POLITECNICO DI MILANO

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Master of Science in Management Engineering

A SYSTEM DYNAMICS MODEL FOR PREDICTING THE EFFECTS OF POLICY ACTIONS ON CIRCULAR ECONOMY BUSINESS MODELS FOR COMPOSITE MATERIALS

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Master Thesis by

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

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“Se chegares sempre onde quiseres, ganhaste”

– Paulo Mendes Campos, *Para Maria da Graça*

ABSTRACT

Fighting climate change is one of humanity's greatest challenges, and requires a new type of organization of the world's economy. Currently, Circular Economy is a paradigm guiding the transition towards more sustainable, circular business models, characterized by closed-loops in the utilization of resources. However, composites represent one material category whose industry is lagging to embrace the principles advocated by the approach, thus still largely reproducing the current linear model in their utilization. This thesis aims to assist the definition of policies encouraging the establishment of Circular Economy business models for composite materials. It seeks to develop a model, grounded on the theory of System Dynamics, to evaluate the effects of different policies in the adoption of composites produced by de-manufacturing processes. For this purpose, it explores the topics relevant to the context, presenting Circular Economy and the concepts it involves, with special attention to de-manufacturing; characterizing composites and their uses; and revising System Dynamics theory. It also investigates the current scenario of the specific industry, providing an overview of the environment related to composites' fabrication. The model generated hosted the simulation of different regulatory scenarios, each containing experiments reproducing the variety of effects that policies can produce. The work shows it is possible to decouple the technical system from the regulatory scenario by using an innovative model environment, and that the effects from policies can be translated into technical elements of the model. The results suggest policies directed to the development of de-manufacturing and collection activities are more successful in the promotion of the employment of composites arising from de-manufacturing processes, and that those focusing on the increase of the demand for these materials have limited benefits for their adoption under present circumstances. The outcomes indicate, therefore, policies such as incentives to the development of de-manufacturing technology and promotion of actions increasing producers' awareness about this pathway should be a priority in policymakers' agenda. Studies further detailing the industry and decreasing the level of aggregation used for its representation can contribute to increase the precision of the recommendations and validate findings connected to the simulations. In addition, the model can be generalized to other sectors and help the implementation of new Circular Economy business models, supporting the transition towards the circular model and assisting in the battle against climate change.

Keywords: Circular Economy; de-manufacturing; composites; policies; System Dynamics

SOMMARIO

La lotta al cambiamento climatico è una delle più grandi sfide dell'umanità e richiede un nuovo tipo di organizzazione dell'economia mondiale. Attualmente, l'Economia Circolare è un paradigma che guida la transizione verso modelli di business circolari, più sostenibili e caratterizzati da cicli chiusi nell'utilizzo delle risorse. Tuttavia, i compositi rappresentano una categoria di materiali la cui industria è in ritardo per adottare i principi propugnati dall'approccio, riproducendo così ancora in larga misura il modello lineare nel loro utilizzo. Questa tesi mira ad assistere la definizione di politiche che incoraggino la creazione di modelli di business dell'economia circolare per i materiali compositi. Essa cerca di sviluppare un modello, fondato sulla teoria di System Dynamics, per valutare gli effetti delle diverse politiche nell'adozione dei compositi prodotti dai processi di de-manufacturing. A tal fine, esplora i temi rilevanti per il contesto, presentando l'Economia Circolare e i concetti che essa comporta, con particolare attenzione alla de-manufacturing; caratterizzando i compositi e il loro utilizo; e rivedendo la teoria di System Dynamics. Indaga inoltre lo scenario attuale dell'industria, fornendo una panoramica dell'ambiente legato alla fabbricazione dei compositi. Il modello generato ha ospitato la simulazione di diversi scenari normativi, ognuno dei quali contiene esperimenti che riproducono la varietà di effetti che le politiche possono produrre. La tesi mostra che è possibile disaccoppiare il sistema tecnico dallo scenario normativo utilizzando un ambiente di modello innovativo e che gli effetti delle politiche possono essere tradotti in elementi tecnici del sistema. I risultati suggeriscono che le politiche dirette allo sviluppo delle attività di de-manufacturing e raccolta hanno più successo nella promozione dell'impiego di compositi derivanti dai processi di de-manufacturing, e che coloro che si concentrano sull'aumento della domanda di questi materiali hanno limitati benefici per la loro adozione. I risultati indicano che politiche come gli incentivi allo sviluppo della tecnologia di de-manufacturing e la promozione di azioni che aumentino la sua conoscenza tra i produttori dovrebbero essere una priorità nell'agenda dei decisori. Studi descrivendo in più dettaglio l'industria e che riducono il livello di aggregazione utilizzato per la sua rappresentazione possono contribuire ad aumentare la precisione delle raccomandazioni e a convalidare i risultati connessi alle simulazioni. Inoltre, il modello può essere generalizzato ad altri settori e aiutare l'implementazione di nuovi modelli di business dell'economia circolare, sostenendo la transizione verso il paradigma e aiutando nella battaglia contro il cambiamento climatico.

