking, and Oscillation. These three fundamental modes of behavior can be combined, leading to additional behaviors like S-shaped growth, S-shaped growth with Overshoot, and Overshoot and Collapse, to mention some. Moreover, there are further patterns such as Stasis, Randomness, and Chaos, which do not arise from the combination of the fundamental behaviors and usually entangle non-linearity.

2.3.2.2. Stocks and Flows

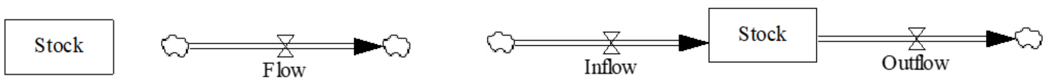
Stocks and flows are, together with feedbacks, key concepts in SD theory. Stocks are defined as accumulations that describe the state of the system and provide the information base used in decision-making. They grant systems with inertia, memory, and delays, arising as the difference between inflows and outflows of a process adds in the form of stocks. They represent sources of disequilibrium in systems as well. Flows, instead, are the mechanisms altering the value of stocks, their inflows and outflows, respectively increasing or detracting the quantity accumulated. Although these elements' common presence in everyday life, they are frequently confused with one another, inducing underestimation of time delays, short-term orientation, and policy resistance.

In dynamic systems theory, stocks and flows can be represented either with diagrams or with mathematics. In diagramming, by convention stocks are described with rectangles, whilst arrows or pipes depict flows. If the source or the terminal of the represented flow lies outside the boundaries defined for the analysis of the system, they contain a cloud at their beginning or at their end to disclose this information. Additionally, flows contain valves to highlight the presence of regulators that provide control over them. In ***Figure 5***, it is possible to see the diagrammatic representation of a stock and a flow, and an example of stock and flow structure, respectively, from left to right. Regarding the mathematical notation, the stock and flow structure can be represented in two ways, either by Integral or by Differential equations, respectively shown in ***(3)*** and ***(4)***.

$$Stock(t) = \int_{t_0}^{t} (Inflow(s) - Outflow(s))ds + Stock(t_0) \qquad \textbf{(3)}$$

$$\frac{d\ Stock(t)}{dt} = Inflow(t) - Outflow(t) = Net\ Flow\ Rate \qquad \textbf{(4)}$$

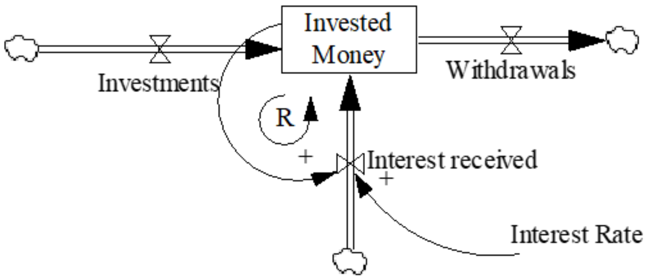
Figure 5 – Diagrammatic representation of Stocks, Flows, and Stocks and Flows structures



Source: Adapted from Sterman (2000)

The diagrammatic representation of stocks and flows gives rise to a second way of describing a system used in System Dynamics, the Stock and Flow Network, also Stock and Flow Map. Such a tool goes beyond Causal Loop diagrams since it allows the segmentation between the physical flows and the information feedbacks connecting them, which are all responsible for the dynamics observed in the system. By using this map, it is possible to evidence the impact that stocks and flows have on each other, increasing the observers' understanding of the system's behavior. Therefore, it should be applied to describe the elements whose patterns are important to the assessed dynamics, in combination with the feedback structure. ***Figure 6*** displays an example of a simple Stock and Flow Network.

Figure 6 – Example of Stock and Flow Network



Source: Author's elaboration

The approach taken in SD is called the state variable approach or the state-determined system approach, meaning that the variation of stocks can only be caused by its inflows or outflows, which in turn are determined by the firsts' values. Consequently, systems are a network of stocks, flows and the information exchanged between them, through which stocks alter the flows. Nonetheless, there can be additional determinants of flows, namely constants and exogenous variables. Constants are state variables that change over time horizons much greater than the one assessed in the model, so their increase is barely noticed and this enables their representation by a fixed value. Exogenous variables are stocks left outside of the model's boundary by design, possibly because there are no important feedbacks from the system to them, but that somehow contain relevant information for the dynamics. A further element that can be present in Stock and Flow Maps are auxiliary variables, which are functions of stocks used as intermediates for clarity and comprehension facilitation reasons. However, the aforementioned approach implies there will never be causal links targeting a stock; they will either depart from it or target another type of element.

Therefore, as there are relationships between stocks and flows, their states influence the other's behavior and vice versa, thus the analysis of the interplay can be revealing for the understanding of the dynamics. Starting with stocks, when their values do not change they are said to be in equilibrium, and if all the stocks in the system are in equilibrium, the system is in equilibrium as well. For the equilibrium dynamics to arise, the net flow rate to the stock must be zero, and this can happen in two ways: either all inflows and outflows are zero, called a static equilibrium; or the sum of every inflow and that of every outflow have the same value, characterizing a dynamic equilibrium. If, however, the value of a stock is increasing over time, the net flow rate is positive, whilst in case the level decreases with time, this rate is negative. Thus, by knowing the stock level variation it is possible to determine the behavior of the net flow rate. Instead, having the net flow rate allows discovering by how much the stock has changed.

When mapping stocks and flows, the decision regarding their aggregation, both sequential and parallel, must be taken following the purpose of the model. The choice of aggregation involves mainly two elements: the level of aggregation and the boundaries for these internal stocks and flows.

Considering that Stock and Flow networks also describe the system's feedback structure, the way they are organized and their interactions will give rise to the previously mentioned modes of behavior alike. The most basic system structure able to create any of them is a first-order, linear feedback system, which is composed of only one stock and flows whose equations are linear combinations of the state variables and exogenous inputs. If the feedback loop represented by this structure is positive, it gives rise to exponential growth behavior. Instead, if the represented loop is a balancing one, the arising pattern can be goal-seeking or exponential decay. If multiple loops are combined and non-linearity is present, more complex behaviors can be observed, such as S-shaped growth. Worth of note that oscillation behavior cannot happen in first-order systems, just from second-order structures onwards.

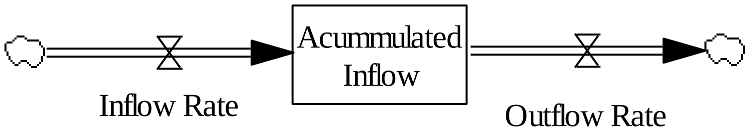
2.3.2.3. Time delays

Time delays are one major source of dynamics in almost every system and are very important for the assessment of the system's behavior, being also frequently observed in real processes. Time delays are procedures whose output laggardly trails the input in a certain fashion, thus, inside every delay, there is an embedded stock, in which the difference between the output and the input accumulates.

There are two main types of delays: Material delays and Information delays. In material delays, the delay process applies to a physical flow of materials so it must conserve the flow. Whereas, information delays portray the progressive adjustment of opinions and inferences based on the observation of current facts. In this case, the stock is the belief itself, altered by the new information received, and there is no conservation of flows involved, implying different structures are needed to represent the two kinds of time delays.

The most common stock and flow structure used to represent material delays is shown in ***Figure 7***. The outflow from a material delay depends on the inflow to it, which must be conserved, and on additional constraints imposed by the system's resources. However, if the capacity of a delay is considerably greater than the inflow, the outflow may be assumed to revolve around just the past input rates, and in such cases, it will be characterized only by the quantity of the inflow and the time passed since the entry. Therefore, defining the output rate using this approximation requires awareness about the processes' average residence time (or average delay time) and how the output is distributed around it.

Figure 7 – Stock and Flow Structure of a Material Delay



Source: Adapted from Sterman (2000)

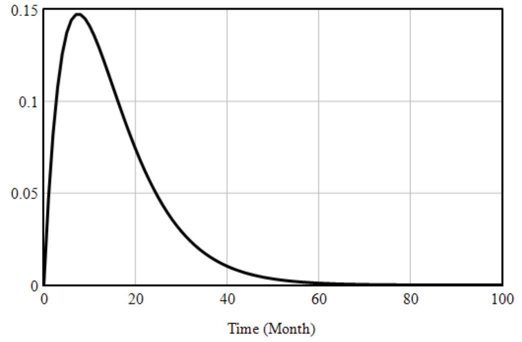
The output distribution around the average residence time is influenced by the specific activities originating the time delay. The order of the units leaving the stock, which can affect their residence time, is determined by the service rule adopted for the processing of items by these activities and by the degree of mixing introduced during operation.

Consequently, material delays can be classified based on their mixing level that in turn will characterize the outflow. Pipeline delays are structures in which the output fully respects the input order, and items leave the delay exactly after the residence time, thus the output rate can be defined as in ***(5)***. At the other extreme, in First-Order material delays there is the assumption of perfect mixing that disregards the order of entry of units, in this way the outflow determines the exit of units based only on the number of items in the stock. The output rate of a first-order material delay can be written as in ***(6)***. In between, there are innumerous intermediate cases in which the service discipline is affected by a certain degree of mixing, classified as Higher-Order material delays, frequently arising when delays involve many sequential processing stages, each introducing some level of mixing. The order of these delays is defined by the approximation of the number of chained stages involved in the processing, each one represented by a first-order material delay. This cascaded combination produces results in which the output is distributed around the average residence time in a curve, as shown by the specific example in ***Figure 8***.

$$Outflow\ (t) = Inflow(t - Average\ Residence\ Time) \qquad \textbf{(5)}$$

$$Outflow(t) = \frac{Accumulated\ Inflow}{Average\ Residence\ Time} \qquad \textbf{(6)}$$

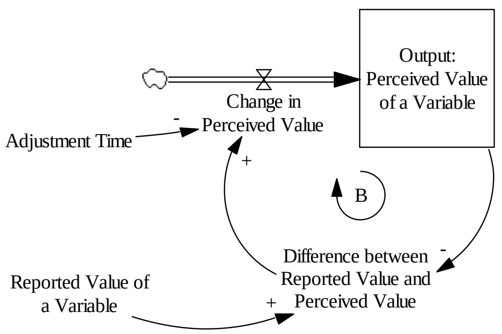
Figure 8 – Output distribution of a Second-Order Material Delay following a pulse input



Source: Adapted from Sterman (2000)

Regarding information delays, the stock and flow structure used in their description, depicted in ***Figure 9***, is different from that of material delays, since conservation of the inflow to the delay is not applicable. The simplest and one of the most widespread information delay structures used to model the refinement of assumptions given the availability of new information is Exponential Smoothing/Adaptive Expectations. In this case, the mismatch between the belief and the information is progressively corrected until the difference is extinguished; this is enabled by making the rate of change in the perception proportional to the discrepancy between the values.

Figure 9 – Stock and Flow Structure of Adaptive Expectations



Source: Adapted from Sterman (2000)

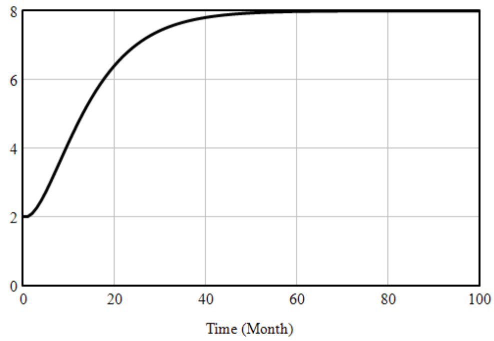
Different from material delays, in information delays the output is the stock itself. By close observation, it is possible to recognize that the model of exponential smoothing is the stock and flow structure of a first-order negative feedback loop. Therefore, it can assume either goal-seeking or exponential decay behaviors. Adaptive expectations introduce delays in systems because the error between the inference and the real value is corrected over time, not immediately, smoothing temporary changes and avoiding overreactions; its mathematical expression is the one in ***(7)***.

$$Change\ in\ Perceived\ Value = \frac{Reported\ Value - Perceived\ Value}{Adjustment\ time} \quad \textbf{(7)}$$

Similar to material delays, there are cases in which first-order information delays offer an inaccurate representation of the behavior observed since it implies the response of the system to a change is immediate. Thus, there are also pipeline and higher-order information delays. In a pipeline delay structure, the output, or the reported value, is the observed value that lagged the reporting delay; it is described by the expression in ***(8)***. Moreover, reporting procedures are generally composed of multiple stages, each introducing a certain degree of smoothing. Consequently, higher-order information delays, which contain a cascade of first-order structures, are more adequate to represent the dynamics verified in the system. In these cases, the change in the perceived value starts increasing up to a maximum rate, progressively falling after that until the observed gap disappears; ***Figure 10*** shows an example of it.

$$Reported\ Value\ (t) = Observed\ Value\ (t - Reporting\ Delay) \quad \textbf{(8)}$$

Figure 10 – Output distribution of a Second-Order Information Delay following a Permanent Change in the Observed Value



Source: Adapted from Sterman (2000)

An additional aspect that should be considered when modeling delays regards the delay time, either constant or variable. In case of the delay times vary, it can happen endogenously or exogenously. The response of material and information delays to variations in the delay time is different, especially because of the flow conservation requirement, thus the correct classification of the type of delay represented is of paramount importance in these cases.

2.3.3. Modeling and Applications

The development of a successful System Dynamics model involves following certain steps during the process. Initially, there is the Problem Articulation step, in which the issue to be assessed is identified along with the reasons behind its characterization as a problem and the key variables and concepts affecting it. Additionally, there is the definition of the time horizon to consider for the analysis, and the collection of the system's historical behavior, searching for insights regarding its dynamics.

The following step encompasses the formulation of Dynamic Hypothesis, initial assumptions for explaining the undesired behavior, which should be focused on the system's elements themselves rather than blaming the erratic pattern on exogenous factors. Moreover, there is also the mapping of the system's causal structure grounded on the generated hypotheses and additional available information. In this stage, the diagrams representing the system emerge, thus, there is the definition of the model's boundaries and the representation of subsystems, as well as the development of Causal Loop diagrams, describing the mental models and feedback structure, and Stock and Flow maps, which further detail the functioning of the system, apart from other tools.

In sequence, there is the formulation of the Simulation Model, which specifies the structure and decision rules adopted by agents, estimates parameters, behavioral relationships, and initial conditions, and tests the model built for purpose and boundary adequacy. Then, additional testing is performed in an ulterior step, this time focusing on the reproduction of reference modes, robustness, and sensitivity.

Finally, in the policy design and evaluation stage, there is the specification of the possible scenarios to be faced and policies to be implemented, along with the conduction of sensitivity analysis, hypothetical case assessment, and policy interaction effects observation. Although it seems a cascaded process, modeling is iterative. Therefore, downstream steps may generate the need for upstream changes in the model, a loop fed by additional knowledge and information about the system.

System Dynamics models find various applications in the real world and are used in many different contexts. In general, it is preferred for studies in strategy development and improvement, policy design, and decision-making. The application's background normally is the assessment of complex and dynamic domains by a variety of users, from academics to private enterprises and even government agencies (ALAMEREW; BRISSAUD, 2020).

Additionally, Nassehi and Colledani (2018) point out SD is particularly good to model and assess long-term policies and strategies, and their effects on production, which is largely verified by the number of studies available having this as finality, and they apply it together with agent-based techniques for the study of remanufacturing under Circular Economy scenarios. Scholz-Reiter et al. (2005) use the technique to model an autonomously controlled shop floor in comparison to discrete-event simulation, finding out SD does not require much programming effort to implement autonomous control strategies in the model and offers a description of the logistic processes with a high-level of aggregation. In their study, Tailer and Garsson (2005) use System Dynamics to analyze public policy impacts on new ventures' growth rates, directly inserting into the model parameters representing the policy effects and varying their values for testing different scenarios. Sterman (2000; 2002) presents a series of practical applications of SD theory in occasions such as vehicle leasing, epidemics spreading, and technology adoption, among many others.

One relevant highlight from Franco (2019) says that despite frequent doubts about the convenience of System Dynamics models given their considerable demand for data and complexity, they have an incontestable ability to return relevant insights and policy recommendations, notwithstanding any lack of data.

Regarding the Circular Economy perspective, marked by overall systemic optimizations, rather than meticulous, SD's fitness for the investigation of complex systems in industrial or environmental contexts makes its use a common ground. It is possible to find SD models studying CE contexts such as sustainable development, closed-loop supply chains, recycling, and remanufacturing to mention a few (FRANCO, 2019).

Gao et al. (2019) also support the use of System Dynamics for Circular Economy studies. They claim SD can offer clear and complete models that enable the understanding of the system's internal structure, the capture of its behavior, and the effective simulation of the real system to achieve the best decisions to make. Moreover, they advance saying CE's pressing issues require analysis tools that are broadly accepted and contain embedded models, which must cope with dynamic but actual information inflows and allow the inclusion of indicators containing socio-economic and demographic data, to conclude that they are thus suited to be modeled following SD approach.

The main motivation to use System Dynamics in the study of Circular Economy is the presence of dynamic complexity in most of the transitions towards CE. The implementation of circular models is a process that entangles most of, if not all the characteristics that result in dynamic complexity, as thoroughly explained by Guzzo (2020). Thus, the utilization of a modeling technique able to properly cope with dynamic complexity is of paramount importance for the study of systems in the context of the Circular Economy. Additionally, another advantage of SD for assessments under the same background is its ability to investigate different alternatives for the problem using the same model dynamically, which makes it a prominent technique in the investigation of CE systems (GUZZO, 2020). Indeed, Galvão et al. (2020) formally recommend the employment of System Dynamics for the analysis of CBMs.

Many examples of studies using System Dynamics to model EoL circularity strategies can be found in the recent scientific literature (ALAMEREW; BRISSAUD, 2020). For example, Wang et al. (2014) apply the theory to assess the impacts of subsidy policies on recycling and remanufacturing of auto parts in Chinese territory, offering a bunch of examples of policy types and arriving at the conclusion that combining different policies provides better results to the system under analysis. Poles (2013) models remanufacturing under System Dynamics to evaluate strategies aimed at improving a production system. Zamudio-Ramirez (1996) investigates the economic aspects related to automobile recycling in the United States of America using SD, the same country analyzed by Taylor (1999), who employs the approach on the paper industry, including both forward and reverse flows, and discovers that sending more paper to recovery pathways does not guarantee an increase in paper reuse for new paper production.

Moreover, Dong et al. (2012) develop a model to comprehend the impacts generated by regulations focused on cleaner production in the context of the Chinese electroplating industry. In Gao et al. (2019), System Dynamics is applied to the investigation of the Circular Economy in Guangdong Province, China, providing key insights on the changes necessary for the development of CE locally. Worth of note that the outcome of their work is a list of three recommendations of policy measures to be enforced in the region. Besides, Cheng et al. (2019) use SD to investigate the dilemma of ‘ecological Fragility-Economic poverty’ and how to solve it by aiming for the establishment of CE, first discoursing about the suitability of the technique for their analysis, covering many of the aforementioned reasons for its use in the context of reference and then disclosing the model created and the simulations’ results.

Finally, Georgiadis and Vlachos (2004) use System Dynamics to assess decision-making in the context of reverse logistics, and in Vlachos, Georgiadis and Iakovou (2007) they adopt it for studying remanufacturing capacity planning in a closed-loop supply chain situation. At last, while Chaudhary and Vrat (2020) employ SD to the assessment of a CE model that assesses gold recovery from cell phones in India, Pinto and Diemer (2020) use it to analyze strategies for supply chain integration and circularity in the European steel industry, the results of the work being once more policy insights.

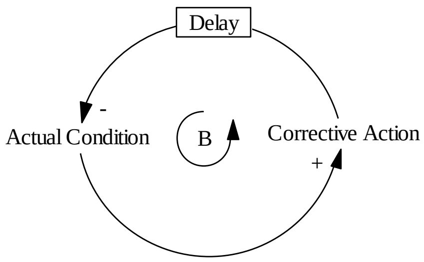
2.3.3.1. System Archetypes in CE-SD models

System Archetypes are recurring patterns of structures present in the field of systems thinking. By being able to recognize such generic structures, users can better understand the dynamics they observe and leverage existing knowledge to comprehend the behaviors of the system under their scrutiny. The existence of these structures is proof that systems of different natures are subject to similar dynamics, thus their problems and possible solutions for them can be analogous in terms of dynamics. Therefore, awareness of system archetypes assists agents in finding solutions for the challenges they face (SENGE, 1990).

In the review of SD-CE scientific literature during the present study's development, some of the archetypes from the collection presented by Senge (1990) were frequently encountered. These structures, which characterize System Dynamics models under the context of Circular Economy, are disclosed henceforth.

The first archetype is called the Balancing Process with Delay, whose structure is depicted in ***Figure 11***. This structure represents the adjustment of agents' behavior when acting towards a goal. Usually, the system's response to their actions embeds a delay, which they may be unaware of. In such cases, stakeholders may implement excessive actions, since systems lag to respond to the interferences that are then reinforced, or even cease to act, given their efforts seem to have no results. This archetype is often used to model changes in expectations and decision-making processes (SENGE, 1990).

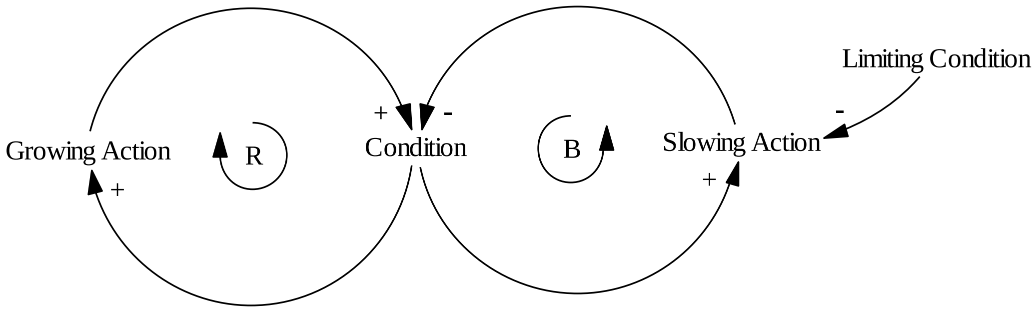
Figure 11 – Balancing Process with Delay Archetype



Source: Adapted from Senge (1990)

Another archetype common to SD-CE models is Limits to Growth, represented in ***Figure 12***. This structure describes the process of growth of something, in the case assessed normally the demand for a good or its production, that after a moment of acceleration begins to lose its pace until halting or even start collapsing. The growth phase is marked by reinforcing feedback loops, whilst the balancing stage derives from the presence of an embedded limit for the growth, either endogenous or exogenous, about which agents are conscious or not, that creates balancing loops (SENGE, 1990).