Parole chiavi: Economia Circolare; de-manufacturing; compositi; politiche; System Dynamics

EXECUTIVE SUMMARY

Purpose of the Study

The fight against climate change mobilizes efforts from different types in all regions across the planet, but stopping global warming and its hazardous consequences requires the transition towards new economic models, based on environmental sustainability. Therefore, the world must abandon the linear model it follows, guided by the “take-make-dispose” logic, and embrace alternatives that incorporate the sustainability of natural resources in their practices. One of the proposed alternatives for this transition is represented by the paradigm of Circular Economy, which aims to develop an economy powered by renewable energy, in which materials’ use cycles are the longest possible and there is ideally no generation of waste and pollution.

The establishment of a Circular Economy involves a series of additional concepts, one of which is De-manufacturing, described in general terms as the series of operations required for the retrieval and recovery of the materials embedded in products. Thus, de-manufacturing processes encompass multiple stages, each containing several activities, which allow the prevention of the disposal of materials still useful to the economy. Despite available for practically every product, there are still some sectors sluggish in the adoption of this solution for handling the end-of-life phase of the goods they manufacture, resulting in the disposal of items inaccurately classified as waste.

The industry producing composites is one example of the previous situation. Composites, also named fiber-reinforced plastics, are materials usually composed by the combination of fibers and resins. The most common types of fibers used are carbon and glass fibers, whilst in terms of resins polymeric are the most frequent choice. Composites are chiefly valued for being lightweight materials with great mechanical properties, apart from additional characteristics. This type of material is suitable for applications in a wide range of sectors, from aeronautical and automotive to building and energy, and its adoption experienced a steady growth over recent years.

Although widely employed and in expansion in the market, composites frequently end in landfills once they reach the end of their use cycle. Therefore, the amount of composite waste landfilled is expected to increase in the near future unless stakeholders embrace practices that prevent the disposal of end-of-life fiber-reinforced plastics.

Hence, the current situation of this particular industry motivates efforts to prove the feasibility of Circular Economy business models for composite materials, promoting their establishment. This is the background of this thesis, which aspires to evolve into a tool to support policymakers in their regulatory decisions. For this purpose, it pursues the generation of a model that represents the industry based on System Dynamics theory, which will test the effects of regulatory modifications on the environment in which composites are fabricated. To this extent, it will provide relevant insights on the definition of policies for the development of business models for composite materials under Circular Economy's principles.

Current Scenario

Among the different types of composites in the market, glass-fiber-reinforced plastics and carbon-fiber-reinforced plastics are the most popular materials, with market shares around 95% and 2% respectively. Their main client sectors are the construction, energy and transportation, including aerospace and automotive, industries. Accordingly, these businesses also represent those with the greatest potential to be the source of composite waste for de-manufacturing activities.

Currently, the majority of composites reaching the end of their use life follows disposal pathways, with landfilling being the primary solution to handle this type of waste. However, recently this practice has been constricted with some countries prohibiting the landfilling of composites, and others are expected to follow. Therefore, the alternative is the destination of waste flows to de-manufacturing pathways, but there are many issues involved in this choice.

The collection of composites in their end-of-life normally aggregates discarded flows from different sources, increasing the waste mixing level, which hampers activities downstream in the chain such as sorting. Once composites are gathered, different techniques can be used to process the waste flow, but they commonly undergo recycling operations to recover the fibrous content. Despite being the cheapest solution, mechanical recycling considerably damages the fibers, compromising their mechanical resistance. In contrast, thermal and chemical recycling methods are able to recover fibers almost without impairing their mechanical properties, but their costs are significantly higher. Thus, given the low price of glass-fiber composites, mechanical processes usually handle this type of fiber-reinforced plastics, whilst the treatment of those with carbon fibers uses the other techniques, whose costs are inferior to the product's value. Additionally, repair and remanufacturing techniques still require further technological improvement to become competitive alternatives.

Although feasible, the de-manufacturing of composite waste still finds barriers to its implementation. The main ones involve the mindset of stakeholders, which have costs as the paramount concern, and of customers, who consider recovered materials a subclass compared to virgin ones. Moreover, the evolution of these processes still needs the development of new technology and methods to improve their economic performance. Furthermore, current legislation ruling the matter is complex and creates drawbacks to the establishment of business models for managing composites in the end of their use lives.

Notwithstanding, the de-manufacturing of fiber-reinforced plastics provides relevant savings in terms of energy, material consumption and generation of waste. In addition, the introduction of this practices offer several market opportunities to make profit from the recovery of composite waste for stakeholders willing to participate in these activities.

Methodology

To fulfill its goal, this thesis applies the theory of System Dynamics, introduced by J. W. Forrester in the 1950s at the Massachusetts Institute of Technology, in the development of a quantitative model to investigate the effects of policies in the intake of composites originated from de-manufacturing processes.

The modelling procedure involved the collection and analysis of information regarding the composite industry in order to capture its structure, dynamics and the relations between stakeholders. From this stage, the system's Causal Loop diagram emerged, containing the main elements present in the system and the causal relations between them. After the completion of the Causal Loop diagram, the successive stage transformed it into a Stock and Flow map, a more detailed representation of the industry that also served as the structure of the proposed model, developed within the *AnyLogic*© software environment. In sequence, the model received the mathematical expressions for the relations between the elements inside its structure and the values for the parameters, estimated based on literature investigation. Meanwhile, the design of the simulations produced the policy scenarios to undergo testing, formulated from the knowledge generated during the characterization of the industry.