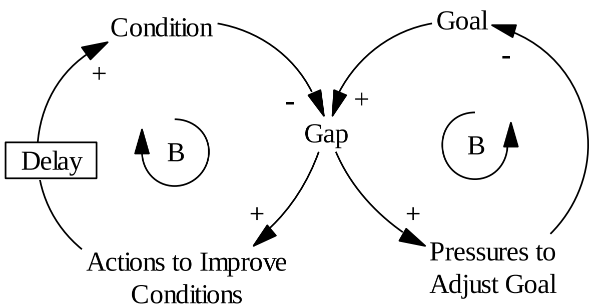
Figure 12 – Limits to Growth Archetype



Source: Adapted from Senge (1990)

The next structure frequently found in System Dynamics models studying Circular Economy systems is labeled Eroding Goals and is depicted in ***Figure 13***. This archetype represents the decrease in a long-term objective given short-term difficulties. In the context of CE, it is applied for modeling adjustments in expectations, fulfillment of performance targets, and accomplishment of policy objectives to mention a few use cases (SENGE, 1990).

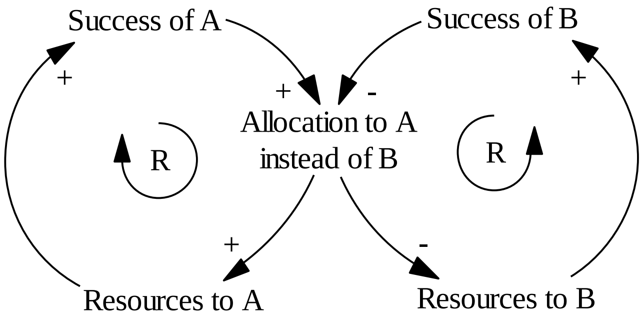
Figure 13 – Eroding Goals Archetype



Source: Adapted from Senge (1990)

The Success to the Successful system archetype, depicted in ***Figure 14***, represents the competition of two activities for the same inputs. The more favored one is during resource allocation, the greater its success and thus the more inputs it receives next. This structure is often employed to model the dispute between goods stemming from linear and circular systems for customer demand (SENGE, 1990).

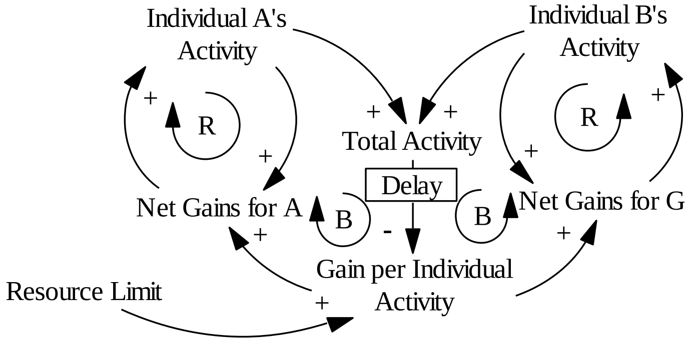
Figure 14 – Success to the Successful Archetype



Source: Adapted from Senge (1990)

A further archetype present in CE models using SD is the Tragedy of the Commons structure, shown in ***Figure 15***. This archetype is primarily employed when modeling the dynamics of natural resources' consumption by players operating in linear models, in contrast to the circular scenario investigated. The Tragedy of the Commons structure describes the use of a limited common resource by individuals depending only on individual needs. In the beginning, agents are rewarded for the use, but when scarcity starts to play a role, the diminishing returns that are present make them increase their consumption efforts, which further deteriorates the returns obtained. In the end, the resource reserves are either strongly depleted or even exhausted, bringing harm to all agents in the system (SENGE, 1990).

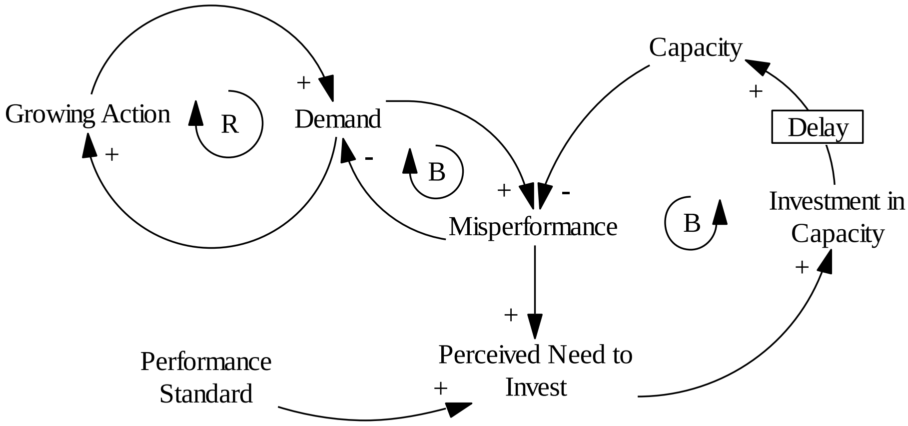
Figure 15 – Tragedy of the Commons Archetype



Source: Adapted from Senge (1990)

The last addressed archetype observed in SD-CE models is Growth and Underinvestment, whose structure is presented in ***Figure 16***. This archetype is verified in model sections representing industrial systems' capacity planning and expansion decisions. This structure describes the behavior of stakeholders in situations where growth approaches a limit that can be overcome with aggressive and timely investments. However, given the risks implied by these requirements, agents may decrease goals and performance standards to support the decision not to invest. In consequence, the company may enter a vicious circle in which the inferior objectives result in lower expectations that are confirmed by nether performance, all as a result of the underinvestment policy (SENGE, 1990).

Figure 16 – Growth and Underinvestment Archetype



Source: Adapted from Senge (1990)

3. RESEARCH METHODS

This section presents the method followed during the development of the work. It is divided into three parts, namely Research Stages, Data Collection, and Data Analysis.

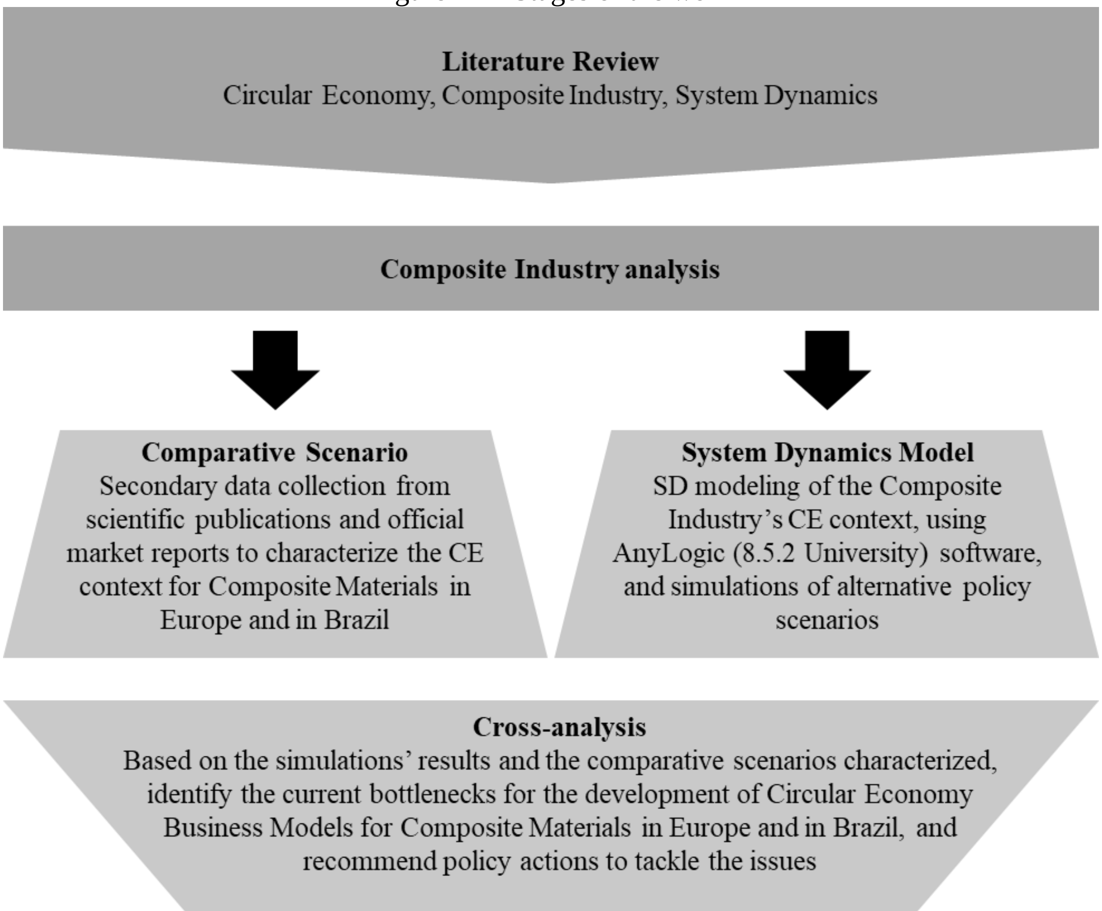
3.1. Research Stages

The initial research plan of the present work was to have two main data collection phases. The first stage would consist of a review of the composite industry's literature, whilst the second stage would be collecting timely industrial and operational data during visits to composite producers and interviews with their employees. However, because of the outbreak of the Sars-Cov-2 pandemic, the second stage was at first suspended, and then effectively abandoned given market conditions. Thus, it was only possible to proceed with the first of the intended research stages.

The objective was to have sufficient data to assess both the European and the Brazilian contexts of CBMs for composite materials, allowing the execution of a mirror study. Therefore, market information gathered, such as demand and production figures, was constrained to these locations. The timeframe for literature sources was restricted to publications from 2001 to 2020, with a preference for data from the last decade whenever available.

After acquiring knowledge about the composite industry, the work then would continue to the model development phase. At this point, the SD model of the industry would be developed and tested, enabling the execution of scenarios' simulations. Then, the results from the industry analysis and those from the model would be combined in a cross-analysis to provide policy recommendations for the promotion of CBMs for Composite Materials in both regions. An overview of the research stages is shown in ***Figure 17***.

Figure 17 – Stages of the work



Source: Author's elaboration

3.2. <u>Data Collection</u>

The objective of the data collection phase was to gather sufficient information to provide a deeper description of the composite industry's current scenario both in Europe and in Brazil, covering its characteristics, practices, and trends, with the spotlight on the present CE contexts. The inquiry's information about manufacturing practices and European market figures bases mainly on the findings displayed by project FiberEUse (2017a; 2017b; 2018a; 2018b) or develops from them, unless differently indicated. Nonetheless, data availability proved to be a critical aspect in the Brazilian context's characterization, since official information was difficult to obtain and if available was frequently limited and outdated. Most of the market data that could be obtained originate from *Associação Latino-Americana de Materiais Compósitos* (ALMACO), the Latin American industrial association of the sector, or the country's

Governmental Bodies. Also, the works from Campos (2014) and Conke (2018) provided relevant information about reverse activities' context in this specific territory.

The SD model required a considerable amount of data about the industry to be simulated, which proved to be a significant constraint. The absence of information from Brazil prevented the use of the model for simulations regarding the country. Although it could be employed in the case of Europe, the parameters embedded in the model represent the case of CFRP used by the aerospace industry, selected for the sake of data availability as well. The information entered in the model's industrial parameters originates from FiberEUse (2017a; 2018a; 2018b), Vlachos, Georgiadis and Iakovou (2007), and Vo Dong et al. (2018), whilst demand information comes from Lefeuvre et al. (2017). A list with the data inputs can be seen in ***APPENDIX A – DATA INPUTS***.

After completed, the SD model developed went through a validation process, in which it was tested for consistency and behavior reproduction, besides being submitted to a sensitivity analysis. The verification process led to minor adjustments in its structure until the reproduction of the current industry's behavior was satisfactory, proceeding only then to the execution of the scenario simulations.

3.3. Data Analysis

Data analysis includes the secondary data gathered to understand the European and Brazilian composite industry scenarios and the quantitative analysis through the SD model. The data analysis explored six main aspects of the composite industry in both locations: Industry Overview; Waste Source Sectors; Processes; Market Opportunities; Barriers; and Regulatory Aspects.

In addition, the SD model was tested under eight different simulation scenarios resulting from the industry analysis's findings, each of them assessing the introduction of different policies for the sector and their effects. The scenarios experimented on were: Promotion of de-manufacturing among producers; EPR and EoL regulation; Customer education activities; Information exchange along the supply chain; Discovery of new applications; De-manufacturing technology improvement; Transportation regulation simplification; and

Adoption of waste management practices. The simulation period was set at 30 years in all the experiments.

For the analysis of the results, more important than the absolute value the decision variable gets is its relative difference over distinct scenarios and the variation of the share of the market detained by FRP at the end of the experiments. In this way, the prioritization of the actions to implement can be developed despite any inaccuracy in the absolute values that might arise because of the assumptions made during the modeling process. The assessment compared the results of each scenario to a baseline, an approach inspired by the work from Cheng et al. (2019). Scenario testing is particularly good for policy-making since it can allow the experimentations of distinct scenarios to base decisions on without incurring the upfront costs of policy implementation (GUZZO, 2020).

The outputs of the model simulations were loaded on Microsoft Excel (2013), in which they went through regression analysis. The results were then presented to composite-industry experts, members of the FiberEUse consortium, who provided a qualitative validation to the findings.

4. RESULTS

This chapter presents the results obtained by the work and is segmented in the approaches followed, namely the comparative analysis of composite industry's CE context in Brazil and Europe, the System Dynamics model simulations, and the Cross-analysis of their results.

4.1. A Comparative Analysis of Composite Industry European and Brazilian Scenario

The analysis hereafter disclosed is segmented in six different sections: Industry Overview; Waste Source Sectors; Processes; Market Opportunities; Barriers; and Regulatory Aspects.

4.1.1. Industry Overview

As previously mentioned, two types of fibers – glass and carbon – mainly dominate the FRP market. GFRP is the most widespread group, accounting for approximately 95% of the market's total volume. European figures for 2019 show glass-fiber-reinforced plastics' production volume should have been around 1,141 million tons, the same level as in the previous year, opposing the recent trend of moderate yearly growth of around 2%. However, this may be only a regional issue, since the causes behind it are mainly production migration, thus in the worldwide aggregate, the trend may have continued. The main consumers of GFRP in Europe are the sectors of Construction and Infrastructure, with a 36% market share, Transportation, representing 34% of the market, Electro and Electronic, detaining 15% of market's figures, and Sports and Leisure, the destination of 14% of the production. Regarding the fabrication methods employed, the most adopted processes are mold compounding, whose application continues to spread, followed by hand and spray lay-up, with a progressively decreasing share; the two groups of processes account for approximately 50% of the market. Additionally, there is a significant utilization of transfer molding techniques around 12%, which show a general fast-paced growth trend, and continuous processes as well, of approximately the same 12% (AVK - FEDERATION OF REINFORCED PLASTICS, 2019).

Regarding CFRP, global demand in 2019 was forecasted at 141.500 tons, a 10,1% expansion in comparison to the previous year, representing between 1-2% of the global market for FRP. Europe accounted for approximately 27% of the market in terms of demand, but regarding production capacity, its stake falls to 16%. In 2014, the carbon-fiber-related activities' turnover was around US$1,98billion, being its main clients the Aerospace and the Automotive industries, which detain, respectively, 38% and 21,8% shares of the total demand. The majority of carbon fibers processed worldwide is embedded in composites, most likely in thermoset matrices, whose turnover accounts for 71,5% of the total polymeric-resin composites' turnover, while thermoplastic resins represent 26,3% of the total; the remaining fraction is attributed to hybrid matrices, elastomer and other polymers (AVK – FEDERATION OF REINFORCED PLASTICS, 2017, 2019; FIBEREUSE, 2017a, 2017b; INDUSTRYARC, 2020).

In the case of Brazil, more detailed market information could only be obtained for thermoset composites. In 2019, the Brazilian industry grew 5,6% in production value and 8,3% in terms of raw-material consumption, breaking the stability pattern observed in previous years. However, there is still space for meeting demand increases, since the industry's operational levels are at 62% of the sector's capacity. In terms of the type of material, glass fibers represent 27,5% of the total amount of raw material used in the industry in the same year, with almost 60.000 tons consumed, whilst carbon fibers account for 1,2% of the total. In terms of final product utilization, the demand for epoxy and polyester thermoset FRP in 2019 exceeded 134.000 tons. Regarding production processes for polyester composites, hand and spray lay-up are the most diffused procedures, being used in more than 50% of applications. In the case of epoxy matrices, infusion procedures are employed in almost 90% of the industry's output (ALMACO, 2020).

The main consumers of thermoset composites (only regarding epoxy-matrix and polyester-matrix FRP) in the Brazilian territory are the Construction sector, with a 27,04% share of the market, followed by Transportation, Sanitation, and Energy (especially wind energy) sectors, whose market shares are respectively 22,81%, 18,59% and 17,18% (ALMACO, 2020). Although a rise in utilization can be perceived over recent years, the Brazilian reinforced plastics market is still minor in the international scenario.

Composites are adopted in many different components particularly because they combine low weight and great mechanical properties, which positions these materials as great substitutes for metals in applications requiring mechanical resistance, a replacement that is even intensified by their resistance to corrosion. Furthermore, FRP is a durable material, with lifetimes varying between 10 years, in the case of recreational boats and car components, to more than 20 years, if considering sailboats and wind turbines, before achieving the EoL condition (FIBEREUSE, 2017b).

The value range of composite materials is particularly wide, and is strongly correlated with the type of fiber embedded and, within the same fiber type, with the properties the compound exhibits. The higher utilization of GFRP in comparison to CFRP even though the latter possess superior properties can be understood if the price differences of these fibers are observed. Virgin glass fibers can be acquired in the market from around 2€/kg, whilst carbon fibers start at prices much higher, of 10€/kg. Concerning recovered fibers, the figures for those made of glass and carbon are, respectively, 1,35€/kg and 6€/kg (FIBEREUSE, 2017b).

The players operating in the sector can be classified as members of one of the following groups of activities: Manufacturing; De-Manufacturing; Logistics; and Consumption. It is important to say that the same actor can be responsible for more than one activity, but the separation evidences the roles that are present in the industry. Some examples of companies operating in each of the activities may be useful for the understanding; worth of note that not necessarily all the mentioned enterprises currently handle composites. In the case of Manufacturing, there is Siemens Gamesa, a producer of parts for wind turbines; Batz, a manufacturer of automotive parts; and Rivierasca, a company that operates in the building industry, all making use of FRP. Referring to Logistics, Saubermacher is a service provider that offers waste removal and logistics services. Additionally, the company also operates as a recycler, thus representing players involved in De-manufacturing activities. Companies and consumers making use of composite applications in their daily routines constitute the actors inside the Consumption cluster (FIBEREUSE, 2018a).

4.1.2. Waste Source Sectors

Predictably, the sectors listed as the main clients of the Composite Industry's forward activities are also the primary sources of waste flows for its reverse processes. The Transportation sector, embracing automotive, aviation, and marine industries, is one of the main producers of composite waste material that can be used as input for de-manufacturing activities; still, its majority ends in landfills. In 2014, around 8kg of car's weight was composed of fibers, content expected to double by 2020, and the 2016 European production of cars reached 16 million units (FIBEREUSE, 2017b). Brazilian figures indicate there were more than 58 million cars in circulation in the country in 2021, almost 1,5 million more in comparison to the previous year (GOVERNO FEDERAL; MINISTÉRIO DA INFRAESTRUTURA, 2021). These numbers show a market potential of around 140.000 tons/year of composites disregarding the growth, or 280.000 tons/year if the predictions of expansion have been confirmed; the composition is mainly 92% glass fibers, 7% natural fibers, and 1% carbon fibers. Concerning aviation, 6.000 commercial planes, whose composite percentage reaches from 30% up to 50% (80% carbon fiber and 20% glass fiber), are expected to reach EoL by 2025, adding 100.000 tons of composite waste to the figures, apart from the predictions of fleet expansion and replacement that can even boost these flows (FIBEREUSE, 2017b).

Another significant source of composite waste lies in the Construction and Infrastructure sector, whose refuse comprise roofing panels and wind blades made from fiber-reinforced plastics. By 2034, 225.000 tons of rotor blade material are predicted to be available for recycling worldwide; however, current pathways for these components mainly comprise landfilling and incineration with energy recovery. In 2020, the volume expectation was around 50.000 tons of these materials, with shares of 70% for glass fibers and 30% for carbon fibers (FIBEREUSE, 2017b).

Moreover, there are additional inflow possibilities for de-manufacturing processes coming not from EoL materials, but industrial waste and production scrap. In an internal survey among the partners of the consortium, FiberEUse (2017b) estimated an average of 15,8% of the GFRP material used ended up in production waste flows. Industrial scrap flows, in theory, have lower levels of contamination and embed higher knowledge about their composition and properties in comparison to EoL waste flows. Consequently, the reverse processes downstream experience less stress having production scrap as input material since they must cope with lower inflow variability.

4.1.3. Processes

The establishment of a supply chain for composite materials under Circular Economy's perspectives grants the stages and processes supporting it with some particularities, discussed hereupon. The initial procedure in the reverse value chain refers to the collection of waste material, which gives rise to the inflows for de-manufacturing activities.

Currently, these flows arise in different locations spread over the territory, which require great capillarity of the collection network and are aggregated for many reasons, such as space savings or cost-efficiency, before they enter regeneration stages, bestowing variability in their content. For instance, Conke (2018) discloses data from Brazil showing that in 2010 around 80% of the total waste collected was in the form of commingled waste. The considerable mixing level in these flows, characterized by containing different materials with different characteristics, generates additional problems, as the adequate methods to apply for their processing may vary from one another.