The simulation period used in all the experiments was thirty years, comprehensive enough to accommodate more than one use cycle of composite materials. All the runs occurred in the environment provided by the software *AnyLogic*©. The simulations belonged to one between two possible groups, the first experimenting within the industry's current context and the second testing the enforcement of policies altering the sector's background. Therefore, the experiments allow the comparison of the benefits provided by each regulatory scenario, helping the selection of the most adequate policies to foment the use of de-manufactured composites.

Main Findings

The analysis of the results shows that the introduction of policies is able to contribute with the expansion of the adoption of fiber-reinforced plastics restored under Circular Economy business models. The simulations indicate policies targeting the development of better de-manufacturing and collection activities are more effective in improving the market's intake of recovered composite material. They also suggest that actions benefiting the distribution stage, thus focusing on consumers and on the demand, poorly contribute to the employment of these materials. Furthermore, the work found 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, goals that are more ambitious narrow the spectrum of choices.

The high-level responses achieved allow the establishment of a priority agenda for the policies regarding the composite sector. Measures as incentives to de-manufacturing technology improvement and the promotion of the practice among producers should be the priority of policymakers, since they have stronger effects on de-manufacturing. Following, they should give preference to those that also affect collection, and ultimately, after the development of the reverse loop, the focus should proceed to the issues related to the market's absorption of the materials, for instance, customers' perception about them.

Research Limitations

Providing forecasts of the industry is not the goal of the model, instead, it seeks to offer a basis for the comparison of different policy alternatives, given the system's performance under the scenarios tested.

In addition, the model aggregates the many processes, types of composites and stakeholders in a high-level representation, preventing the evaluation of individual aspects under the environment simulated. Therefore, the assessment is limited to a single de-manufacturing method, type of composite and market of reference at a time. The generalization of the parameters' values found in literature to the sector in general may also result in distortions in the industry's actual scenario.

One of the assumptions made in the modelling phase considered flexible capacity in all of the stages part of the supply chain, since the model operated in the industry level, despite the sector having, in theory, a limit of capacity. Therefore, it does not account for the possibility of exceeding the processing capacity and thus its consequences, which may affect some of the scenarios' results.

Practical Implications

This work provides the basis for the reorientation of the current efforts promoting the establishment of de-manufacturing chains for managing composite waste. The results show that changing the regulatory environment over the industry provides benefits to the use of composites produced by reverse processes. Policymakers may use the information on the sector's behavior when subject to different types of policies to define the measures to implement, basing the actions on the additional knowledge about their potential effects.

Novelty

This thesis proved the feasibility of the decoupling of the technical system from the regulatory context. By 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 ambience regulating it employing a high-level quantitative model. In addition, it is at the forefront of the studies assessing the feasibility of Circular Economy business models for composite materials, and if generalized it can assist the assessment of policy opportunities in other sectors, contributing to the dissemination of Circular Economy and to the fight against climate change.

SOMMARIO ESTESO

Scopo dello Studio

La lotta contro il cambiamento climatico impegna sforzi di vario tipo in tutte le regioni del pianeta, ma per fermare il riscaldamento globale e le sue pericolose conseguenze è necessaria la transizione verso nuovi modelli economici, basati sulla sostenibilità ambientale. Il mondo deve quindi abbandonare il modello lineare che segue, guidato dalla logica del "prendi e butta", e abbracciare alternative che incorporino la sostenibilità delle risorse naturali nelle sue pratiche. Una delle alternative proposte per questa transizione è rappresentata dal paradigma dell'Economia Circolare, che mira a sviluppare un'economia alimentata da energie rinnovabili, in cui i cicli di utilizzo dei materiali siano i più lunghi possibili e non vi sia idealmente alcuna generazione di rifiuti e inquinamento.

La creazione di un'Economia Circolare comporta una serie di concetti aggiuntivi, uno dei quali è il De-manufacturing, descritto in termini generali come la serie di operazioni necessarie per il recupero dei materiali incorporati nei prodotti. I processi di de-manufacturing comprendono quindi più fasi, ciascuna contenente diverse attività, che permettono di prevenire lo smaltimento di materiali ancora utili per l'economia. Nonostante sia disponibili praticamente per ogni prodotto, alcuni settori sono ancora lenti nell'adozione di questa soluzione per la gestione della fase di fine vita dei beni che producono, con il risultato di smaltire articoli classificati come rifiuti in modo impreciso.

L'industria che produce compositi è un esempio della situazione precedente. I compositi, chiamati anche plastiche rinforzate con fibre, sono materiali solitamente composti dalla combinazione di fibre e resine. I tipi di fibre più comuni utilizzati sono le fibre di carbonio e di vetro, mentre in termini di resine le polimeriche sono la scelta più frequente. I compositi sono per lo più apprezzati per le loro grandi proprietà meccaniche nonostante la loro leggerezza, a parte le caratteristiche aggiuntive. Questo tipo di materiale è adatto ad applicazioni in una vasta gamma di settori, dall'aeronautico e automobilistico all'edilizia e all'energia, e la sua adozione ha registrato una crescita costante negli ultimi anni.