Hence, the present organization of the collection activity increases the need for sorting in the system and can make it more intricate, though sorting is always necessary for any level of variability to tackle potential contamination. Both processes, collection, and sorting, are of paramount importance in the costs of the de-manufacturing supply chains, representing nearly two-thirds of the total cost of the recyclate. Thus, they have a significant influence on the price of the final regenerated product (FIBEREUSE, 2017b).

Once the composite waste is collected, it enters the recovery chain and can be destined to one of the available pathways for these materials. Current legislation allows alternatives from Reuse to Disposal, this latter including landfilling, and apart from the reuse option, the pressing issues associated with these pathways are presented next.

To start, although a current preferential destination for composite materials given its low cost, landfilling of FRP has started to be prohibited in some countries, a decision that is presumed to be followed by other nations soon. Even with the landfilling ban, disposal is supposed to continue to be relevant in the form of incineration, being it with or without energy recovery, since this option will remain, under current circumstances, cheaper than any other pathway for managing composite waste (FIBEREUSE, 2017b).

Regarding FRP recycling, the previous chapters presented the main strategies for treating these materials, namely mechanical, thermal or chemical recycling, which will be discussed in more detail.

In mechanical recycling, the flow is submitted to size-reduction procedures, including crushing, milling, shredding to obtain fine grains or a powder that can be reused in other applications. Yet, before that, it can go through additional sorting procedures for the separation and extraction of specific constituents (FIBEREUSE, 2017b). Such particles can find different destinations; for example, one possibility is their introduction in cement kilns, especially if dealing with glass fibers, which is the recommendation of the European Composite Industry Association and ALMACO's sustainability project for these materials.

In this way, the mineral components of the fibers are absorbed into the cement clinker, and the energy recovery procedure helps in reducing the CO2 emissions of the clinker's fabrication. However, the economic benefit of this utilization is low or none, and all the value embedded in composites' resins and fibers is primarily lost. Furthermore, the fiber-rich content of the remaining powder makes it a potential reinforcing agent to insert in other composites, which usually is done by adding it as filler in compounds used during fabrication by injection or compression molding. Despite harmful to fibers, since chopping tends to reduce their mechanical properties, mechanical recycling techniques are among the cheapest solutions available, hence particularly viable and preferred for the low-value EoL GFRP (FIBEREUSE, 2017b).

Thermal recycling is mainly performed through pyrolysis processes, which decomposes materials with the aid of heat, normally functioning in temperatures between 400°C and 700°C and happening in or without the presence of oxygen or steam. This treatment permits the recovery of fibers; however, the resin content is mainly lost because of its volatilization into gases or its degeneration into char. The recovered fibers maintain a significant fraction of their mechanical properties and can be used again in production processes. Nonetheless, if they are employed once more in FRP, the potential char deposits on the fibers' surface become an issue as they may compromise the attachment to a new matrix (FIBEREUSE, 2017b).

About chemical recycling, solvolysis is the most used technique for treating composite material. In this treatment, a solvent is applied to the flow for the degradation and removal of the resin part, favoring the recovery of fibers with low contamination at the expense of high volumes of waste liquid generated (FIBEREUSE, 2017b). Still, both reactors and reagents can render this process noticeably costly, limiting its application to a vast set of low-priced FRP.

Both thermal and chemical recycling entangle higher treatment costs that make them economically unviable for GFRP treatment, so their application is concentrated on CFRP waste flows. Apart from prices, they are usually the route for carbon fiber composites because of the better preservation state of fibers' properties achieved, which provides higher commercial value to the output of the recycling process (FIBEREUSE, 2017b).

Concerning repair and remanufacturing, there is still the need for further technology improvement and validation if they are to compete against other pathways. Both activities could leverage advancements in inspection operations since they consist of manual procedures in general, or available automated technology is limited by application specificity. The development of inspection and maybe its automation could produce a rise in efficiency that would benefit the efficiency of processes downstream on the supply chain as well. Additionally, new applications of existing technologies to perform repair and remanufacturing activities on the production of composites must be investigated, aiming at improving the economic viability of these routes (FIBEREUSE, 2017a).

The main estimated savings related to the adoption of de-manufacturing activities in comparison to the fabrication of new composites from virgin materials lie in resource savings in terms of energy and raw material. There would be a higher availability of materials in the market because of the new flows generated by Circular Economy business models, and the producers embracing them would reduce their need for raw materials, replaced by those arising from de-manufacturing, avoiding the purchase and thus the related capital requirements. In addition, without the need for the same quantity of virgin materials, there is a predicted reduction of up to 70% in the energy consumption associated with their extraction. Whereas, during manufacturing and logistics operations, this replacement makes the use of energy fall to only 10% of the newly manufactured products' levels and the forecasted reduction in the product lifecycle's CO_2 footprint is at 40% (FIBEREUSE, 2017a).

4.1.4. Market Opportunities

The option for CE business models can bring new market opportunities to the adopting companies. To tackle the issue formerly discussed regarding fibers' loss of properties, especially mechanical resistance, stakeholders can implement a cross-sectorial cascaded use of recycled fibers. It consists of FRP waste from industries characterized by high standards for composites' mechanical properties to be used, after de-manufacturing processes, by different sectors in applications that require a lower level of mechanical resistance. In this way, materials once considered scrap and waste for the manufacturers can turn into additional revenue sources provided the proper treatment. Such symbiosis contributes to the valorization of composite waste material, proving FRP leftovers' positioning in stakeholders' mindsets must shift from an incurred cost to a company asset (FIBEREUSE, 2018a).

Although the usual focus of the discussion around de-manufacturing activities rests on their costs, they are economically viable and profitable in many cases and can originate new business units if established by companies. Still, the main reluctance lies in the low margins in which the systems would operate, which reduces the related investment's attractiveness, thus, their arousal. Notwithstanding, if these businesses are created, firms can use them for their benefit and yet become a service provider for the market. In this way, they would be able to increase processing flows and compensate for the low margin by handling higher volumes.

There are also overarching aspects that can increase the entire de-manufacturing supply chain's economic competitiveness if pursued. One of them is the adoption of design for de-/remanufacturing approaches, which would consider products' returning loop from the moment of their design. Hence, the choice of the good's materials and structures would contemplate the EoL phase, increasing the efficiency of their de-manufacturing process. Another helpful aspect is the presence of an information management structure along the supply chain that would distribute knowledge and information regarding the flows among stakeholders, thus generate gains in efficiency alike. Efficiency in de-manufacturing supply chains can reduce their associated costs, so that they can compete alongside disposal pathways in economic terms for manufacturers' preference, apart from their additional benefits in other areas. These are further business opportunities of which players already operating within the composite industry or not can take advantage to reap profit (FIBEREUSE, 2018a).

4.1.5. Barriers

The former sections already glimpsed some of the existing barriers regarding the introduction of Circular Economy business models for composites. First, and one of the major issues, is the comparison of the cost savings brought by these procedures and the additional costs entangled by their setup. Commonly, the savings are not sufficient to compensate the expenditures in an acceptable time interval for stakeholders in their current mindsets, leading to underinvestment.

The enhancement of the economic viability of FRP's de-manufacturing processes might require the introduction of new methods and technologies in such activities, an aspect formerly explored. However, this action may find resistance among stakeholders, for example, operators and managers accustomed to the usual practices and procedures (FIBEREUSE, 2018a). They would have to change their behaviors adapting to the new circumstances, not to mention eventual training efforts that would represent additional costs to enterprises. If high enough, this reluctance can eventually bar the company's adoption of circular practices, especially if shared by decision-makers.

Additionally, technological development requires investments, a sensitive matter already discussed. Also, the related boundaries and limitations are still unclear, a factor that limits leadership and the definition of integrated strategies for innovation, and raises the risk the investor must bear thus inhibits its willingness to finance such projects. Financing is indeed an obstacle since sources of funds usually base their lending decisions on risks and returns, characteristics that are not the allure of FRP's Circular Economy business models, and there is no alignment across the industry regarding the search for funds and pricing methodologies. The latter aspect forces players to compete against each other for the scarce resources under an undefined basis, which is detrimental for the whole sector's advancement (FIBEREUSE, 2017a).

Another issue that might arise halting the development of CE solutions in the industry regards the compatibility of proprietary systems among different players along the supply chain (FIBEREUSE, 2018a). It was previously stated that integration and information exchange in the supply chain could boost circular practices on the market. Yet, if different stakeholders adopt solutions that do not communicate, all the potential benefits are lost, so de-manufacturing systems' development may struggle to thrive or even stall .

In addition, there may be limits in respect to the market penetration and applications that could hamper the implementation of circular chains for composites. Concerning the co-processing of GFRP waste on cement kilns, there is a limit of around 10% of the fuel input not to compromise cement's properties, particularly because of E-glass fibers boron content. Moreover, the amount of powder to add in compounds as reinforcement or filler is curbed according to the requirements for FRP's final properties and not to disturb fiber-matrix adhesion (FIBEREUSE, 2017a). Consequently, recycled composites may not be suitable substitutes to virgin fiber-reinforced plastics in all their applications under the allegation of unsafety, especially in those with the most demanding mechanical properties' standards. The argument of unsafety referring to rFRP correlates with a current belief in society, which belittles recycled materials, conceiving them as a class of products of inferior quality. Although alarming for Circular Economy business models' evolution, since recycled products may face resistance in their uptake, there are also present trends of environmental responsibility opposing this belief, which boost the development of circular solutions.

Beyond, governance aspects may represent further barriers to the implementation of Circular Economy systems for handling composite materials. The success of de-manufacturing supply chains processing FRP waste may require the association of several players from different sectors. Nevertheless, the dispersion of stakeholders across many industries might bring coordination challenges and result in misalignments when claiming for policies that would aid the creation and prosperity of these chains; hence, establishing communication mechanisms is foremost. Stakeholders' appeals regarding composites must loom amid a lack of priority in legislators' agendas even though plastics are in the spotlight of discussions, which discourages agents from engaging in composite de-manufacturing activities (FIBEREUSE, 2017a).

4.1.6. Regulatory Aspects

Though previous sections and chapters briefly discussed regulation, a formal introduction is still lacking. In Europe, composite collection and de-manufacturing activities have no specific regulation. Yet, there is general legislation on waste handling that must be followed by stakeholders operating in the industry within the block's territory.

The principal standard currently in place in the block is the European Directive on Waste (2008/98/EC) that provides fundamental concepts and definitions regarding the management of waste flows. It defines waste, discerning it from by-products, and processes related to its processing, as recycling and recovery. However, it poorly embraces remanufacturing activities and does not go in-depth on technical aspects providing standards and metrics.

Additional frameworks that affect Circular Economy business models are the Directive on End-of-Life Vehicles (2005/53/EC) and the Extended Producer Responsibility (EPR) Legislation (2002/96/EC). While the first imposes recycling requirements in weight fractions for vehicles reaching their EoL state, the second obliges producers to offer customers return possibilities for the products upon the end of use so they enter pathways compliant to the legislation for that type of good. Both regulations include important stakeholders in the products' EoL handling and decision-making; they also define targets and timelines based on items' type, not on composition, but still lack specifications on the extent of stakeholders' obligations.

Landfill Directive (1999/31/EC) regulates the different types of landfills available, determines the waste flows that can be landfilled in their EoL, and establishes a tax for this action. It defines landfilling as the least desirable option for goods, but in the case of non-hazardous composites, it still allows it to occur. Notably, a few countries have already forbidden this practice for EoL FRP, for instance, Germany, and others are expected to adhere to that decision; there are further legislation packages under discussion that will impose extra restrictions on landfilling in general.

Withal, supervising the movement of waste flows within the European Union (EU) there is the Waste Shipment Regulation (2006/1013/EC) and its amendment (2014/660/EU), which enforce a need for notification of competent authorities and their approval before the movements of waste imported by, exported by or in transit through EU member states. Regarding transboundary shipments, legislation is even stricter and establishes that all the countries crossed by the route must be notified about the movement. These terms contribute to an increase in the complexity of collection activities, hence to the overall complexity in respect to the organization of Circular Economy business models. This aspect is particularly relevant to the case of composites, in which waste movements are necessary to achieve higher volumes needed to compensate for the low margins.

The abovementioned directives are eventually complemented by country- and region-specific rules, the levels enforcing the measures. Nonetheless, these complementary rulings deviate between countries and regions according to the specific circumstances within their territories. Consequently, there is a misalignment between regional regulations concerning FRP, yielding intricateness and inconsistency, which imply stakeholders in different locations must comply with divergent standards. Once more, the complexity related to the establishment of composite de-manufacturing supply chains increases since these would likely contain players spread over different regions, thus subject to disparate rules, to which the system would have to comply.

There are aspects still lacking regulation that if organized within a framework could aid the development of FRP Circular Economy business models. For example, a directive on waste management would be helpful to composite materials, as it would define the practices to be adopted to handle waste at the time of its generation, possibly after the creation of standards for residues and offering waste generators information on such materials' pathways. It could lead to higher availability of flows to de-manufacturing systems and better sorting, increasing their efficiency, and better education of people on opportunities arising from waste, maybe changing their perceptions about EoL materials and about the products they originate.

Regarding the regulation in Brazil, disposal practices are governed by Law n° 12.305/10, *Política Nacional de Resíduos Sólidos* (PNRS), the national policy for solid waste, created in 2010. The framework presents a series of important definitions for the terms used in this context, such as the differentiation between waste and residues, and some of the available procedures, and establishes a national ban on dumping grounds, the destination of almost 20% of the country's solid waste in 2012; recycling rates in the country were at 13% in 2008 (CAMPOS, 2014). Unfortunately, more advanced industrial options within Circular Economy, for instance, repair and remanufacturing, are missing. The regulation is somewhat in the vanguard of worldwide rules, as already in 2010 it recognized reusable and recyclable solid waste as an economic good with social value, capable of generating work, wealth and promoting citizenship (BRASIL, 2010). This recognition is particularly important in the Brazilian case since, as Campos (2014) presents, selective collection in the country is based on the utilization of the labor force of waste pickers working informally, both by local governments and by recycling industries. In 2012, almost 600.000 people subsisted from the waste collection in Brazil, most of them deprived of formal instruction, labor rights, and basic sanitary working conditions, and whose monthly earnings frequently stay below the national minimum wage (CAMPOS, 2014).

The PNRS also recognizes the shared responsibility of manufacturers, consumers, and de-manufacturers for goods' EoL, considering integrated management solutions such as industrial symbiosis and shared information systems. It establishes responsibility primarily on waste generators for waste management and contingency plans, and most importantly, it defines that outsourcing the service does not exonerate the generator from any harm caused by its residues (BRASIL, 2010).

However, probably because of the moment in which written, the rule stresses items' recycling in the EoL stage rather than other preferable alternatives in terms of value recovery now available. The law also defines several documents and plans for waste management that must be created by players all over the economy, both public and private, and splits surveillance responsibility for the federation entities, which may be prevented from receiving Federal funds if they fail to meet their obligations. The regulation also proposes a classification for solid waste based on its origin and danger, and the establishment of performance goals for recovery processes (BRASIL, 2010).

Overall, it is possible to characterize the PNRS by its focus on prevention, the inclusion of social aspects in waste management, a relevant country particularity, and its ambition. Notwithstanding, composite materials are not explicitly mentioned within the rule, so they must comply with the general principles it defined but have no particular rules, which brings challenges close to those faced by the European industry players. Most of the spheres missing regulation in the EU presented earlier also are lacking in the Brazilian rules, making the opportunities and the barriers for the development of CE business models for fiber-reinforced plastics similar in the two regions.

4.2. System Dynamics Model

This section presents the quantitative model produced as the tool to investigate some of the many regulatory scenarios conceivable, tackling the multitude of issues portrayed in this document heretofore. The model grounds on System Dynamics theory, and seeks to assess policy effects and to help in the prioritization of the necessary aspects to focus the ruling efforts, which represent bottlenecks to the development of Circular Economy business models for composites. It acts in this purpose by deepening the high-level contexts in which policies are inserted, translating their implications to technical systems that are still represented in an aggregated way. The presentation of the model is divided into three sections, namely Model Structure, Simulation Scenarios, and Simulation Results.

The intended objective is not to produce forecasts of the composite industry's future, but to obtain a basis for the comparison of the sector's alternative prospects. Using the model's results in comparison one to another attenuates eventual modeling deviations from reality since any bias present in the model is canceled by the adoption of a comparative approach given that all experiments are reproduced employing the same tool. Therefore, by opting for the comparative evaluation, the dissimilarities between the outcomes of the runs compared to those of a reference case are consequences of the variations in input parameters between the two simulations.

4.2.1. Model Structure

The initial step in modeling under the System Dynamics approach is to identify the problem present in the system. The current target issue is the fact that significant amounts of composite material are disposed of after the use phase despite the possibility to reenter the market if processed by de-manufacturing supply chains within Circular Economy business models. The problematics around this practice rests on the loss of all the value embedded in these materials once disposal pathways are adopted, on the generation of waste, and on the need to commit additional resources otherwise spared, such as raw fibers, resins, and energy, on the fabrication of new composites.

The study of the system began following the definition of the problem, aiming to increase the comprehension of the system's dynamics and behaviors, which included activities as listing the variables related to the observed phenomena, in the pursuit of gathering the elements necessary to the object's understanding. Simultaneously, the decision regarding a reasonable period for the simulation, which had to be sufficient to capture the FRP lifecycle, started. Since the usual composite's use life does not exceed 25 years, the time horizon selected for a model run was 30 years.

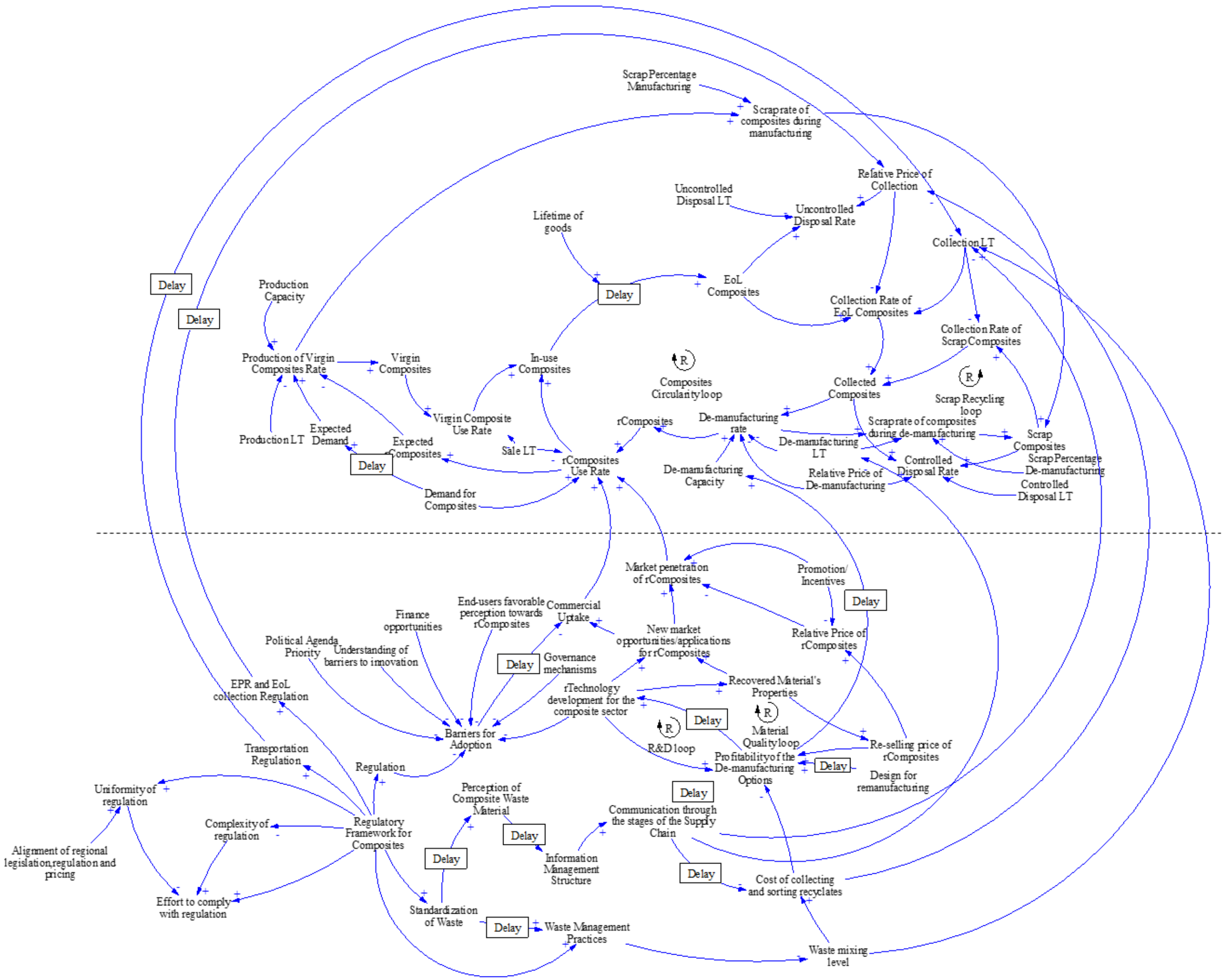
The increase in knowledge about the system's modes of operation and characteristics enabled the beginning of the representation of the verified actual causal relations and feedback loops. In parallel, as the causal structure became clearer it allowed the formulation of initial explanations for the undesired behavior, based on the information about the industry. Initial causes were: i) composite materials do not enter de-manufacturing chains because producers and the agents who get these products before their disposal are unaware of this opportunity for this kind of waste; ii) fiber-reinforced plastics follow other pathways because Circular Economy business models for their processing are economically unviable or unattractive given the related costs; iii) the recycled product may not be fit for the applications it had before reaching the EoL phase; iv) customers are unwilling to consume recycled composites; v) current legislation complicates the handling of waste materials thus delays the processes required for de-manufacturing to occur; vi) the lacks of regulation and incentives in some areas critical to the prosperity of Circular Economy business models prevent their arousal.