Anche se ampiamente impiegati e in espansione sul mercato, i compositi finiscono spesso nelle discariche una volta raggiunto il termine del loro ciclo di utilizzo. Pertanto, si prevede che la quantità di rifiuti compositi smaltiti in discarica aumenterà nel futuro prossimo, a meno che le parti interessate adottino pratiche che impediscano lo smaltimento delle plastiche rinforzate con fibre a fine vita.

Pertanto, l'attuale situazione di questo particolare settore industriale incoraggia gli sforzi per dimostrare la fattibilità di modelli di business a economia circolare per i materiali compositi, promuovendone la creazione. Questo è lo sfondo di questa tesi, che aspira ad evolversi in uno strumento per sostenere i decisori politici nelle loro decisioni normative. A tal fine, essa persegue la generazione di un modello che rappresenti l'industria basata sulla teoria di System Dynamics, che metterà alla prova gli effetti delle modifiche normative nell'ambiente in cui i compositi sono fabbricati. A tal fine, fornirà spunti rilevanti sulla definizione di politiche per lo sviluppo di modelli di business per i materiali compositi secondo i principi della Circular Economy.

Scenario Attuale

Tra i diversi tipi di compositi presenti sul mercato, le plastiche rinforzate con fibra di vetro e le plastiche rinforzate con fibra di carbonio sono i materiali più popolari, con quote di mercato rispettivamente intorno al 95% e al 2%. I loro principali settori clienti sono l'edilizia, l'energia e i trasporti, comprese le industrie aerospaziali e automobilistiche. Di conseguenza, questi settori rappresentano anche quelli con il maggior potenziale di essere la fonte di rifiuti compositi per le attività di de-manufacturing.

Attualmente, la maggior parte dei compositi che raggiungono la fine del loro ciclo di vita segue percorsi di smaltimento, con lo smaltimento in discarica come soluzione primaria per la gestione di questo tipo di rifiuti. Tuttavia, questa pratica è stata limitata, con alcuni paesi che vietano lo smaltimento in discarica dei materiali compositi, e altri sono tenuti a seguire. Pertanto, l'alternativa è la destinazione dei flussi di rifiuti ai percorsi di de-manufacturing, ma ci sono molte questioni coinvolte in questa scelta.

La raccolta dei compositi a fine vita normalmente aggrega i flussi di rifiuti scartati da diverse fonti, aumentando il livello di miscelazione dei rifiuti, che ostacola le attività a valle della catena, come la differenziazione. Una volta raccolti i compositi, si possono utilizzare diverse tecniche per trattare il flusso dei rifiuti, ma essi vengono comunemente sottoposti a operazioni di riciclaggio per recuperare il contenuto fibroso. Nonostante sia la soluzione più economica, il riciclaggio meccanico danneggia notevolmente le fibre, compromettendone la resistenza meccanica. Al contrario, i metodi di riciclaggio termico e chimico sono in grado di recuperare le fibre quasi senza compromettere le loro proprietà meccaniche, ma i loro costi sono significativamente più elevati. Così, dato il basso prezzo dei compositi in fibra di vetro, i processi meccanici di solito trattano questo tipo di plastica rinforzata con fibre, mentre il trattamento delle fibre di carbonio utilizza le altre tecniche, i cui costi sono inferiori al valore del prodotto. Inoltre, le tecniche di riparazione e rigenerazione richiedono ancora ulteriori miglioramenti tecnologici per diventare alternative competitive.

Anche se fattibile, la de-manufacturing di rifiuti compositi trova ancora ostacoli alla sua realizzazione. Le principali riguardano la mentalità delle parti interessate, che hanno i costi come preoccupazione principale, e dei clienti, che considerano i materiali recuperati come una sottoclasse rispetto a quelli vergini. Inoltre, lo sviluppo di questi processi richiede ancora lo sviluppo di nuove tecnologie e metodi per migliorare le sue prestazioni economiche. Peraltro, l'attuale normativa che regola la materia è complessa e crea inconvenienti alla definizione di modelli di business per la gestione dei compositi a fine vita.

Ciononostante, la de-manufacturing di plastiche rinforzate con fibre fornisce risparmi rilevanti in termini di energia, consumo di materiali e produzione di rifiuti. In aggiunta, l'introduzione di queste pratiche offre diverse opportunità di mercato per trarre profitto dal recupero dei rifiuti compositi per le parti interessate che desiderano partecipare a queste attività.

Metodologia Adotatta

Per raggiungere il suo obiettivo, questa tesi applica la teoria di System Dynamics, introdotta da J. W. Forrester negli anni '50 presso il Massachusetts Institute of Technology, nello sviluppo di un modello quantitativo per indagare gli effetti delle politiche di assorbimento dei compositi originati dai processi di de-manufacturing.

La procedura di modellazione prevedeva la raccolta e l'analisi delle informazioni relative all'industria dei compositi al fine di coglierne la struttura, le dinamiche e le relazioni tra gli stakeholders. Da questa fase è nato il Causal Loop diagram del sistema, che contiene i principali elementi del sistema e le relazioni causali tra di essi. Dopo il completamento del Causal Loop diagram, la fase successiva lo ha trasformato in una Stock and Flow map, una rappresentazione più dettagliata dell'industria che è servita anche come struttura del modello proposto, sviluppato all'interno dell'ambiente del software AnyLogic©. In sequenza, il modello ha ricevuto le espressioni matematiche per le relazioni tra gli elementi all'interno della sua struttura e i valori dei parametri, stimati in base all'indagine della letteratura. Nel frattempo, il disegno delle simulazioni ha prodotto gli scenari di politiche da testare, formulati a partire dalle conoscenze generate durante la caratterizzazione del settore.