The establishment of causal relations continued and, as the process produced results, it required the periodical update of the system's conceived structure. The diagrammatic representation of such structure started to yield the Causal Loop diagram of the system, an activity that spanned until the feedback structure therein contained was adequate to the comprehension of the dynamics. The complete Causal Loop diagram achieved in the scope of this work was represented using Vensim® PLE (8.0.9) software.

4.2.1.1. Causal Loop Diagram

In ***Figure 18*** it is possible to see the Causal Loop Diagram produced. One of the first elements grabbing the viewer's attention is the traced line that divides the diagram into two parts. Although not fundamental for the understanding, it helps in distinguishing between the two main contexts represented in the figure, the technical system and the regulatory environment, contained in the top and bottom parts, respectively. Both parts will go under additional detailing, starting with the technical system's components and then moving on to the regulatory environment's elements.

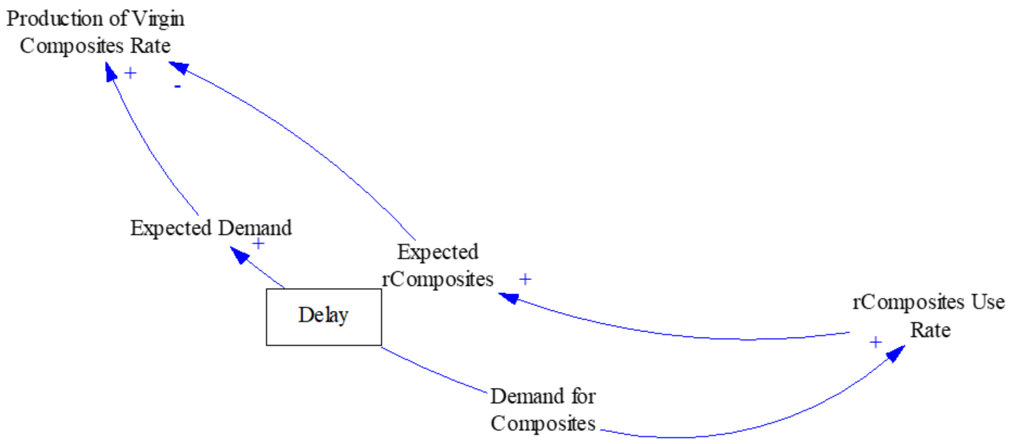
Figure 18 – Causal Loop diagram



Source: Author's elaboration

The technical system part of the model can be divided into two smaller subsystems that interact with each other. The first is the demand subsystem, shown in ***Figure 19***, which aims to represent the effect demand has on the other variables present and how it shapes the dynamics observed.

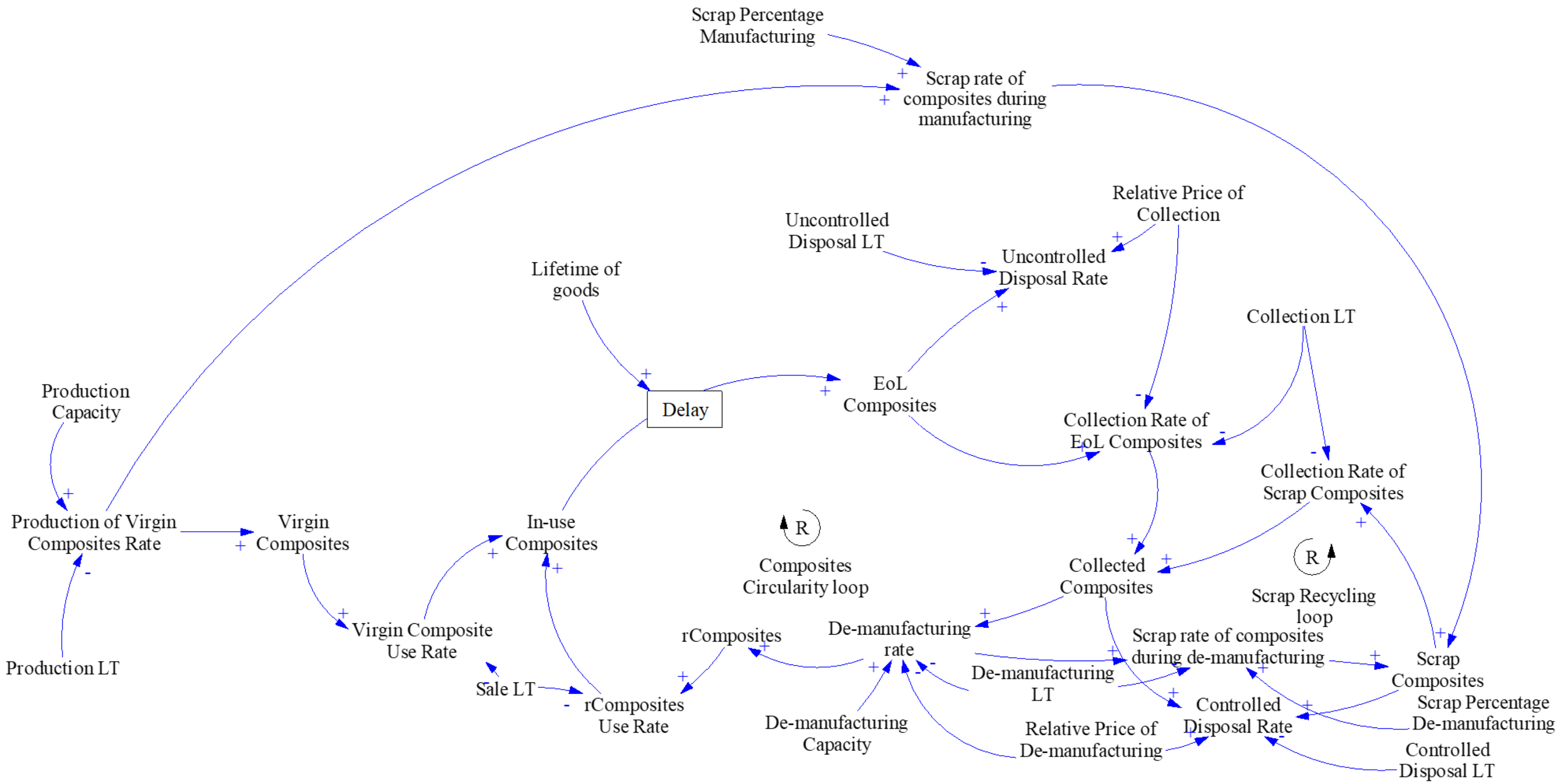
Figure 19 – Demand Subsystem



Source: Author's elaboration

The second subsystem, depicted in ***Figure 20***, displays the composite's entire production chain. Inside that, there are the parameters and elements that integrate both linear and circular perspectives and the identified causal relations between them, in an attempt to elucidate the system's ways of working and thus enable the understanding of the behaviors it demonstrates.

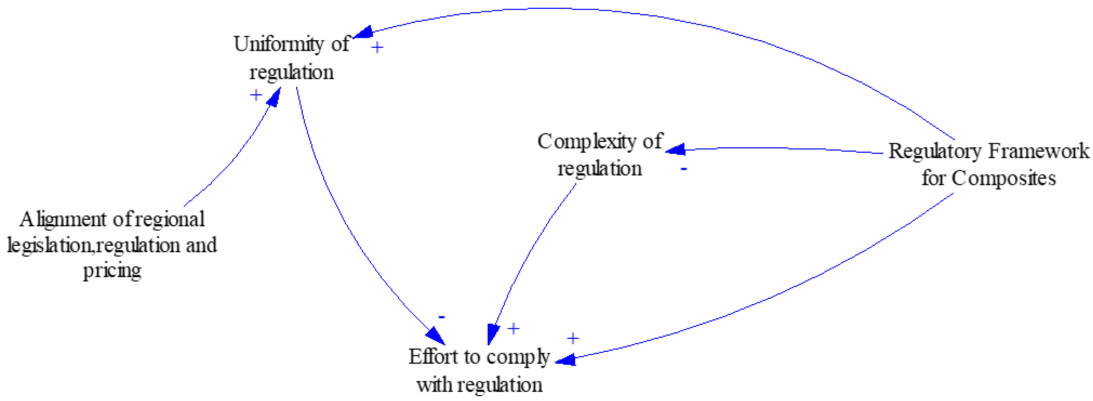
Figure 20 – Production Subsystem



Source: Author's elaboration

The second part of the Causal Loop diagram, which refers to the regulatory environment, also contains subsystems inside its structure, particularly: policy compliance, barriers for adoption, and regulatory frameworks and their effects subsystems. The policy compliance subsystem, shown in ***Figure 21***, describes the implications of rules for the stakeholders that must adhere to them.

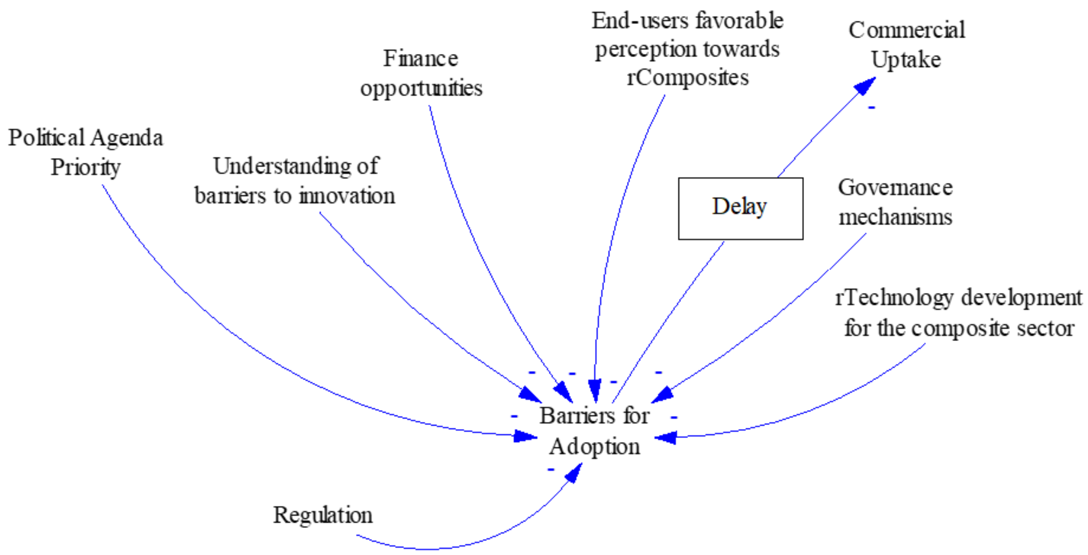
Figure 21 – Policy Compliance Subsystem



Source: Author's elaboration

The barriers for adoption subsystem, displayed in ***Figure 22***, it pictures the interplay of the barriers and obstacles for the diffusion of Circular Economy business models for composite materials discussed over the last chapters.

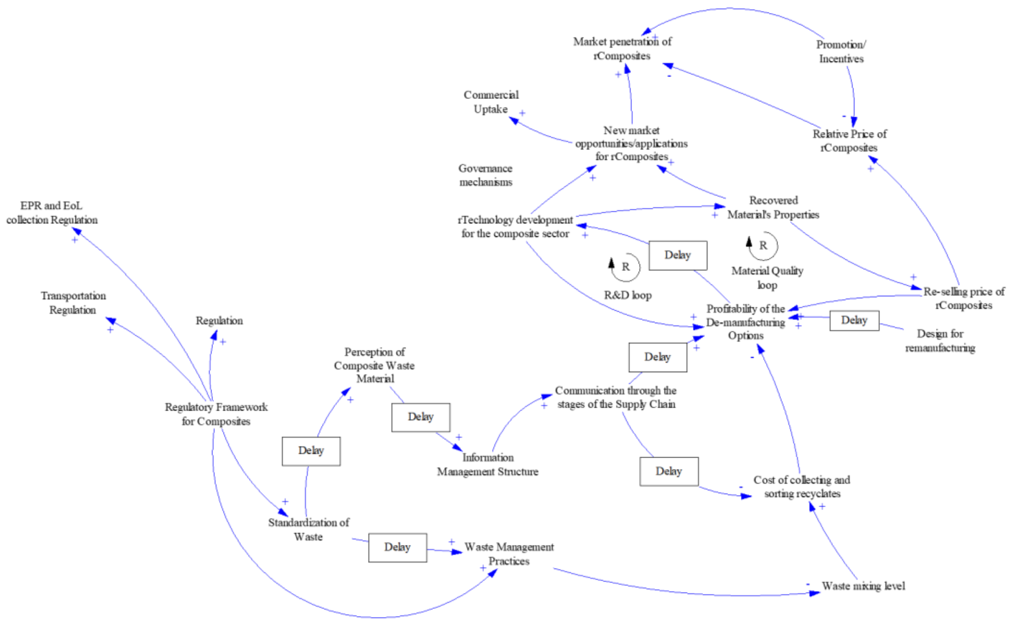
Figure 22 – Barriers for Adoption Subsystem



Source: Author's elaboration

The remaining subsystem, pictured in ***Figure 23***, explores the different implications and effects of the introduction of a regulatory framework for composites, which would tackle many elements present in the context of these materials. At the outset, a regulatory framework addressing FRP's de-manufacturing supply chain contributes to the organization of the activities involved in the network, with impacts in different areas. These schemes would influence the regulation of the subject, thus affect the barriers for their adoption, as well as set directions for these materials' transportation, EoL collection and manufacturers' duties, waste management, and standardization. Accordingly, the Causal Loop diagram shows links between Regulatory Framework for Composites and Regulation, EPR and EoL collection Regulation, Transportation Regulation, Standardization of Waste, and Waste Management Practices.

Figure 23 – Regulatory Frameworks and their Effects Subsystem



Source: Author's elaboration

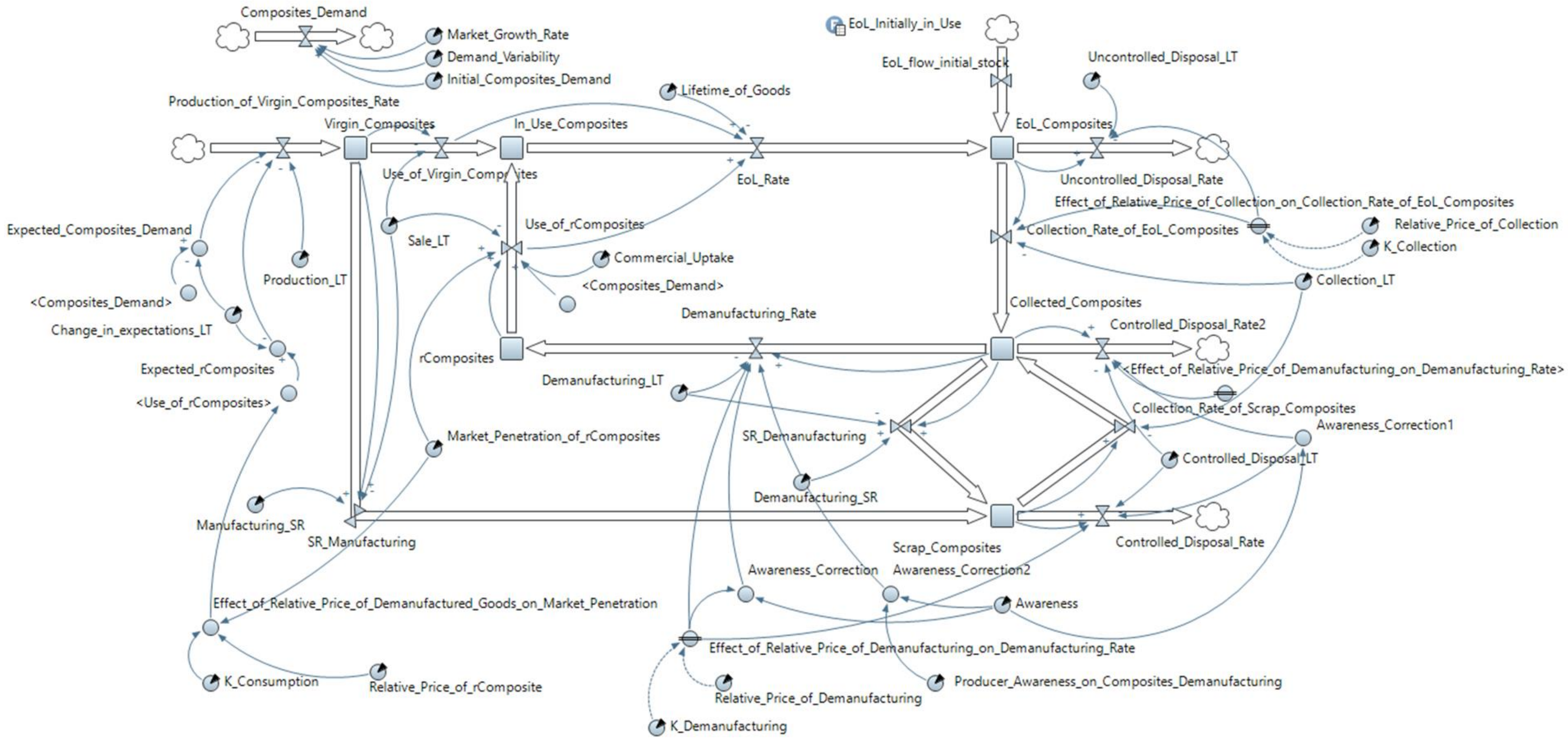
Rigorous observation of ***Figure 18*** reveals some causal links constitute joints between the technical system and the regulatory environment parts of the diagram. These links represent the influences of the regulatory environment on the technical system's parameters, thus on its operation and behavior.

4.2.1.2. Stock and Flow map

After completing the Causal Loop diagram representing the system, the detailing of the elements within the latter started. This process included the differentiation between stocks, flows, and the other components present in SD models, which would result in the Stock and Flow map of the referred system. This map constitutes the structure of the quantitative model proposed and used to investigate different regulatory contexts. Therefore, it was already developed under the simulation environment offered by AnyLogic (8.5.2 University) software. During the modeling activity, translating the regulatory environment portion of the system in quantitative terms proved to be challenging, mainly because of the high abstraction and subjectivity of many of its components. The solution for the dare was to introduce, in the technical system, parameters that would directly represent the effects distinct policies would have in the operation and whose modifications would emulate scenario changes; this approach was inspired in the work of Trailer and Garsson (2005). These compose the joints between the two parts of the system's Causal Loop diagram.

Additionally, the model's structure was conceived assuming the existence of decision points in the system that determine the direction waste flows should follow, either to disposal or de-manufacturing pathways. In the present case, such decisions are made at first when goods reach their end-of-life phase, and for the second time after they have been collected; the decisions are taken based on the costs of the activities, like in the study by Georgiadis and Vlachos (2004). Moreover, both production and de-manufacturing capacity are unconstrained since the representation comprises the overall sector and not just single firms, granting greater flexibility in capacity. Also supporting this decision, the studies by Tailor (1999) and Georgiadis and Vlachos (2004) already evidenced the need to ensure de-manufacturing capacity is sufficient to cope with an increase in the input before sending additional waste flows to the reverse loop, otherwise, the impacts are detrimental to the value chain. These previous premises can be considered the general assumptions regarding the design of the model, equivalent to the system's Stock and Flow map in terms of structure, which is depicted by ***Figure 24*** and also detailed in ***APPENDIX B – MODEL DETAILS*** that presents the model attributes in detail.

Figure 24 – Model of Composite Materials' Value Chain under Circular Economy



Source: Author's elaboration

Notwithstanding, a Stock and Flow Network contains additional elements apart from the stocks and flows, including constants, exogenous variables, and additional variables, which help to comprehend the systems' behavior. Indeed, the structure in ***Figure 24*** includes elements of these types, fundamentally used in the description of the interactions between stocks and flows. However, modeling such interplays quantitatively by using equations entangles the establishment of assumptions regarding these ancillary elements, which may even impose the need to add further elements to the model. For example, the previous assumption of decision points governing the path waste flows shall follow call for variables to base the choices on. The additional assumptions defined during the characterization of the variables and relationships present in the system are presented in ***Table 2***.

Table 2 – Model's Detailed Assumptions

Domain of the assumption	Assumption
Demand	The rate of virgin composites' production depends on the rate of production of de-manufacturing processes (WANG et al., 2014; VLACHOS; GEORGIADIS; IAKOVOU, 2007)
	Demand was modeled subject to an overall growth trend throughout the assessment with induced local disturbances
Production	The flow of de-manufacturing products to the market depends only on their availability but is bounded by demand
	Production related outflows from stocks depend only on stock level and the activity's lead time (GEORGIADIS; VLACHOS, 2004)
	Stakeholders' decisions regarding the path of waste flows is represented by an effect of the relative price of the activity on its corresponding flow (GEORGIADIS; VLACHOS, 2004)

Source: Author's elaboration

4.2.1.3. Mathematical formulation

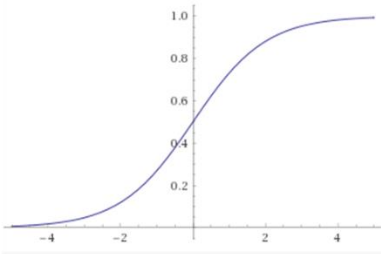
Following the introduction of all the elements in the software environment, the mathematical formulation of their relationships and dynamics could be loaded in the application. The complete list of equations within the model can be found in ***APPENDIX C – MODEL EQUATIONS***; nonetheless, this section will explain the overriding formulations.

4.2.1.3.1. Sigmoid functions

As already presented, the model operates based on a decision-making process happening in two different points. To represent this procedure mathematically, it employs sigmoid functions, which produce sigmoid curves, also referred to as S-shaped curves. In ***Figure 25***, it is possible to see an example of a sigmoid curve together with its equation.

Figure 25 – Sigmoid Function and Curve Example

$$f(x) = \frac{1}{1 + e^{-x}}$$



Source: Author's elaboration

Georgiadis and Vlachos (2004) used sigmoid functions in their work for the decision rules within the reverse logistics function, which returned the percentage of the flow submitted to the activity modeled by the equation based on a given parameter represented in the horizontal axis, in their case normalized cost differences of the alternative flows. In line with this approach, the present work employed sigmoid functions for decision-making on three occasions, two of them regarding the reverse logistics function and the third involving market penetration.