Il periodo di simulazione utilizzato in tutti gli esperimenti è stato di trent'anni, abbastanza completo da poter ospitare più di un ciclo di utilizzo dei materiali compositi. Tutti i cicli si sono svolti nell'ambiente fornito dal software AnyLogic©. Le simulazioni appartenevano ad uno tra due possibili gruppi, il primo sperimentando all'interno del contesto attuale dell'industria e il secondo testando l'applicazione di politiche che alterano lo scenario del settore. Le sperimentazioni permettono quindi di confrontare i benefici forniti da ogni scenario normativo, aiutando la scelta delle politiche più adeguate per fomentare l'utilizzo di compositi prodotti per i processi di de-manufacturing.

Principali Risultati Ottenuti

L'analisi dei risultati mostra che l'introduzione di politiche è in grado di contribuire con l'espansione dell'adozione di plastiche rinforzate con fibre ripristinate secondo modelli di business circolari. Le simulazioni indicano che le politiche mirate allo sviluppo di migliori attività di de-manufacturing e raccolta sono più efficaci nel migliorare l'apporto del mercato del materiale composito recuperato. Suggeriscono anche che le azioni a beneficio della fase di distribuzione, concentrandosi quindi sui consumatori e sulla domanda, contribuiscono poco all'impiego di questi materiali. Inoltre, il lavoro ha evidenziato una certa flessibilità negli obiettivi di miglioramento, definiti per gli elementi del sistema, per raggiungere il livello di assorbimento desiderato; tuttavia, obiettivi più ambiziosi restringono lo spettro delle scelte.

Le risposte di alto livello ottenute consentono di stabilire un'agenda prioritaria per le politiche relative al settore dei compositi. Le misure come incentivi al miglioramento delle tecnologie di de-manufacturing e la promozione della pratica tra i produttori dovrebbero essere la priorità dei decisori politici, in quanto hanno effetti più forti sulla de-manufacturing. In seguito, dovrebbero dare la preferenza a quelle che riguardano anche la raccolta e, in ultima analisi, dopo lo sviluppo del ciclo inverso, l'attenzione dovrebbe concentrarsi sulle questioni relative all'assorbimento dei materiali da parte del mercato.

Limiti dello Studio

L'obiettivo del modello non è quello di fornire previsioni del settore, ma piuttosto di offrire una base per il confronto di diverse alternative politiche, date le prestazioni del sistema negli scenari testati.

Inoltre, il modello aggrega i numerosi processi, i tipi di compositi e gli stakeholder in una rappresentazione di alto livello, impedendo la valutazione dei singoli aspetti sotto l'ambiente simulato. Pertanto, la valutazione è limitata ad un unico metodo di de-manufacturing, un unico tipo di composito e le caratteristiche di uno specifico mercato alla volta. La generalizzazione dei valori dei parametri riscontrati in letteratura al settore in generale può anche comportare distorsioni nello scenario reale del ramo di attività.

Una delle ipotesi fatte in fase di modellizzazione è stata la capacità flessibile in tutte le fasi della filiera, in quanto il modello operava a livello di industria, nonostante il settore avesse, in teoria, un limite di capacità. Pertanto, non tiene conto della possibilità di superare la capacità di trasformazione e quindi delle conseguenze che ne derivano, che possono influire sui risultati di alcuni degli scenari.

Utilizzi Pratici

Questo lavoro fornisce la base per il riorientamento degli attuali sforzi volti a promuovere la creazione di catene di de-manufacturing per la gestione dei rifiuti compositi. I risultati mostrano che il cambiamento del contesto normativo nell'industria fornisce benefici all'uso dei compositi prodotti da questi processi. I responsabili politici possono utilizzare le informazioni sul comportamento del settore quando è soggetto a diversi tipi di politiche per definire le misure da implementare, basando le azioni sulle conoscenze addizionali sui loro potenziali effetti.

Novità

Questa tesi ha dimostrato la fattibilità del disaccoppiamento del sistema tecnico dal contesto normativo. Utilizzando un ambiente modello innovativo, lo studio ha trasformato le politiche in parametri tecnici, che hanno permesso di separare gli elementi tecnici del sistema dall'ambiente politico che lo regola attraverso un modello quantitativo ad alto livello. Inoltre, è in prima linea negli studi che valutano la fattibilità di modelli di business ad economia circolare per i materiali compositi e, se generalizzata, può essere di aiuto nella valutazione delle opportunità di politiche in altri settori.

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CE – Circular Economy
CFRP – Carbon-Fiber-reinforced Plastics
EoL – End-of-Life
EPR – Extended Producer Responsibility
EU – European Union
FRP – Fiber-reinforced Plastics
GFRP – Glass-Fiber-reinforced Plastics
rComposite – Recycled Composite
rFRP – Recycled Fiber-reinforced Plastics
SCW – Supercritical water
SD – System Dynamics

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CHAPTER 1: INTRODUCTION

1.1. Context and motivations

In recent years, climate change has progressively gained more attention worldwide, being 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, mostly led by the future generations, demanding concrete actions by the nations' leaders towards the protection of the environment. The World Economic Forum's *The Global Risks Report 2020* [32] lists climate change and other related environmental issues among the top five global risks in terms of both likelihood and impact, and reveals that the arrival of the problem's consequences anticipates expectations and causes damages stronger than what forecasts suggested.

To oppose climate change, the development standard underlying the global economy must incur a transformation. There are several approaches intending to guide this process, and one of the most prominent paradigms advocated is Circular Economy, 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. According to the Ellen MacArthur Foundation, one of the actors leading the circular movement, Circular Economy is able to 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 CO_2 emissions related to the production of four key materials, namely steel, aluminum, plastics and cement [6].

A study by McKinsey&Company [18] strengthens the plea for Europe to embrace Circular Economy, since it concluded the net economic benefits of the introduction of Circular Economy's 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's 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.

Among the materials featured before, 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.

Nevertheless, despite the great 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 the combination between plastics and fibers, and find multiple applications in many different economic sectors. Given their huge utilization and its increase, the amount of composites discarded grows every year, but the majority of these waste flows does 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 their impairing may 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, as the mentioned European package foresees the establishment of an enabling policy framework, for example. 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 context and motivations introduced, the present work seeks to develop a model of the composite industry that will allow the generation of insights for the definition of policies encouraging the development of business models for composite materials based on the principles of Circular Economy. Additionally, the study pursues the formulation of a priority guideline for the set of policies capable of modifying the industry's regulatory environment and reality. Hence, this study aims to become a tool for policymakers, which they can use to support their decision-making process when discussing solutions for improving the current scenario regarding the end-of-life of fiber-reinforced plastics.

1.3. Methodology

To achieve its goal, the work first investigates the current context of the composite industry, trying to understand the sector's characteristics and pressing issues. Having gathered the sufficient knowledge, the study uses it as the foundation for the listing of policies for the evolution of the industry. In parallel, it applies the theory of System Dynamics, first proposed by Jay W. Forrester in the 1950s, to build a model representing the industry and its overarching environment, on which simulations designed to test the scenarios modified by policies will occur. Sequentially, the work discloses and discusses the results obtained, providing conclusions and recommendations derived from the data.

1.4. Structure of the work

The work contains five additional chapters, each covering one part of the process presented above, which may include sections and further subsections within their structure. Briefly, *Chapter 2* explores the literature on the topics of relevance for the study, while *Chapter 3* investigates and discloses the main aspects of the composite industry. In *Chapter 4,* it is possible to discover the development process followed to obtain the model, whilst *Chapter 5* offers the results from the simulations and their discussion. Finally, *Chapter 6* provides the conclusions from the work, its limitations and recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

This chapter introduces the theoretic 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 (CE) is one of the current perspectives shaping the transition to a more sustainable growth path towards the future. It is attributed to the Ellen MacArthur Foundation [5] and opposes the present linear consumption model, based on a "take-make-dispose" standard. A Circular Economy is defined as "[…] an industrial system that is restorative or regenerative by intention and design […]" [5, p.7], and has as its building principles [6]:

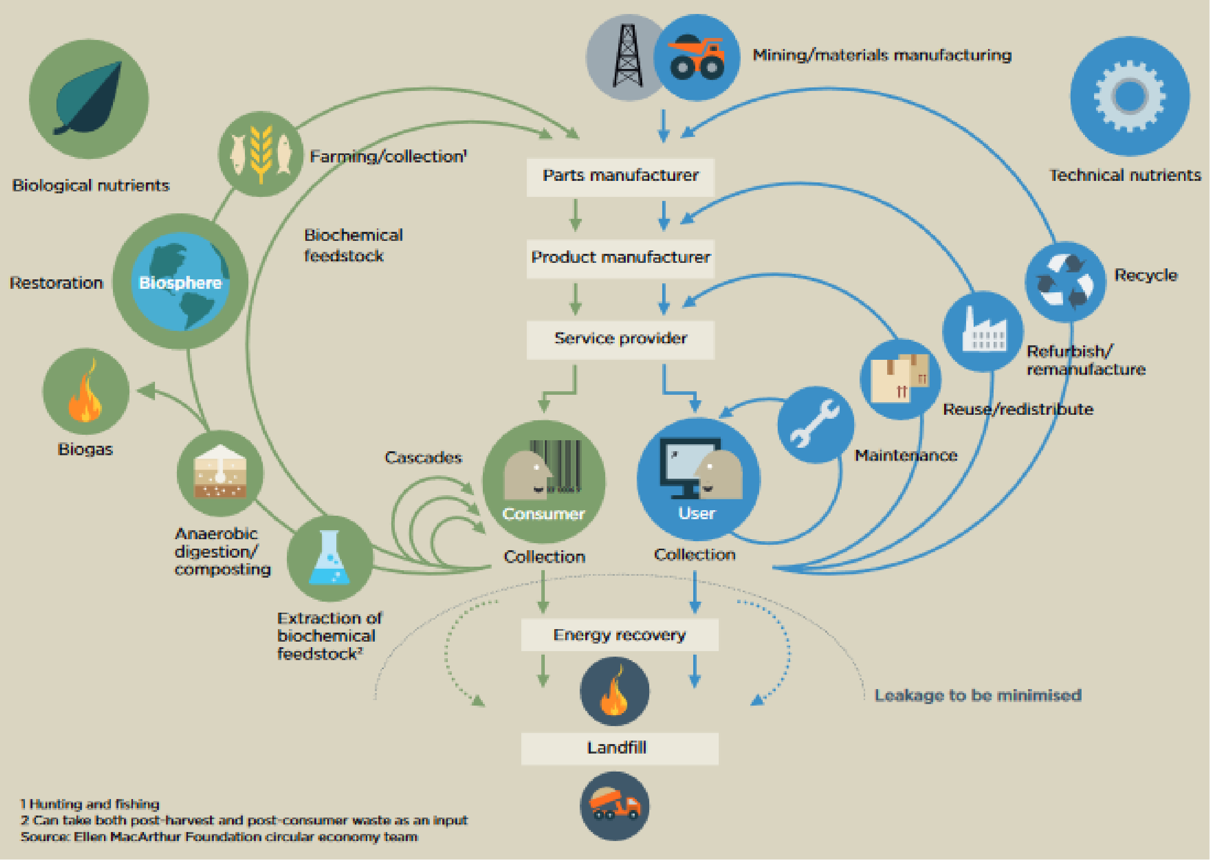
a) Design out waste and pollution: if products are conceptualized within biological and technical materials cycles – biological material cycles referring to the regeneration of biologically based materials and technical material cycles to the recovery and restoration of products, materials and components – considering disassembly and refurbishment, waste does not exist;