The first use of sigmoid functions governs the collection of EoL composites and aims to represent the final user's decision whether to send FRP to the most preferable collection routes according to the hierarchy of EoL alternatives within Circular Economy or just discard them anyhow. The model assumes consumers base their choice on economic factors such as the price to pay for the service and eventual fines, amongst others, which can be translated into monetary terms. The expression in ***(9)*** describes the sigmoid equation representing the decision rule governing the collection of EoL composite materials.

$$Effect\_of\_Relative\_Price\_of\_Collection\_on\_Collection\_Rate\_of\_EoL\_Composites = \frac{1}{1 + e^{-K\_Collection * Relative\_Price\_of\_Collection - 1}} \quad \textbf{(9)}$$

where

K_Collection is a parameter that alters the slope of the sigmoid curve, thus can be used to introduce stakeholders' price sensitivity regarding the collection activity;

Relative_Price_of_Collection represents the variable used for the cost comparison between the two alternatives for the flow, calculated as in ***(10)***.

$$Relative\_Price\_of\_Collection = \frac{Cost\_of\_Collection}{Cost\_of\_Disposal} \quad \textbf{(10)}$$

The second occasion that employs a sigmoid function concerns deciding whether to send collected FRP materials to de-manufacturing processes or dispose of them using one of the allowed disposal pathways these components can follow. Alike in the previous case, the decision grounds on economic factors and was formulated as in ***(11)***.

$$Effect\_of\_Relative\_Price\_of\_Demanufacturing\_on\_Demanufacturing\_Rate = \frac{1}{(1 + e^{-K\_Demanufacturing \; * Relative\_Price\_of\_Demanufacturing \; - 1})} \quad \textbf{(11)}$$

In which

K_Demanufacturing is a parameter like *K_Collection*, but used to introduce stakeholders' price sensitivity regarding the de-manufacturing activity;

Relative_Price_of_Demanufacturing represents the variable used for the measurement of the additional costs' difference between the two alternatives for the flow in relation to the production cost of the materials, calculated as in ***(12)***.

$$Relative\_Price\_of\_Demanufacturing = \frac{Cost\_of\_Disposal - Cost\_of\_Demanufacturing}{Cost\_of\_Production} \quad \textbf{(12)}$$

The third adoption of a sigmoid function was to give composites exiting de-manufacturing processes a range of market penetration according to their price in comparison to the pricing of newly manufactured FRP. Such effect was described using the equation in ***(13)***.

$$Effect\_of\_Relative\_Price\_of\_Demanufactured\_Goods\_on\_Market\_Penetration = 2 * Market\_Penetration\_of\_rComposites * \left(\frac{1}{1+e^{-K\_Consumption*Relative\_Price\_of\_rComposite-1}} - 0{,}5\right) \quad \textbf{(13)}$$

In which

K_Consumption is a parameter analogous to the ones presented before yet concerns the consumers' price sensitivity when buying rFRP.

Relative_Price_of_rComposite is the variable that evidences the discrepancy in price between recycled and virgin composites, calculated as the ratio between these two figures, respectively as numerator and denominator.

4.2.1.3.2. Time Delays

The two types of delays, namely material and information delays, have been employed in the model on different occasions. Fortunately, the software environment contained embedded functions for modeling delays that were applied accordingly.

Regarding information delays, these structures were inserted in the model to describe stakeholder's expectations and their evolution over time. Therein, based on their expectations about demand and the inflow of de-manufactured composites to the market, stakeholders, specifically producers, choose the quantity of virgin composites to manufacture (STERMAN, 2000).

There were two different expectations to be modeled, the first concerning the demand for FRP whereas the second concerning the market's inflow of de-manufactured composites. Notwithstanding, these expectations were described using different formulations since it was assumed that the resistance to update expectations regarding changes in demand is higher than that to accept new values for the flow of de-manufactured composites going to the market, because of demand's higher volatility. Hence, expectations about the demand were modeled by a third-order information delay, whilst those referring to the inflow of rFRP to the market were regulated by a first-order information delay; both expectations are subject to the same average delay time, which is the manufacturers' average review interval of their expectations. The equations used for the pair of expectations are the ones in ***(14)*** and ***(15)***.

$$Expected\_Composites\_Demand = smooth3(Composites\_Demand, Change\_in\_Expectations\_LT) \quad \textbf{(14)}$$

$$Expected\_rComposites = delayInformation(Use\_of\_rComposites, Change\_in\_Expectations\_LT) \quad \textbf{(15)}$$

As for material delays, they have been applied to describe the rate of transition between stages comprehended in composites' lifecycle. The model comprises two types of these structures, namely first- and third-order material delays, used under different circumstances. Almost all of the cases in which material delays have been used are with first-order structures, consisting of exponential decays of the stock level over the average delay time for the activity. The only exception is the rate at which FRP reaches their EoL phase, described by a third-order delay of the rate at which they enter the market. Georgiadis and Vlachos (2004) adopted the same representations of first-order material delays. Alike in their study, the initial values of all the stocks were set to zero; the third-order material delay of sales was also used in a similar context by Vlachos, Georgiadis and Iakovou (2007), being common in the examples of Sterman (2000) as well.

Nevertheless, as composites are lasting products whose lifetime exceeds a decade, to ensure flow conservation and account for the stock in use by the market a separated EoL rate was created. Therefore, the model has in its structure two EoL rates: one for the items already in use at the beginning of the simulation and another for those entering the use phase afterward. The expressions for both EoL rates and an example of a first-order material delay are provided in ***(16)***, ***(17)***, and ***(18)***. Note that the expression *year()* is a translation of a year in model time units, specifically weeks.

$$EoL\_Rate = delay3(Use\_of\_Virgin\_Composites + Use\_of\_rComposites, Lifetime\_of\_Goods * year()) \quad \textbf{(16)}$$

$$EoL\_flow\_initial\_stock = \frac{EoL\_Initially\_in\_Use(getYear())}{year()} \quad \textbf{(17)}$$

$$Use\_of\_Virgin\_Composites = \frac{Virgin\_Composites}{Sale\_LT} \quad \textbf{(18)}$$

4.2.2. Simulation Scenarios

In parallel to the completion of the model occurred the specification of the scenarios to undergo evaluation. This process produced eight different settings, each assessing the effects of modifications in the regulatory context through the establishment of policies. Besides, there were four preliminary runs considering the industry's present context, performed mainly to observe behavior reproduction and consistency. A summary of all the tests executed is shown in ***Table 3***. Runs 1 to 4 concern the preliminary experiments used in model validation, whilst runs 5 to 12 represent the policy scenarios assessed.

Table 3 – Detailing of the Simulation Scenarios

Run ID	Scenario Name	Description
1	Baseline: CFRP Thermal Recycling	This run regards the case in which CFRP undergo thermal recycling treatment as part of their de-manufacturing process. The option to use this case as the baseline grounds on it being an economically viable method for the recovery of carbon fiber composites added its limited damage to the material's properties, which makes it a typical market choice.
2	CFRP Mechanical Recycling	The simulation evaluates the case in which mechanical recycling is applied for treating CFRP waste, a method that, compared to the baseline, has a lower price but yields a recyclate with inferior properties. Therefore, in the model, the *Relative_Price_of_Demanufacturing*, affected by the cost of the activity, and the *Market_Penetration_of_rComposites*, influenced by the properties of the output, have had their values altered to account for these differences.
3	CFRP Chemical Recycling	The run refers to the occasion in which chemical recycling, specifically the SCW process, is used for the recovery of carbon-fiber composites. In this situation, the cost of the operation is much higher than that of the baseline, however, the fibers it obtains show property levels close to newly-manufactured virgin ones. Hence, like in the previous experiment, the divergence from the baseline lies on *Relative_Price_of_Demanufacturing* and *Market_Penetration_of_rComposites*.
4	Fixed Demand	The execution assumes a scenario almost equal to the baseline, except for the absence of growth in the market's demand for composites. By assuming a fixed demand, stakeholders' expectations tend to converge to the accurate quantity needed by the market and the gap between de-manufacturing processes' output and market's requirements is likely to contract the more products are sent to de-manufacturing pathways. The latter situation might not be necessarily true in the baseline since growth in demand can outweigh the increase in the de-manufacturing rate, requiring the imperative production of virgin FRP to fulfill orders in their totality. Consequently, possible domination of the market by recovered composites may never be verified under such circumstances, encouraging the experiment that eliminates the growth bias. In this context, the change in parameter values for this simulation is only in the *Market_Growth_Rate*, which is set to zero.
5	Promotion of De-manufacturing among Producers	The run analyzes the effect of implementing policies promoting actions that make producers aware of the possibility of sending composites to de-manufacturing processes. Even though the baseline assumes a perfect case, in which there is full knowledge about this pathway, in reality, there may be stakeholders who still only consider the disposal option for these materials. Consequently, this run assesses the impact of awareness on the usage of rCFRP, mirroring the effects of rules endorsing actions that disseminate in the market the possibility to employ de-manufacturing processes to handle the composite waste. The run conducts different experiments by gradually varying the parameter *Producer_Awareness_on_Composites_Demanufacturing* value according to a defined step variation within a predetermined range of values to attain its objective. In this way, it allows the observation and comparison of the system's dynamics under contexts with different information levels about the option closing the loop.
6	EPR and EoL Regulation	The scenario addresses the impacts of introducing additional regulation regarding extended producer responsibility and end-of-life procedures, tightening current rules, and establishing further obligations. Particularly, it evaluates the consequences of a rise in the costs of disposal, caused, for example, by an increase in the taxes of disposal activities, rising the fees charged for them, or by the introduction of landfilling fines or bans. Therefore, the parameters directly affected by this policy are the two considering the costs of disposal, namely *Relative_Price_of_Collection* and *Relative_Price_of_Demanufacturing*, which alike in the previous case receive different values within a defined range that change steadily between experiments at a fixed step variation. The collection-related variable varied until it reached 50% of its baseline value, emulating a doubling in the uncontrolled disposal cost, whilst the de-manufacturing-related one progressed until the cost of controlled disposal matched the cost of de-manufacturing.

Table 3 - continued

Run ID	Scenario Name	Description
7	Customer Education Activities	The test reproduces the introduction of policies targeting the education of customers about products stemming from Circular Economy business models after undergoing stages of de-manufacturing. These actions try to defeat people's distrust around recovered goods and make them support and consume the restored products. It fights against the aversion arising from common beliefs of inferior quality and performance by informing people about the characteristics of restored parts, their quality equivalence compared to new products and the warranties included, the environmental benefits embedded in the part, etc. Accordingly, the experiments in the run have varying values for the parameter *Commercial_Uptake*, which measures customers' acceptance of de-manufacturing processes' output, mimicking the change in customers' willingness to consume products marked by such characteristics.
8	Information Exchange along the Supply Chain	The run portrays the introduction of mechanisms stimulating the exchange of information between stakeholders inside FRP's supply chain, disseminating knowledge regarding the flows to be processed, which directly affects the efficiency of reverse operations. With information available, the most suitable techniques for treating flows can be selected immediately, speeding the stages inside collection and de-manufacturing activities such as sorting, inspection, cleaning, disassembly, etc. The increase in speed renders the process more productive, which in the model is represented by the reduction in the value of the parameters representing the lead-times of the activities within the reverse loop *Collection_LT* and *Demanufacturing_LT*. The experiments considered efficiency gains up to 40% in both collection and de-manufacturing stages, using 10% step variations.
9	Discovery of New Applications	The run considers the institution of policies encouraging the discovery of novel market applications for rFRP, for example, the provision of economic incentives for their adoption. If established, these inquiries investigate recovered composites' properties looking for compatibility with additional utilization in industries currently employing FRP or in others still to familiarize with them. As a result, they increase the market penetration of composites proceeding from de-manufacturing chains, translated to model terms by variations in *Market_Penetration_of_rComposites*. The experiments emulated scenarios in which rFRP are applied in between 30% and 75% of their virgin counterparts' use cases, with a step change of 15% between successive tests.
10	De-manufacturing Technology Improvement	The run correlates to the establishment of policies that promote research and development (R&D) activities regarding de-manufacturing methods and technologies, for instance, tax incentives based on the amount of money invested with this goal. Enhanced or novel de-manufacturing technologies have the potential to trigger gains for the process by reducing its costs and lead-time and increasing the property levels of its outcomes. In consequence, to imitate the effects of regulations on the topic, the model assumes shifting values for the *Demanufacturing_LT*, *Market_Penetration_of_rComposites*, and *Relative_Price_of_Demanufacturing*, which represent, respectively, the effects on lead-times, properties of the de-manufacturing output, and cost of the process.
11	Transportation Regulation	The scenario replicates alterations in the regulatory context concerning the transportation of composite waste. Previous chapters discussed the complexity of the rules' system the activity must comply with, marked by strict controls that inhibit the movement of discarded FRP and thus prevent scale gains achieved by aggregating EoL flows from different sources. Consequently, a policy targeting to reduce such complexity might support the establishment of feasible de-manufacturing chains in the industry since it will increase the efficiency of collection activity by improving its overall lead-time. Accordingly, the parameter suffering value variations in this run in *Collection_LT*, tested until a 40% improvement was reached, with step variation between executions of 10%.

Table 3 - concluded

Run ID	Scenario Name	Description
12	Waste Management Practices	The last run of the model relates to the enforcement of policies that seek to define waste management practices for composite materials. By introducing a classification to be followed and preferred procedures for handling FRP waste, this kind of policy facilitates and improves the performance of sorting activities downstream in the circular value chain, diminishing the disbursements associated with their execution. Since sorting is responsible for a significant portion of the costs of collection and de-manufacturing operations, these processes become cheaper, which in turn can cause the price of the final recovered composite to fall. To replicate the effects of such policies, *Relative_Price_of_Collection*, *Relative_Price_of_rComposite*, and *Relative_Price_of_Demanufacturing* experimented variations in their values.

Source: Author's elaboration

4.2.2.1. Evaluation of the different scenarios

Indicators were adopted to evaluate the results from the different simulation scenarios. The selected decision variable that bases the appraisal of the model's results is the accumulation of the quantity of de-manufactured composites that has been employed by the market under the specific context, called *Used_rComposites* and expressed as ***(19)***. This variable also represents the amount of FRP that, in the absence of de-manufacturing lines, would finish in disposal pathways even though it could be recovered to a functioning state and have additional use phases. Therefore, the decision variable is a measure of the volume of composite material prevented from being lost, whose value embedded is saved owing to Circular Economy business models.

$$Used\_rComposites = \int_0^t Use\_of\_rComposites(t)\, dt \tag{19}$$

For comparison, the same accumulated quantity of virgin composites used by the market was calculated using expression ***(20)***, called *Used_Virgin_Composites*. These two variables allow the obtainment of a third value used for assessing the scenarios, which represents the share of recovered composites in the total market's use of FRP, arising from equation ***(21)***.

$$Used\_Virgin\_Composites = \int_0^t Use\_of\_Virgin\_Composites(t)\, dt \tag{20}$$

$$Share\_of\_rComposites = \frac{Used\_rComposites}{Used\_rComposites + Used\_Virgin\_Composites} \tag{21}$$

4.2.3. Simulation Results

The results achieved by the simulation of the model under different contexts can reveal relevant aspects about the dynamics of the European rCFRP industry, which can be largely extended to the situation of the region's rFRP sector in general. This section analyses the outcomes achieved and reasons about them, in an attempt to derive conclusions from the insights that emerged from the simulations executed with the model. Detailed information about the results from the simulations can be found in ***APPENDIX D – SIMULATION RESULTS***.

To begin, the initial simulations treating the industry's present context unveil interesting facts about the current discussions permeated in the sector. The runs regarding the three recycling techniques embed the trade-off between the property level of the product after the process and the cost to apply the referred technique. In terms of the quantity of composite material saved from the disposal pathway, which is also the quantity of composites de-manufacturing business can provide the market with, the consequences of choosing to produce a recyclate whose properties are greater but the fabrication process more expensive are negative. Under these terms, the model showed the cost of the reverse activity is more detrimental to the consumption of the produced rFRP than the material's properties. The latter resolution is exemplified by the comparison of the results from the baseline against the two other methods assessed, namely mechanical and chemical recycling. In mechanical recycling, which costs less but yields a material with worse properties, the run ended displaying a higher volume and share of composites produced by the de-manufacturing process than the baseline. In contrast, in the case of chemical recycling, in which the outcome has higher quality in terms of properties but costs more to be obtained, the volume and share of rFRP were smaller.

The previous result is rather unusual, since currently in the market the most preferable recycling methods for CFRP are thermal processes, given the property downgrading incurred by using mechanical recycling techniques. For this case, the difference in the considered market penetrations from the two procedures, which are a consequence of the disparity in property levels of the outputs of the processes, might not have reflected usual mechanical recycling techniques, but instead avant-garde mixed solutions for mechanical recycling that allow the achievement of better property standards or technological evolutions incorporated in the activity. It might be the case as the values were estimated based on data from the FiberEUse project, which proposes modern and innovative solutions for the processes within de-manufacturing.

Staying with the runs regarding the industry's present context, the scenario that considers a fixed demand performed better than the baseline, implying the growth in the market's requests of composite materials is in its majority fulfilled by virgin FRP. This also means the speed at which de-manufacturing activities grow, measured by the pace of increase in the volume of composites generated, is behind the rate of expansion of the market's capacity of absorption. Therefore, if the industry's characteristics maintain their as-is conditions, it will be difficult to see de-manufactured composites occupying a better market position in the future.

Seeing that there must be changes in the sector's characteristics to make the usage of rFRP evolve, the results from the simulations assessing the different regulatory modifications that can be enacted employing policies offer the opportunity to prioritize between the alternatives and focus the efforts on where they will be more productive.

The runs testing the impacts of having customer education activities and the discovery of new applications verified these actions have a low effect on the adoption of composites produced in de-manufacturing lines. The two simulations have a common feature: they act on the same part of the Circular Economy business model, responsible for sending the recovered products back to the market once they are ready for reuse. These results may seem counterintuitive, especially since in previous chapters the aversion of consumers and the restrictions to the application of recovered composites were presented as barriers for their utilization. Nevertheless, a closer observation of the model's behavior during these runs showed that the reason behind the outcomes come from this branch of the system operating at its best, meanwhile the limitations it faces standing on the availability of inputs, in this case, ready-for-use-rFRP. Therefore, the evidence implies the current bottleneck for the adoption of de-manufactured composites is not in the market and its rate of absorption of materials of this kind, but rather in other parts of the system.

Knowing the actual bottleneck for the adoption of rFRP does not belong in market elements, i.e. does not arise from the demand for these materials, the alternative is that it resides in their supply. The offer of de-manufactured composites is the responsibility of two branches of the system, one representing the collection of FRP waste, making it available for de-manufacturing processes, and the other characterizing de-manufacturing activities themselves. Starting with the analysis of the collection wing, the run that assesses the enforcement of policies whose scope affects the regulation over the transportation of composite waste provides useful insights since its effects are limited to this branch and alter mainly the lead-time needed to gather discarded FRP. By reducing the time taken to make EoL composites available for de-manufacturing, there was an increase in the adoption of these materials once they had been processed. The consequences of the faster collection are that, in the same period, it is possible to amass a higher amount of composite waste, which in turn led to an increase in the quantity of de-manufactured composites consumed. Hence, the results from the simulation allow the inference that the greater availability of inputs for composites de-manufacturing processes contributes to the growth in the application of their output.

Another manner to increase the availability of EoL FRP for Circular Economy business models grounds on changes in the costs of the collection activity. The analysis of the run assessing the introduction of further EPR and EoL regulation showed that, when observing any of the results' clusters in isolation, the increments in the value of *Used_rComposites* are a consequence of the reduction in the *Relative_Price_of_Collection*. In case the collection of composite waste becomes cheaper, this pathway should gain more of the stakeholders' preference, increasing the amount of waste collected and as a result the availability of FRP for de-manufacturing activities. This outcome, therefore, supports the former conclusion that the greater the availability of EoL composites for de-manufacturing activities, the greater the intake of rFRP-made goods.

The same run enables the investigation of the remaining branch of the reverse supply chain, specifically, the de-manufacturing processes and their components. Instead of the examination of the results within an isolated cluster, the comparison between the different groups composed by experiments revealed the increase in the supply of recovered composites to the market was associated with decreases in *Relative_Price_of_Demanufacturing*. This indicates that if the costs of de-manufacturing activities are closer to those of their alternative, the market's adoption of recovered composites should increase. Indeed, the finding must be the development of the higher preference for de-manufacturing pathways once their costs decline, which results in a more intense waste flow directed to this type of activity, inducing the increase in the produced quantity, later absorbed by the market.

Furthermore, one simulation providing information specific to the de-manufacturing branch tested the effects of policies targeting the promotion of the referred process among producers. The results signaled the lower the awareness of stakeholders about de-manufacturing pathways for composite materials, the lower the adoption of rFRP by the market. With an inferior awareness, less composite waste goes to de-manufacturing, thus the inflow is constrained. This corroborates the understanding that the amount of EoL FRP entering de-manufacturing chains is one determinant factor for the utilization of de-manufactured composites.

The run that scrutinizes the impacts of policies encouraging the development of new de-manufacturing technology mainly acts on the de-manufacturing branch by affecting both the costs and the lead-time of the activity, apart from the market penetration of the composite material generated. However, previously, the assessment of the last parameter concluded it had minimal impacts on the decision variable; hence, the effects observed in the current scenario come mainly from the two other elements. The results demonstrated, once again, that reductions in the relative cost of de-manufacturing positively influenced the quantity of rFRP adopted by the market. Moreover, contractions in the lead-time of the process also spawned the increase of the market's intake of composite materials produced by circular supply chains. If the time taken to perform de-manufacturing activities decreases, their productivity rises, so the amount of rFRP delivered over a fixed period grows, which then proceeds to fulfill the demand. It is also observable that similar levels of improvement were achieved by experiments characterized by different values for these parameters, meaning policymakers have room for maneuver depending on their goals, though more ambitious targets may reduce this flexibility. Therefore, the simulated introduction of policies acting on the de-manufacturing branch provided adjustments in the regulatory context beneficial for the progression of rFRP production and their admission in the market.

Accordingly, the scenario testing an increase in the flow of information along the supply chain, which reduces the activities' lead times, reinforces previous findings. Reductions in lead times in both branches contribute to increasing the market's utilization of reprocessed composites. Therefore, productivity increases in reverse processes along the circular supply chain contribute to the market's utilization of the materials manufactured. Additionally, variations on de-manufacturing lead time impacted more on the decision variable than changes in the collection parameter, indicating the preferential target for policies should be the de-manufacturing branch, as other simulations already suggested.

The final simulation to mention tested the establishment of waste management practices for composite discarded material, which reverberated in all parts of the reverse loop, namely collection, de-manufacturing, and distribution. This run measured the impact of changes in the relative prices embedded in each of the branches, respectively *Relative_Price_of_Collection*, *Relative_Price_of_Demanufacturing*, and *Relative_Price_of_rComposite*, because of overall cost reductions. The outcomes reached reinforce latter conclusions as significant improvement in the application of de-manufactured composites could be verified with reductions in the values of the parameters related to collection and de-manufacturing but not in the one connected to the distribution stage. Furthermore, they also supported what previous tests insinuated: the more comprehensive the policy, with effects on a higher number of parameters, the better the chance for improvement it originated. Nevertheless, the derivation of this causality requires additional investigation, since the results may be a consequence of the set of parameters varying in the experiments.

Concisely, the results showed that modifications in the regulatory environment to which the composite industry is subject, in special the rules over the reverse activities within the sector, have the potential to encourage the application of rFRP by market players. In addition, they suggested concentrating the efforts on the collection and de-manufacturing stages, since the impacts generated by changes in distribution elements were limited compared to those from these parts of the supply chain; if to discriminate between the two, policies influencing more the elements connected to de-manufacturing should receive preference. Moreover, the outcomes indicated the existence of a certain level of flexibility regarding the characteristic affected by and the required intensity of policy effects according to the improvement policymakers fancy, which diminishes the more ambitious the goal pursued. Finally, the results signaled that policies with effects spanning more elements are more effective, but the finding still requires careful additional investigation.

4.3. The Parallel between the Brazilian and European Scenario

Due to the lack of available data, the SD model simulation for the Brazilian case was not possible. Thus, this section explores the European SD simulation in the Brazilian context, grounded on the findings from the comparative analysis.

As mentioned before, the opportunities and barriers both regions face are similar to one another, given the lack of some elements relevant for Circular Economy business models for composite materials within the two places' regulations. This aspect makes the scenarios tested for the European case also applicable in Brazil, with the only difference being on transportation regulation, which in the second should comprise the federal divisions and not countries. Although approved in 2010, the PNRS was further regulated in 2017 and 2020 by decrees and is still under its implementation period in Brazilian territory (BRASIL, 2010). Therefore, the timing for changes in the country might be even more opportune than in Europe, as the reverse supply chain is already being reviewed and redesigned to adhere to the new policy.

Recalling previous sections, recycling rates in Brazil are still low. This could imply poor levels of waste collection activities in the country, as well as popular negligence of reverse processes, which in turn may represent a worse perception of recovered products (CAMPOS, 2014; CONKE, 2018). In the face of this scenario, education actions might be seen as logical options to be pursued. However, results have shown that the development of the collection and de-manufacturing branches before the distribution branch are more relevant if stronger impacts on the utilization of recovered composites are sought. Therefore, policymakers should leave to target the general population consciousness only after enforcing other measures, but manufacturers' awareness around circular practices needs to be increased promptly to ignite CBMs in the country.

The introduction of the PNRS can be seen as the implementation of waste management practices in Brazil. Although in Europe the established Directive on Waste acts as the PNRS, the South-American country's legislation goes beyond since it proposes targets and evaluation metrics for procedures, though both neglect remanufacturing methods in their ruling efforts (BRASIL, 2010; FIBEREUSE, 2017a). In the simulations, the European case assessment has shown that this type of comprehensive measure, which spans the entire reverse supply chain, appears to have more significant effects than isolated actions. Given the results, the reverse supply chain benefits from relative price reductions in all of its branches, which boosts the market's adoption of rFRP.

Therefore, as part of the PNRS implementation, disposal prices in Brazil tend to be increasing, especially as a result of the prohibition of dumping grounds. Consequently, both relative prices of collection and de-manufacturing should decrease in the short-term, naturally favoring the steering of waste flows to reverse activities. To boost this movement, further restrictions on the use of disposal or incentives to circular practices could be enacted, which can lead to increases in waste flows received by de-manufacturing systems. European examples of this kind of actions to inspire Brazilian policymakers are the Landfill directive, EPR legislation and the directive on EoL vehicles. The higher volumes can aid these activities' profitability, possibly attracting more investments in the sector, which leads to further developments in Brazilian reverse supply chains.

A better circular scenario can help in more than the country's recycling rates. As seen before, de-manufacturing activities are normally labor-intensive, and in Brazil, there is an abundance of informality in the labor force working in the reverse industry, most of it under improper sanitary conditions (CAMPOS, 2014). The available workers can be qualified and integrated into de-manufacturing operations, being a valuable asset to circular practices in the country that will benefit from productivity increases, which, nonetheless, calls for additional investments in the sector. This change may also reduce these people's social vulnerability, a mark of the current Brazilian reverse industry.

However, some setbacks can hamper the establishment of CBMs for composite materials in Brazil. The market information collected reveals the demand for composites in the South-American country is much smaller than Europe's (AVK - FEDERATION OF REINFORCED PLASTICS, 2019; ALMACO, 2020). In addition, Brazil is a continental country, thus waste flows, which tend to be small, can even be dispersed all over the territory. As aforementioned, small volumes normally render reverse activities' profits infeasible. Therefore, greater coordination among states might be required to aggregate FRP waste flows in sufficient quantities for de-manufacturing to thrive. Although challenging, the fact that all federation states comply with the same national rule, despite small operational differences, at least makes this process less troublesome in comparison to Europe.

Moreover, Brazil is facing fiscal constraints that can limit the ability of the government to promote some of the policy actions that can stimulate circular practices. The PNRS covers financial aspects when coupling compliance to the transfer of funds by the central government to states and municipalities but does not consider practices more connected to the corporate sector, like subsidies and tax exemptions (BRASIL, 2010). Even though national governments are believed to have a primary role in the circular transition as igniters, private players and society should not be overlooked, as they can also propel changes. Hence, Brazilian players and the general population need to act together, voicing for a Circular Economy transition that will enter the political agenda despite the lack of resources, requesting the necessary regulatory modifications the country's reverse activities require to evolve.

To illustrate the potential implications of policy actions in Brazil, ***Table 4*** explores the Brazilian case with the perspective of the regulatory scenarios simulated for the European context (***Table 3*** Run IDs 5 to 12), revealing the expected differences.

Table 4 – Differences between the European and Brazilian Contexts

Run ID	Scenario	Expected Differences
5	Promotion of De-manufacturing among Producers	Assuming the low recycling rate can be a proxy for the lower awareness of producers about de-manufacturing practices, the promotion of such strategy among Brazilian manufacturers can have stronger effects compared to Europe, as the potential full-awareness state in the country should be more distant from today's reality.
6	EPR and EoL Regulation	Even though the PNRS considers these fields in a general approach, complementary measures could make the legislation more specific, defining the objectives, responsibilities, and targets for the players involved. Their impact in Brazil can be stronger than in Europe as the latter already enforces regulations that target these matters.
7	Customer Education Activities	This kind of action may require more effort in Brazil than in Europe because of the low recycling rates in the country, which can suggest lower popular regard towards the reverse supply chain. There is no reason to believe the measures shall be more effective in the country than in the European context.
8	Information Exchange along the Supply Chain	Barriers to communication in Brazil are smaller than in Europe, given the common language and culture. Although the effects of this action tend to be similar between the two regions, its establishment is easier in the South-American country. Therefore, smaller efforts are required to achieve the same level of results forecasted for the European context, increasing the policy's efficiency if pursued by Brazilian policymakers.
9	Discovery of New Applications	As previously seen, the use of composite materials in Brazil is smaller than in Europe. Therefore, the discovery of additional use cases for rFRP in the country might not be of the same relevance as for the European context, which suggests lower effectiveness for the measure in the South-American country.
10	De-manufacturing Technology Improvement	Given the available labor force in the Brazilian reverse sector and the country's lower wages and income levels, the costs involved in de-manufacturing manual operations are less burdensome in the region. Thus, this kind of measure is expected to be less effective in Brazil than in Europe.
11	Transportation Regulation	This type of measure has limited effects in Brazil since the differences in regulation among federal divisions are not very significant, and there are no restraints on transboundary movements concerning states.
12	Waste Management Practices	The PNRS implementation can be seen as the introduction of this measure. The expected effects for this type of policy are the same in the two regions, but the timing in Brazil can contribute to increasing its efficiency since the debate is already present.

Source: Author's elaboration

In conclusion, in this implementation phase of the PNRS, it is crucial for state and national stakeholders in Brazil, both public and private, to join conversations and come up with a coordinated plan, embedding the knowledge generated by other international experiences. That will enable the country not to miss the opportunity and momentum the PNRS enforcement represents to the consolidation and development of its circular supply chains.

5. CONCLUSIONS, CONTRIBUTIONS AND FURTHER RESEARCH

The present work resides within the context of Circular Economy, one of the most prominent paradigms in the fight against climate change that associates economic development with environmental sustainability. Under this logic, composites represent a type of material for which Circular Economy business models remain poorly developed, legitimizing efforts to prove their feasibility and to encourage their establishment, attempts which this work integrates. The SD model developed aims at supporting policymakers in their regulatory decisions; it represents the industry, based on System Dynamics theory, which would undergo simulation to test the effects of regulatory modifications, providing relevant insights on the definition of policies for business models development for composite materials under Circular Economy.

The in-depth literature review explores the de-manufacturing, the stage that comprises the key activities responsible for enabling circularity. In sequence, it characterized composites, also named fiber-reinforced plastics, providing the materials' peculiarities, primary manufacturing techniques, and principal utilization cases, which can help future endeavor to investigate the composite industry context regarding Circular Economy in other locations.

It also pointed out demand for composites and its trends, and aspects like existing waste sources, applicable de-manufacturing processes, foreseen market opportunities, the main barriers, and the regulatory environments. Hence, the analysis provided the knowledge fundamental for developing the proposed model, helping in comprehending the industry's dynamics, which can support further investigations on the subject using SD theory.

The main contribution of the SD model is paving the ground for additional scrutiny of CE for the composite industry. It provides future researches with the system's Causal Loop diagram and its Stock and Flow map, the latter already created in AnyLogic software, an environment that can host simulations. It also details the mathematical expressions and parameters necessary to reproduce the system dynamics with their respective estimated values, helping those willing to repeat or continue the study. Furthermore, it presents potential policy scenarios and their presumed contributions to the growth of the industry's reverse ecosystem that can inspire policymakers and researchers in the future. Additionally, it compares the discoveries about the European context to the potential impacts in Brazil, endorsing the adoption of sustainable practices in the South-American country.

In conclusion, the study proved the feasibility of the decoupling of the technical system from the regulatory context. Using an innovative model environment, the study transformed policies into technical parameters, which allowed the separation of the technical elements of the system from the policy ambiance regulating it employing a high-level quantitative model.

Furthermore, the analysis of its responses shows that the modification of the regulatory environment overarching the industry contributes to the expansion of the adoption of rFRP produced under Circular Economy business models, in alignment with other studies exposed in Literature Review. The results indicate policies targeting the development of better de-manufacturing and collection activities are, respectively, more capable of resulting in improvements on the market's intake of recovered composite material. They also suggest, counterintuitively, that actions benefiting rFRP in the distribution stage, focusing on consumers and the demand, poorly contribute to their employment. Additionally, the outcomes demonstrated there is a degree of flexibility in the targets of improvement defined for the system's elements to achieve a desired level of absorption; however, the more ambitious the goals, the lower this flexibility. As presented, both the European and Brazilian contexts have much in common, but the South-American country might be facing a better opportunity to act on its reverse supply chains given the timing.

Finally, the high-level responses achieved to allow the establishment of a priority agenda for the policies regarding the composite sector in the two regions. First, policymakers should establish measures with stronger effects on de-manufacturing, such as incentives to de-manufacturing technology improvement and the promotion of the practice among producers. A second moment should follow those that also affect the collection, for instance, the definition of waste management practices for composites and stiffening EPR and EoL regulation, considering the adaptation of transportation rules, apart from introducing information exchange mechanisms in the supply chain. Ultimately, after developing the reverse loop, the focus should go to the issues related to customers and the demand. The order achieved meets the findings from sources in the literature used for this study.

The assumptions made during the development of the work generate some limitations on its results. Initially, given the simplification of the demand in the model, this never intended to produce results that are forecasts of the industry's future. Instead, their appraisal should be comparative, observing the differences in the system's performance under distinct environments, so occasional modeling deviations from reality lose their strength since every experiment displays the same bias, which neutralizes its effect for the evaluation.

In addition, the conception of the model aggregated all types of processes possible during each stage in a high-level representation. This choice disabled the evaluation of different procedures under the same environment by observing the individual response of an activity's performance to the measure implemented. In this way, the assessment is limited to one process per run. The same occurs in the case of the type of composite investigated.

Moreover, to determine the values for the parameters, the work examined both scientific and market literature on the subject. As the model did not differentiate between stakeholders, the figures obtained characterize the entire group of players from a category, for example, manufacturers and logistic providers. Thus, the generalization of the values may have resulted in distortions in the industry's actual scenario, which econometric techniques using individual company's data might reduce, though not in the scope of the study. Additionally, transposing European results to Brazil was the approach selected given the impossibility of simulating the model for the latter's context. However, the recommendations could be different if this information was available, implying possible limitations for utilizing the results.

Finally, the work considered a flexible capacity in all of the stages of the supply chain as it operated at the industry level. However, since individual companies have a constraint for the quantity of composites they can process, and the industry aggregates single companies, the industry itself has a capacity limit as well, though much greater and flexible than firms'. Therefore, the model does not account for the possibility of exceeding the sector's processing capacity and its consequences that would probably decrease the performance of the scenarios in which they occur.

Considering the mentioned limitations, future studies could try to develop from the model and overcome some of the issues discussed. Relaxing a few of the assumptions made and introducing a greater level of disaggregation, for instance allowing experiments with more than one recycling technique employed or with a greater variety of composites assessed simultaneously, could help in designing measures that are more precise and thus have the potential to be more effective. Additionally, these changes could confirm the results obtained by the present work or provide remarks relevant for policymakers' decisions; to exemplify, the inclusion of capacity constraints can supposedly reduce the benefits of measures working on the availability of EoL composite waste for de-manufacturing processes.

Furthermore, future research could investigate findings suggested but not confirmed by the results obtained in this study, for instance, the relationship between the number of elements affected by a policy and the potential improvement it generates. That could shift the efforts towards the establishment of more comprehensive regulations, tackling a multitude of the industry's issues at once, or the introduction of incremental modifications at a time. In the presence of information from Brazil, other studies might investigate the country's situation and reach more precise recommendations for the country's policy agenda for the sector.

To conclude, the created model offers a high-level characterization of the FRP industry that can be generalized and applied to the case of other Circular Economy businesses, helping in the dissemination of the paradigm through the economy. Hence, it constitutes not only a tool for policymakers to fundament their decisions on but a mechanism to promote the adoption of the principles of the Circular Economy.

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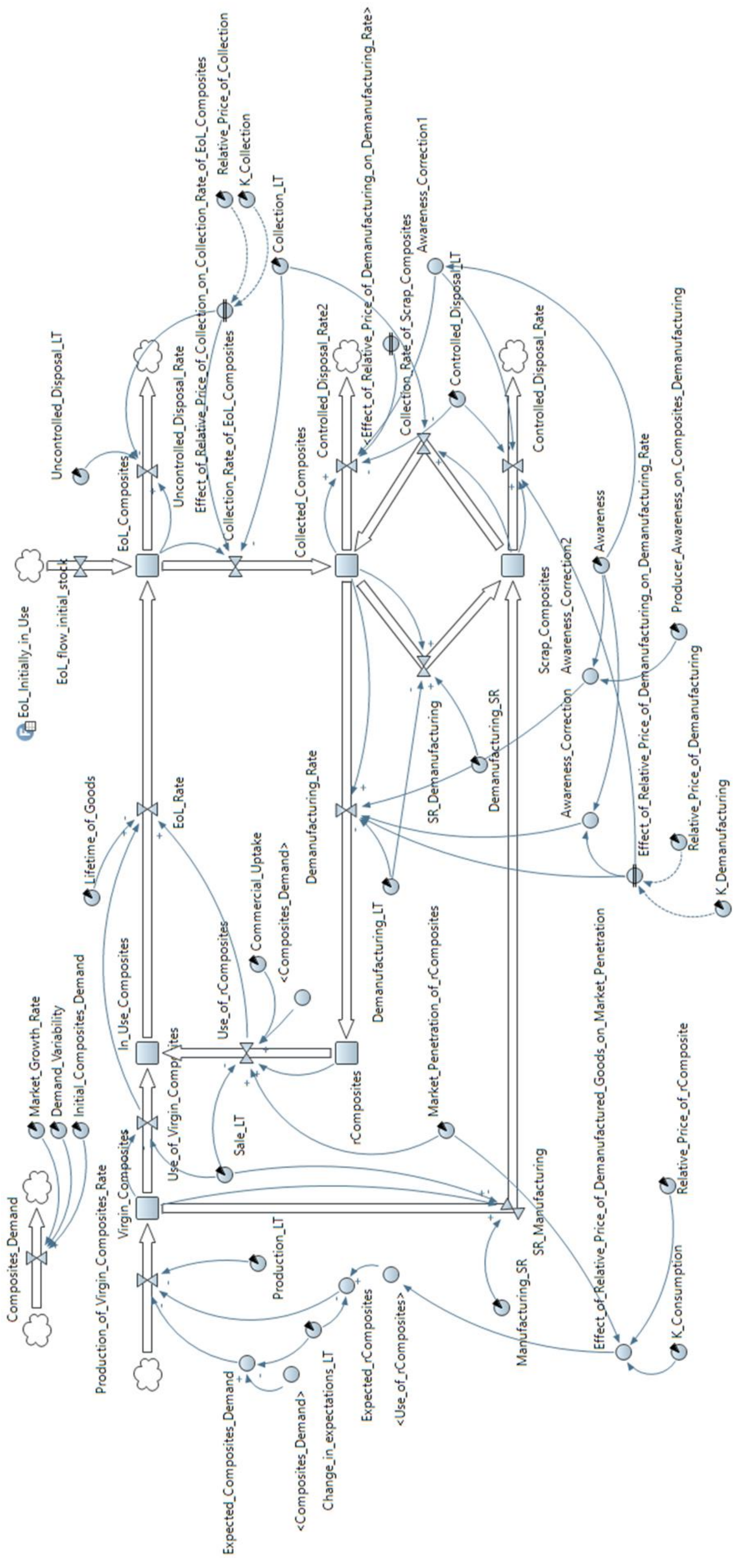
APPENDICES

APPENDIX A – DATA INPUTS

Parameter	Value	Unit of measure	Remarks
EoL flow of composites already in use at the begginning of the simulation Year 2020 Year 2035 Year 2045	 1290 2618 6410	[tons/year]	Source: Lefeuvre et al. (2017) Linear interpolation used for intermediary years
Change_in_expectations_LT	1	[weeks]	No remarks
Collection_LT	0,5	[weeks]	No remarks
Commercial_Uptake	60%	N/A	No remarks
Controlled_Disposal_LT	0,5	[weeks]	No remarks
Cost_of_Collection	40	[£/ton]	Source: FiberEUse (2017)
Cost_of_Demanufacturing Mechanical Recycling Thermal Recycling Chemical Recycling (SCW treatment)	 248 1800 5430	[€/ton]	Source: (Vo Dong et al., 2018) The cost of the recycling process was used as a proxy for the cost of de-manufacturing
Cost_of_Disposal	125	[£/ton]	Source: FiberEUse (2017)
Cost_of_Production	20130	[€/ton]	Source: FiberEUse (2018b) This value corresponds to the selling price of virgin carbon fibers, used as a proxy of production costs
Demand_Variability	5%	N/A	Low variation assumed based on the study of Vlachos, Georgiadis and Iakovou (2007)
Demanufacturing_LT	1	[weeks]	Assumed equal to the lead time of production
Demanufacturing_SR	15%	N/A	Assumed to be equal to the manufacturing scrap rate
Initial_Composites_Demand	48488	[tons/year]	Source: FiberEUse (2018b)
K_Collection	2,5	N/A	No remarks
K_Consumption	2,5	N/A	No remarks
K_Demanufacturing	10	N/A	No remarks

Lifetime_of_Goods	20	[years]	Source: Lefeuvre et al. (2017)
Manufacturing_SR	15%	N/A	Source: FiberEUse (2017)
Market_Growth_Rate	4%	N/A	No remarks
Market_Penetration_of_rComposites Mechanical Recycling Thermal Recycling Chemical Recycling (SCW)	 15% 25% 75%	N/A	Based on information in FiberEUse (2018)
Producer_Awareness_on_Composites_Demanufacturing	100%	N/A	Assumed that the players who operate in the sector are aware about the possibility of de-manufacturing composites
Production_LT	1	[weeks]	Source: Vlachos, Georgiadis and Iakovou (2007)
Relative Price of Collection	0,32	N/A	Calculated as indicated in ***(10)***
Relative Price of De-manufacturing Mechanical Recycling Thermal Recycling Chemical Recycling	 -0,00487 -0,08197 -0,2623	N/A	Calculated as indicated in ***(11)***
Relative_Price_of_rComposite	0,6	N/A	Source: FiberEUse (2018)
Sale_LT	0,5	[weeks]	No remarks
Uncontrolled_Disposal_LT	0,2	[weeks]	No remarks