b) Keep products and materials in use: products should be designed with the aim of durability, reuse, remanufacturing and recycling, in order to keep them in circulation for many distinct economic uses before their structural elements are returned back to natural systems in proper and safe manners;

c) Regenerate natural systems: the economic system should refrain from using non-renewable sources of energy and resources, preserving renewable ones and enhancing them by supporting natural regeneration when returning nutrients to the biological system.

A scheme of a Circular Economy is shown in ***Figure 1***, 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.

Figure 1 – Schematic view of a Circular Economy



Source: Ellen MacArthur Foundation [5]

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 through which economic value is possibly created. According to Ellen MacArthur Foundation [5], the sources of value creation are called 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 on 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 the earliest possible enables the systems to reap the benefits arising from the effect of virgin material substitution and minimize material use compared 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 related to the linear approach [5].

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 [5].

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 [5].

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 the inflows of reverse processes. These properties can be achieved if products are designed following ease of separation, identification of embedded components, and material substitution standards, among others, as well as if the activities in the 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 [5], [27].

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 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 [5].

In their work, Tolio et al. [27] pointed out the first four schools' contributions to the concept. Regenerative Design, introduced by John T. Lyle[1] in the late 1970s, presented the idea of connecting resource regeneration to sustainable development. Performance Economy, presented by W. Stahel and G. Reday[2], offered the economic basis for a migration towards non-linear industrial models, later adapted to include the notion of Cradle-to-Cradle[3] design, a framework aiming at the creation of waste-free by essence, efficient systems. Finally, the Industrial Ecology[4] idea studied 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 a possible input. They also add as a precursor the work by G. Pauli[5] 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 [5] presents it as a notion developed by J. Benyus[6] that studies natural designs, trying to imitate, transform and apply them to create innovations having nature as their primary inspiration with the goal to eradicate human problems.

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

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[1] LYLE, J.-T. Regenerative Design for Sustainable Development. Wiley Ed., 1996

[2] STAHEL, W; REDAY, G. Jobs for Tomorrow, the Potential for Substituting Manpower for Energy. New York: Vantage Press, 1981

[3] MCDONOUGH, W.; BRAUNGART, M. Cradle to Cradle: Remaking the way we make things. New York: North Point Press, 2002

[4] FROSCH, R.; GALLOUPOLOS, N. Strategies for Manufacturing. Scientific American, 261, 1989. p. 144-152.

[5] PAULI, G. The Blue Economy: 10 Years, 100 Innovations, 100 Million Jobs. New Mexico: Paradigm Publications, 2010

[6] BENYUS, J. Biomimicry: Innovation Inspired by Nature. William Morrow & Company, 2002. 320 p.

as Komatsu Ltd., Knorr Bremse, Bosch, Airbus and Mitsubishi Electric Corporation to mention some [5], [27].

Shifting towards Circular Economy in a sustainable way is presumed to be beneficial in terms of the environment, the economy and the society. Regarding the environmental aspects, it can bring significant savings in raw materials and energy consumption comparing to the traditional linear production of goods, with impacts on 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 business are supposed to create new job vacancies given a rise in consumption of sustainable products due to their more affordable prices [27].

2.1.4. De-manufacturing

The establishment of a Circular Economy, if to attain its goals, requires a group of activities entitled of closing the loop/circle of the system, whose 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 De-manufacturing of products, components and materials are found.

According to Duflou et al. [4, p. 2]

> Demanufacturing can be defined as the break down 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 by means of the collection and reprocessing of material flows, whose origins can be industrial residues or actual products. In general, this task alters materials' characteristics downgrading them, although it is possible to preserve the material quality even after recycling in specific cases [4].

Tolio et al. [27] 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 the 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, with the goal of extending 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 a 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.

In order 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 in 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 system their joint capabilities. The process stages are Materials and functions liberation; Sorting and Separation; End-recovery; Inspection; Reconditioning; and Logistics [27].