APPENDIX B – MODEL DETAILS



Type of Element	Name	Unit of measure	Description
Stock	Collected_Composites	[tons]	Represents the amount of waste composite material collected in the system
	EoL_Composites	[tons]	Represents the amount of composite material ending their use life and entering the EoL stage
	In_Use_Composites	[tons]	Represents the amount of composite material currently being used in applications by the market
	Scrap_Composites	[tons]	Represents the amount of composite material rejected either prior to or during processing
	Used_rComposites	[tons]	Represents the accumulated amount of recovered composites used by the system
	Used_Virgin_Composites	[tons]	Represents the accumulated amount of virgin composites used by the system
	Virgin_Composites	[tons]	Represents the amount of virgin composites available for the market
	rComposites	[tons]	Represents the amount of recovered composites available for the market
Flow	Collection_Rate_of_EoL_Composites	[tons/week]	Represents the rate at which composites in the EoL phase are collected
	Collection_Rate_of_Scrap_Composites	[tons/week]	Represents the rate at which scrap composite material is collected
	Composites_Demand	[tons/week]	Represents the market's demand of composite material
	Controlled_Disposal_Rate	[tons/week]	Represents the rate at which scrap composites are sent to disposal pathways
	Controlled_Disposal_Rate2	[tons/week]	Represents the rate at which collected composites are sent to disposal pathways
	Demanufacturing_Rate	[tons/week]	Represents the processing rate of de-manufacturing activities

	EoL_flow_initial_stock	[tons/week]	Represents the rate of composite material known to be already in use reaching the EoL state
	EoL_Rate	[tons/week]	Represents the rate of composite material still to enter the market reaching the EoL state
	Production_of_Virgin_Composites_Rate	[tons/week]	Represents the rate of production of virgin composites
	SR_Demanufacturing	[tons/week]	Represents the rate of composite material rejected by de-manufacturing processes
	SR_Manufacturing	[tons/week]	Represents the rate of composite material scrapped during manufacturing
	Uncontrolled_Disposal_Rate	[tons/week]	Represents the rate at which EoL composite material is discarded incorrectly
	Use_of_rComposites	[tons/week]	Represents the rate at which recovered composites are employed by the market in applications
	Use_of_Virgin_Composites	[tons/week]	Represents the rate at which virgin composites are employed by the market in applications
Dynamic Variable	Awareness_Correction	N/A	Element that cancels the effect of the relative price of de-manufacturing on de-manufacturing rate if there is no awareness about this option
	Awareness_Correction1	N/A	Element that cancels the effect of the relative price of de-manufacturing on controlled disposal if there is no awareness about the de-manufacturing option
	Awareness_Correction2	N/A	Element that regulates the flow to de-manufacturing pathway based on the awareness about the de-manufacturing option
	Effect_of_Relative_Price_of_Collection_on_Collection_Rate_of_EoL_Composites	N/A	Represents the impact of the relative price of collection in the rate of collection of EoL composites

	Effect_of_Relative_Price_of_ Demanufactured_Goods_on_Market_ Penetration	N/A	Represents the impact of the relative price of the de-manufactured goods in their utilization by the market
	Effect_of_Relative_Price_of_ Demanufacturing_on_Demanufacturing_ Rate	N/A	Represents the impact of the relative price of de-manufacturing in the rate of de-manufacturing
	Expected_Composites_Demand	[tons/week]	Represents the volume of composites players expect to be market's demand in a given moment
	Expected_rComposites	[tons/week]	Represents the volume of recovered composites players expect to be entering the market at a given moment
Parameter	Awareness	N/A	Element that determines whether there is awareness about de-manufacturing pathways
	Change_in_expectations_LT	[weeks]	Represents the average delay for expectations to change in the face of new evidences
	Collection_LT	[weeks]	Represents the average time taken to arrange and execute activities related to the collection of products
	Commercial_Uptake	N/A	Represents the share of the market willing to embrace de-manufactured products
	Controlled_Disposal_LT	[weeks]	Represents the average time taken to send materials to disposal pathways
	Demand_Variability	N/A	Represents the amplitude of random variations in demand
	Demanufacturing_LT	[weeks]	Represents the average time taken to perform the whole de-manufacturing process
	Demanufacturing_SR	N/A	Represents the share of material rejected by de-manufacturing processes either due to quality non-conformance or processing scrap
	Initial_Composites_Demand	[tons/year]	Represents the value of the yearly demand of composite materials at the simulation start time

K_Collection	N/A	Measure of stakeholders' price sensitivity regarding collection activity
K_Consumption	N/A	Measure of stakeholders' price sensitivity on the consumption of FRP
K_Demanufacturing	N/A	Measure of stakeholders' price sensitivity regarding de-manufacturing activities
Lifetime_of_Goods	[years]	Represents the average duration of one use cycle of composite products
Manufacturing_SR	N/A	Represents the share of input lost in the form of scrap by manufacturing processes
Market_Growth_Rate	N/A	Represents the average yearly growth rate of the market's demand for composites during the simulation period
Market_Penetration_of_rComposites	N/A	Represents the extent to which recovered composites can be employed in the applications of FRP
Producer_Awareness_on_Composites_ Demanufacturing	N/A	Represents the portion of the market aware about de-manufacturing pathways
Production_LT	[weeks]	Represents the average time taken to perform the entire production process of composite materials
Relative_Price_of_Collection	N/A	Represents the ratio between the cost of collecting and the cost of disposing EoL composites
Relative_Price_of_Demanufacturing	N/A	Represents the ratio of the cost difference between performing de-manufacturing activities or disposing composites and the cost of producing a virgin composite
Relative_Price_of_rComposite	N/A	Represents the ratio between the price of a recovered and that of a virgin FRP

	Sale_LT	[weeks]	Represents the average time taken to make and organize the activities related to the sale of products
	Uncontrolled_Disposal_LT	[weeks]	Represents the average time taken to get rid of EoL composite materials
Table Function	EoL_Initially_in_Use	[tons/year]	Represents the yearly flow of EoL composites initially in use by the market at the start of the simulation

APPENDIX C – MODEL EQUATIONS

$Awareness\_Correction = Awareness == false\ ?\ pow(Effect\_of\_Relative\_Price\_of\_Demanufacturing\_on\_Demanufacturing\_Rate, -1): 1$

$Awareness\_Correction1 = Awareness == false\ ?\ 0 : 1$

$Awareness\_Correction2 = Awareness == false\ ?\ 0 : Producer\_Awareness\_on\_Composites\_Demanufacturing$

$$Collected\_Composites = \int_0^t Collection\_Rate\_of\_EoL\_Composites + Collection\_Rate\_of\_Scrap\_Composites - Demanufacturing\_Rate - Controlled\_Diposal\_Rate2 - SR\_Demanufacturing\ dt$$

$$Collection\_Rate\_of\_EoL\_Composites = \frac{EoL\_Composites * (Effect\_of\_Relative\_Price\_of\_Collection\_on\_Collection\_Rate\_of\_EoL\_Composites)}{Collection\_LT}$$

$$Collection\_Rate\_of\_Scrap\_Composites = \frac{Scrap\_Composites}{Collection\_LT}$$

$$Composites\_Demand = (\frac{Initial\_Composites\_Demand}{year()}) * pow(1 + Market\_{Growth\_}Rate, time(YEAR)) * (1 - normal() * Demand\_Variability)$$

$$Controlled\_Disposal\_Rate = \frac{Scrap\_Composites * (1 - (Awareness\_Correction1 * Effect\_of\_Relative\_Price\_of\_Demanufacturing\_on\_Demanufacturing\_Rate))}{Controlled\_Disposal\_LT}$$

$$Controlled\_Disposal\_Rate2 = \frac{Collected\_Composites * (1 - (Awareness\_Correction1 * Effect\_of\_Relative\_Price\_of\_Demanufacturing\_on\_Demanufacturing\_Rate))}{Controlled\_Disposal\_LT}$$

$$Demanufacturing\_Rate = \frac{Collected\_Composites * Awareness\_Correction2 * (Awareness\_Correction * Effect\_of\_Relative\_Price\_of\_Demanufacturing\_on\_Demanufacturing\_Rate)}{Demanufacturing\_LT}$$

$$Effect\_Relative\_Price\_of\_Demanufactured\_Goods\_on\_Market\_Penetration) * min((\frac{rComposites}{Sale\_LT}), Composites\_Demand)$$

$$Effect\_of\_Relative\_Price\_of\_Collection\_on\_Collection\_Rate\_of\_EoL\_Composites = \frac{1}{(1 + exp(-K\_Collection * (Relative\_Price\_of\_Collection - 1)))}$$

$$Effect\_of\_Relative\_Price\_of\_Demanufactured\_Goods\_on\_Market\_Penetration = 2 * Market\_Penetration\_of\_rComposites * (\frac{1}{(1 + exp(K\_Consumption * Relative\_Price\_of\_rComposite - 1)))} - 0.5)$$

$$Effect\_of\_Relative\_Price\_of\_Demanufacturing\_on\_Demanufacturing\_Rate = \frac{1}{(1 + exp(-K\_Demanufacturing * (Relative\_Price\_of\_Demanufacturing)))}$$

$$EoL\_Composites = \int_0^t EoL\_flow\_initial\_stock + EoL\_Rate - Uncontrolled\_Disposal\_Rate - Collection\_Rate\_of\_EoL\_Composite\ dt$$

$$EoL\_Rate = delay3(Use\_of\_Virgin\_Composites + Use\_of\_rComposites, Lifetime\_of\_Goods * year())$$

$$EoL\_flow\_initial\_stock = \frac{EoL\_Initially\_in\_Use(getYear())}{year()}$$

$$Expected\_Composites\_Demand = smooth3(Composites\_Demand, Change\_in\_expectations\_LT)$$

$$Expected\_rComposites = delayInformation(Use\_of\_rComposites, Change\_in\_expectations\_LT)$$

$$In\_Use\_Composites = \int_0^t Use\_of\_rComposites + Use\_of\_Virgin\_Composites - EoL\_Rate$$

$$Production\_of\_Virgin\_Composites\_Rate = smooth(max(Expected\_Composites\_Demand - Expected\_rComposites, 0), Production\_LT)$$

$$rComposites = \int_0^t Demanufacturing\_Rate - Use\_of\_rComposites \, dt$$

$$SR\_Demanufacturing = \frac{Collected\_Composites * Demanufacturing\_SR}{Demanufacturing\_LT}$$

$$SR\_Manufacturing = \frac{Manufacturing\_SR * Virgin\_Composites}{Sale\_LT}$$

$$Scrap\_Composites = \int_0^t SR\_Demanufacturing + SR\_Manufacturing - Controlled\_Disposal\_Rate - Collection\_Rate\_of\_Scrap\_Composites \, dt$$

$$Uncontrolled\_Disposal\_Rate = \frac{EoL\_Composites * (1 - Effect\_of\_Relative\_Price\_of\_Collection\_on\_Collection\_Rate\_of\_EoL\_Composites)}{Uncontrolled\_Disposal\_LT}$$

$$Use\_of\_Virgin\_Composites = \frac{Virgin\_Composites}{Sale\_LT}$$

$$Use\_of\_rComposites = Commercial\_Uptake * (Market\_Penetration\_of\_rComposites + Effect\_of\_Relative\_Price\_of\_Demanufactured\_Goods\_on\_Market\_Penetration) * min((\frac{rComposites}{Sale\_LT}), Composites\_Demand$$

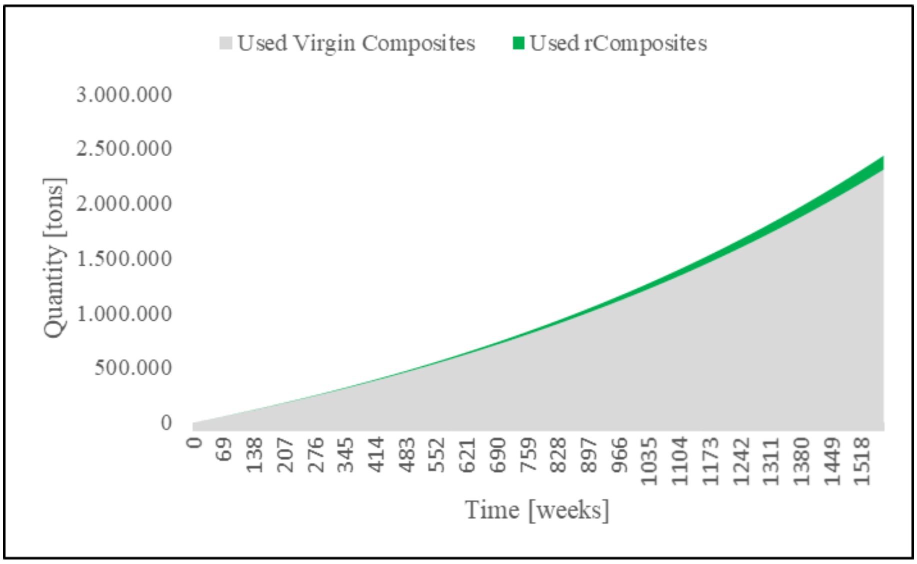
$$Used\_Virgin\_Composites = \int_0^t Use\_of\_Virgin\_Composites \, dt$$

$$Used\_rComposites = \int_0^t Use\_of\_rComposites \, dt$$

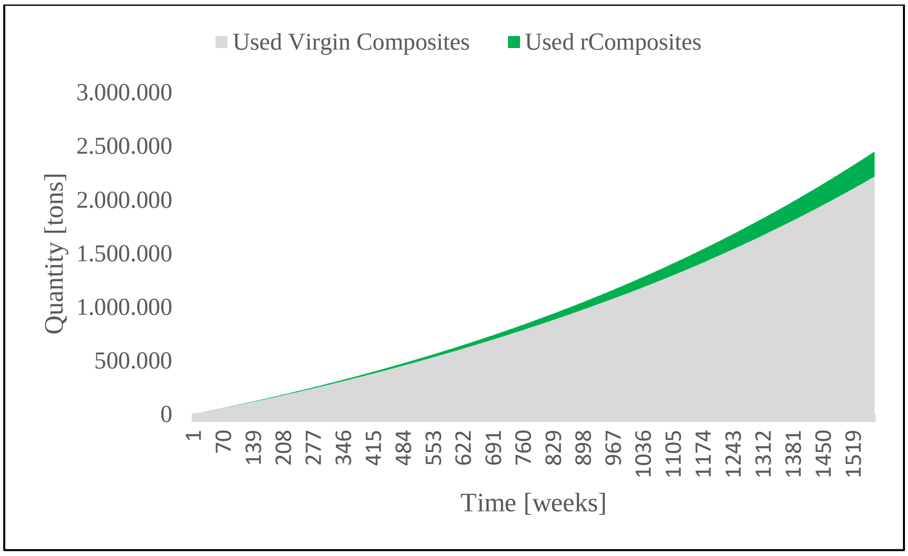
$$Virgin\_Composites = \int_0^t Production\_of\_Virgin\_Composites\_Rate - Use\_of\_Virgin\_Composites - SR\_Manufacturing$$

APPENDIX D – SIMULATION RESULTS

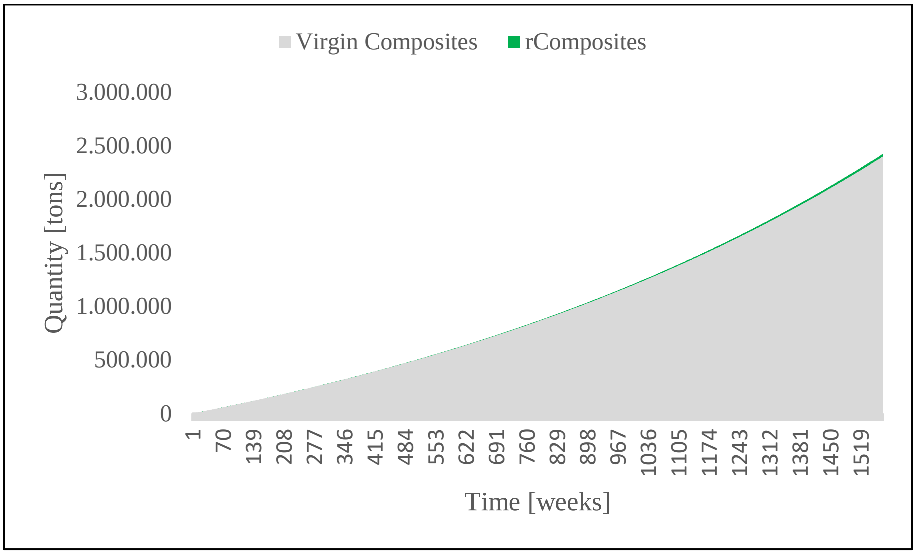
Baseline: CFRP Thermal Recycling



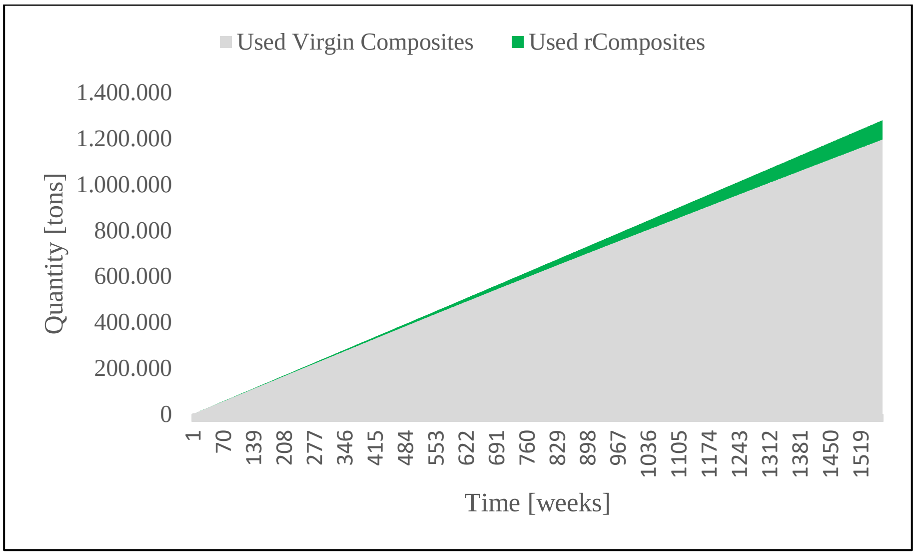
CFRP Mechanical Recycling



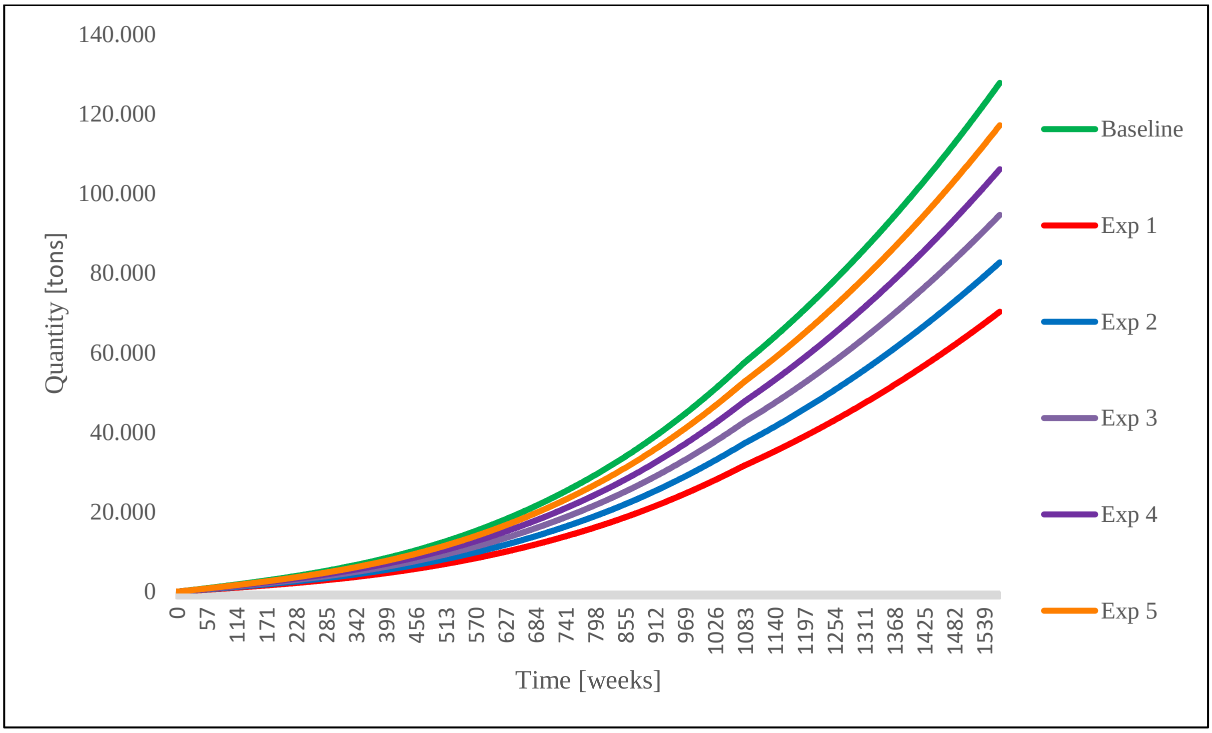
CFRP Chemical Recycling



Fixed Demand

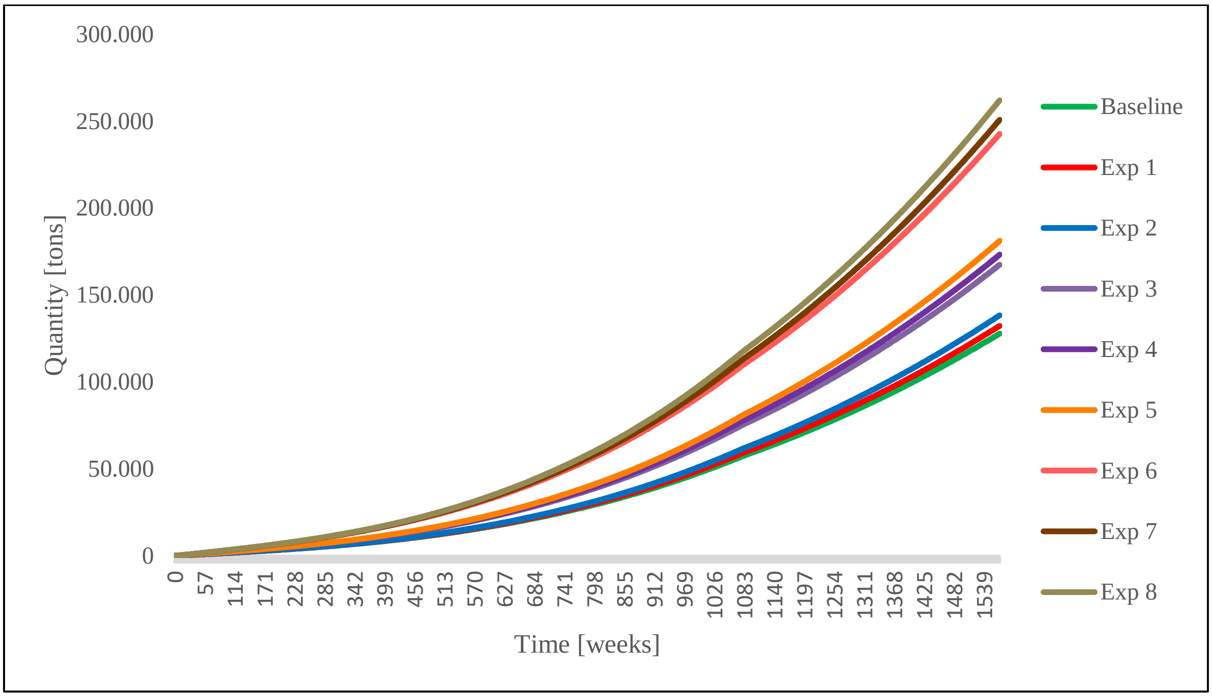


Promotion of De-Manufacturing among Producers



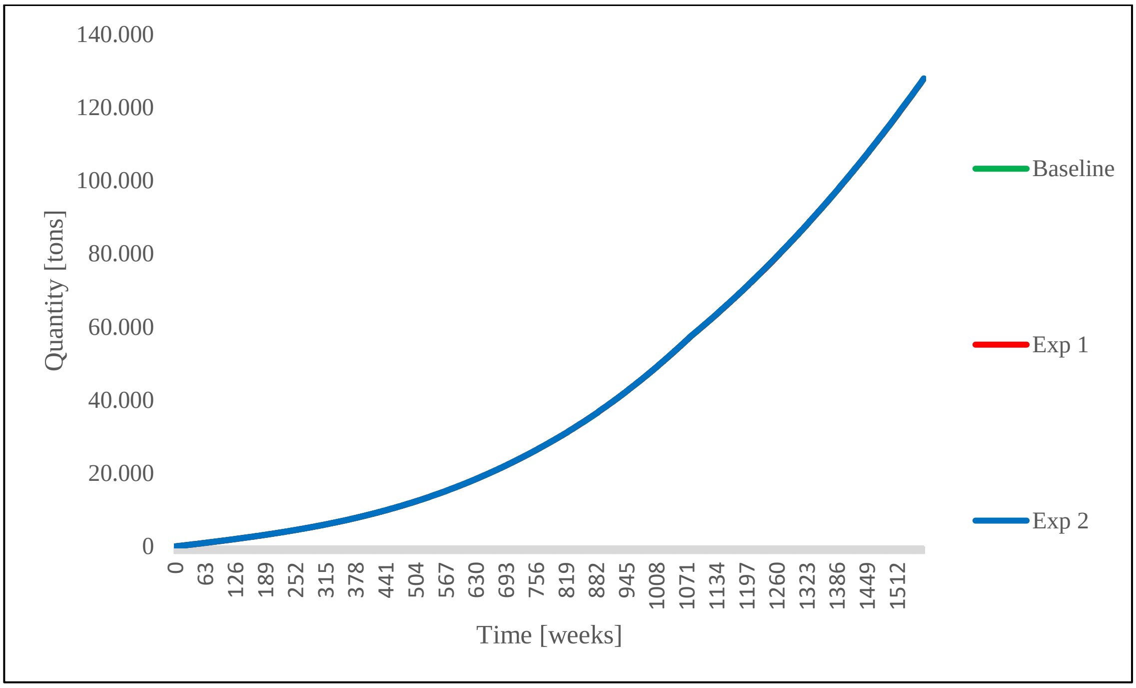
Experiment	Producer_Awareness_on_Composites_Demanufacturing
Baseline	100%
1	50%
2	60%
3	70%
4	80%
5	90%

EPR and EoL Regulation



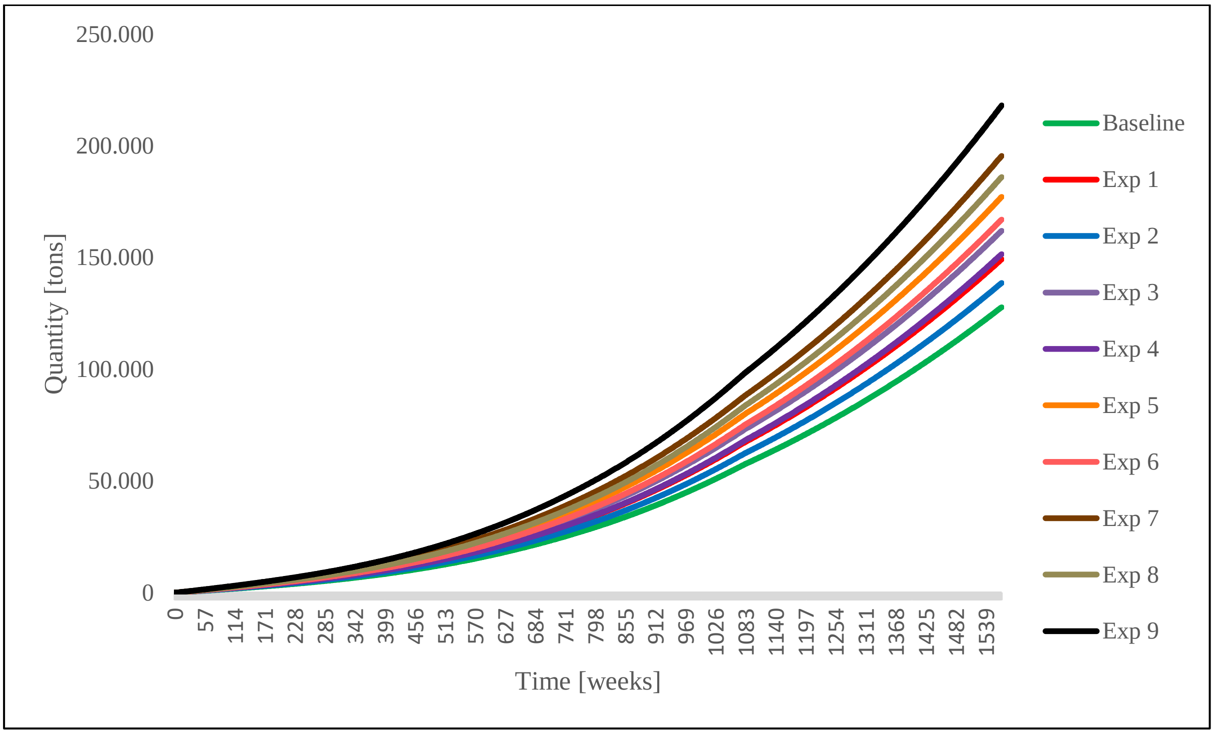
Experiment	Relative_Price_of_Demanufacturing	Relative_Price_of_Collection
Baseline	-0,08197	0,32
1	-0,08197	0,255
2	-0,08197	0,16
3	-0,04918	0,32
4	-0,04918	0,255
5	-0,04918	0,16
6	0	0,32
7	0	0,255
8	0	0,16

Customer Education Activities



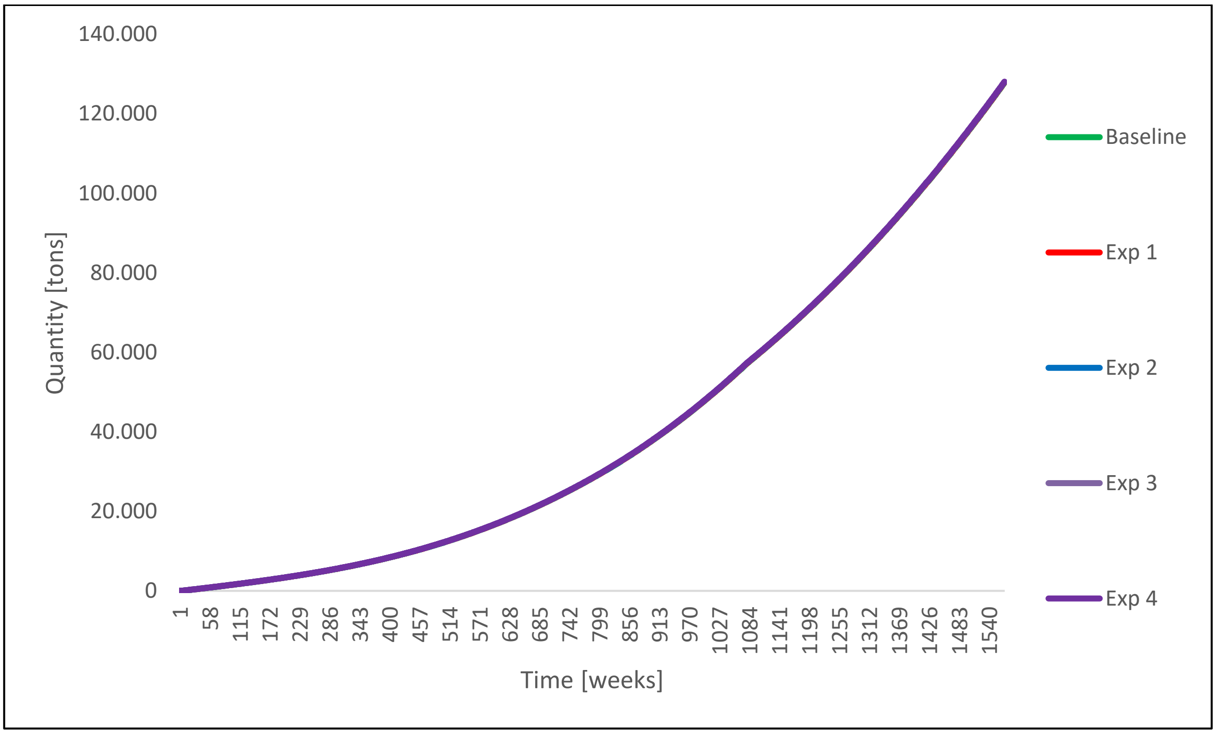
Experiment	Commercial_Uptake
Baseline	60%
1	80%
2	100%

Information Exchange along the Supply Chain



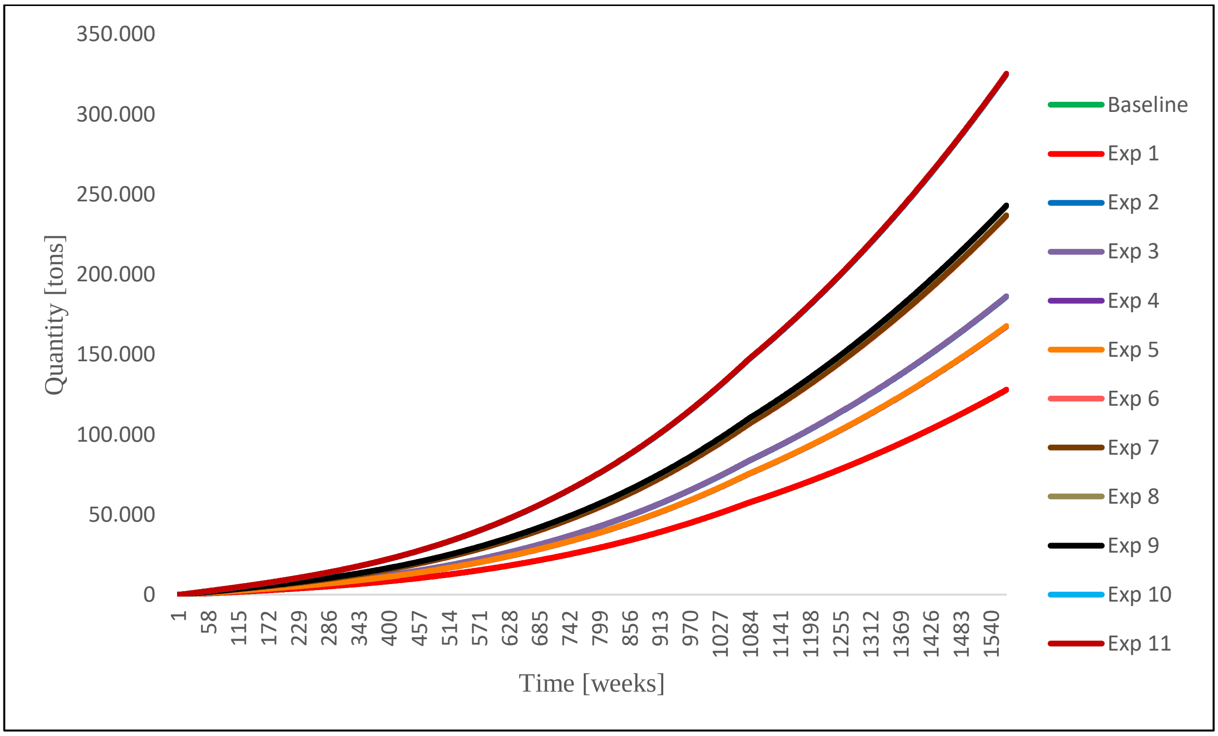
Experiment	Collection_LT	Demanufacturing_LT
Baseline	0,5	1
1	0,3	1
2	0,5	0,9
3	0,3	0,9
4	0,5	0,8
5	0,3	0,8
6	0,5	0,7
7	0,3	0,7
8	0,5	0,6
9	0,3	0,6

Discovery of New Applications



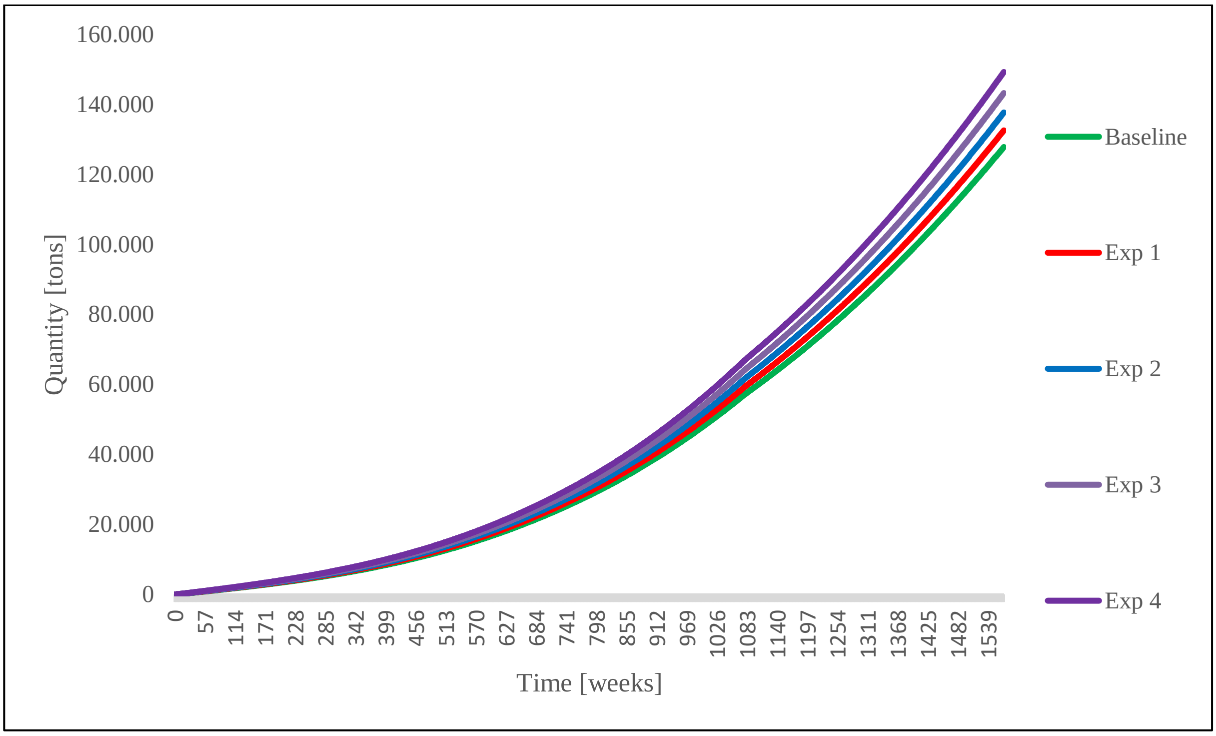
Experiment	Market_Penetration_of_rComposites
Baseline	25%
1	30%
2	45%
3	60%
4	75%

De-Manufacturing Technology Improvement



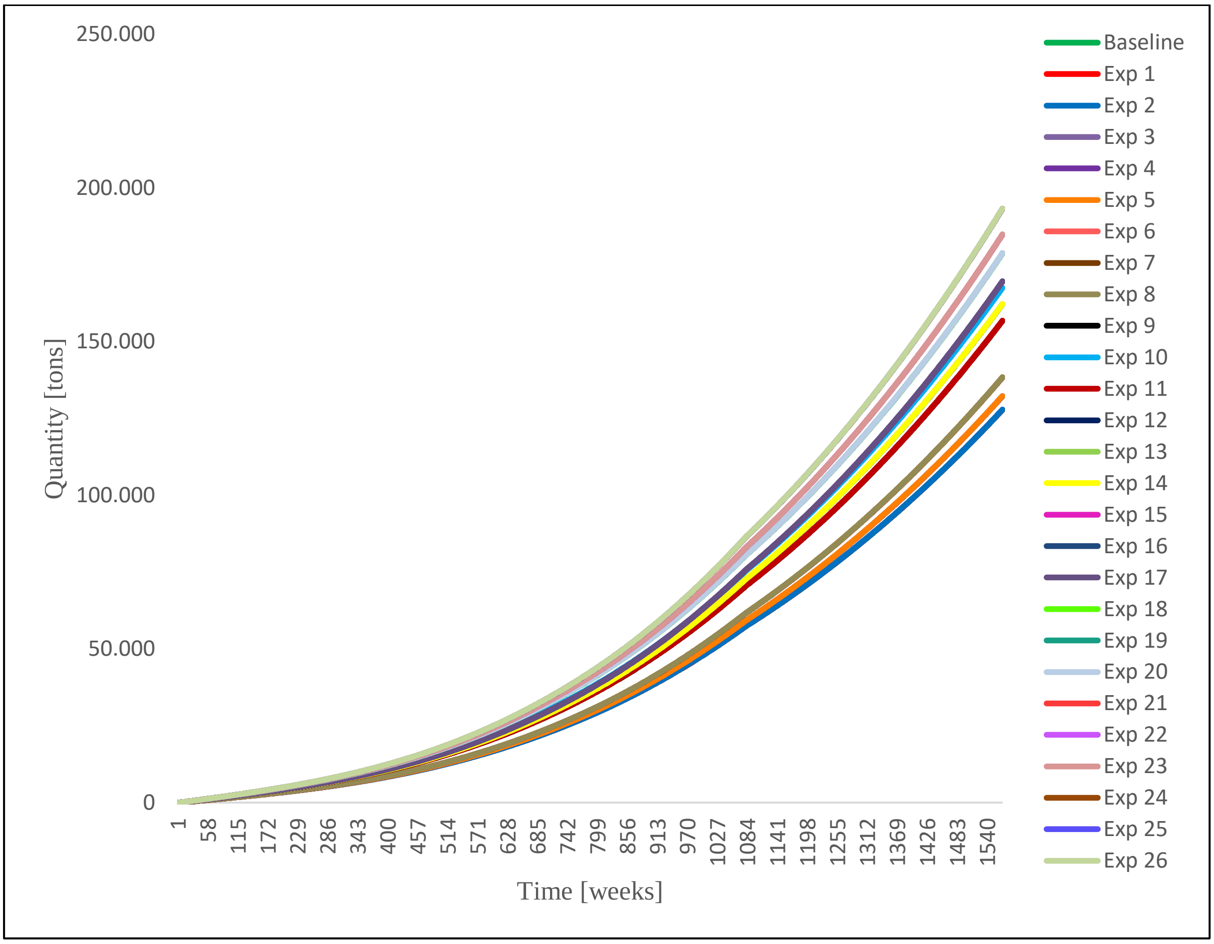
Experiments	Relative_Price_of_ Demanufacturing	Demanufacturing_ LT	Market_Penetration_of_ rComposites
Baseline	-0,08197	1	0,25
1	-0,08197	1	0,5
2	-0,08197	0,6	0,25
3	-0,08197	0,6	0,5
4	-0,04918	1	0,25
5	-0,04918	1	0,5
6	-0,04918	0,6	0,25
7	-0,04918	0,6	0,5
8	0	1	0,25
9	0	1	0,5
10	0	0,6	0,25
11	0	0,6	0,5

Transportation Regulation



Experiment	Collection_LT
Baseline	0,5
1	0,45
2	0,4
3	0,35
4	0,3

Waste Management Practices



Experiment	Relative_Price_of_Demanufacturing	Relative_price_of_Collection	Relative_Price_of_rComposite
Baseline	-0,08197	0,32	0,6
1	-0,08197	0,32	0,48
2	-0,08197	0,32	0,36
3	-0,08197	0,256	0,6
4	-0,08197	0,256	0,48
5	-0,08197	0,256	0,36
6	-0,08197	0,16	0,6
7	-0,08197	0,16	0,48
8	-0,08197	0,16	0,36
9	-0,05738	0,32	0,6
10	-0,05738	0,32	0,48
11	-0,05738	0,32	0,36
12	-0,05738	0,256	0,6
13	-0,05738	0,256	0,48

14	-0,05738	0,256	0,36
15	-0,05738	0,16	0,6
16	-0,05738	0,16	0,48
17	-0,05738	0,16	0,36
18	-0,0410	0,32	0,6
19	-0,0410	0,32	0,48
20	-0,0410	0,32	0,36
21	-0,0410	0,256	0,6
22	-0,0410	0,256	0,48
23	-0,0410	0,256	0,36
24	-0,0410	0,16	0,6
25	-0,0410	0,16	0,48
26	-0,0410	0,16	0,36