Materials and functions liberation normally are processes in the beginning of a De-manufacturing system, and can be divided in 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. In the first, connecting and obstructing components are destroyed partially or completely, while in the second, only the connecting ones are eliminated, and in the third, all the components are preserved. 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, in 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 (composed of more than one type of material), hence it is always a destructive process. Normally, it is used to benefit the quality and feasibility of separation stages downstream [27].

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 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 induce different trajectories in particles according to the value of a property they display; hence, the separation happens by means of 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 [27].

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 [27].

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 [27].

Cleaning processes are essential, since the surface cleanliness strongly influences the capability to execute surface treatments such as inspection, reconditioning, reassembly, painting and finishing, and one 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 [27].

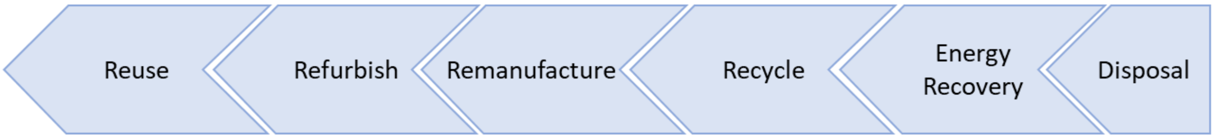
Reconditioning activities restore the features of products, parts and components after the previous stages were executed, and the choice of process depends on the feature to be reconditioned and on the defect type the part exhibits. Although the possible differences in process, they might contain the standard activities of surface and shape defects removal; material addition and deposition; material properties restoration; and surface finishing [27].

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 [27].

In their work, Tolio et al. [27] 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 in the near future 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 2*** 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 cannot be avoided [23].

Figure 2 – Hierarchy of EoL alternatives



Source: Adapted from Seliger [23]

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 than sending goods to landfills, which represents the last remaining option [4].

The adoption of a De-manufacturing strategy has several implications for companies concerning their operations and business models. The main challenges arising from current global trends are [27]:

a) flexibility and reconfigurability;
b) variability of process sequences and processing times;
c) need for Information and Communication Technology solutions and Big Data Management;
d) need for in-line part and materials inspection;
e) need for knowledge-based tools;
f) involvement of the manufacturer;
g) emphasis on business models, inventory and production planning;
h) need for hybrid automation solutions;
i) need for process automation, repeatability and quality assurance;
j) need for human-centric design of disassembly and sorting workstations.

The challenges aforementioned 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 [27].

Tolio et al. [27] argue that modern examples of established Circular Economy business models leverage on the strong participation of the product's manufacturer, which brings crucial information to the De-manufacturing process, and that current models addressing the topic focus only on the product's 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:

a) manufacturing and de-manufacturing systems should be assessed in an integrated approach, focusing on the exploitation of the synergies existing between them;
b) 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, and this higher variability must be tackled and successfully tendered by the system;
c) information flows are of paramount importance in this context, especially those that share design information with the system and/or offer data on the post-use products' conditions;
d) 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 [21] 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. [11] 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, furthermore, 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 are able to 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 [13].

2.2. Composites

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." [20 p. 13]. The report of FiberEUse [8] 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 a 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 [8], [20].

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, as features may not be applicable or even prove to be incompatible depending on the object of assessment and the reasons for its utilization. Moreover, costs and the sustainability of each creation should be analyzed with the entire life cycle as the perspective over views on single activities in isolation [20].

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
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 [20]

2.2.2. Fibers

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 [8], [20].

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 are further differentiations of fibers fabricated with the same material according to their chemical composition, which changes the properties they display such as strength, stiffness, density and chemical resistance. Regarding the length, the main variations are short, long and endless fibers. Short fibers are those whose length is less than 2mm, whilst long fibers have length in the range from 2 to 50mm, and endless fibers refer to those with length over 50mm. The main influence of this aspect is on the composite's mechanical characteristics [8], [20].

Typically, fibers are not only used in isolation, but they can be bundled, resulting in semi-finished products. The most common of those are strands/yarns/rovings, composed of different quantities of fiber filaments; mats, cut fibers, woven-fabrics and laminates; each bundle offering different characteristics, thus suiting distinct applications [8], [20].

2.2.3. Resins/Matrices

The resin, 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 greater distribution of external loads in composites in comparison to fiber bundles, and a higher compression resistance, granted by the resin. Composite's 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 [20].

Thermosets are resins that exhibit no melting behavior when exposed to heat, ultimately disintegrating instead. Upon the most common resins of this type are polyester, vinylester and epoxy. On the other hand, Thermoplastic matrices are those that melt upon heating, making them ductile in high-temperature environments so they can be conformed to desired shapes that are maintained when temperature decreases. Frequently, the fabrication of thermoplastic composites requires high pressure and temperatures, and some common polymers used are polypropylene and polyamide. Worth of notice that the segmentation between thermoplastics and thermosets is ill-defined, as there are cases in which, under specific conditions, one polymer that predominantly behaves in a certain way can exhibit the other type of behavior [8], [20].

2.2.4. 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. A brief description of each process follows [10]:

a) production processes for thermoplastics:
   - injection is the process in which a mold is filled with melted plastic material by using pressure, resulting in a final good that is a replica in shape of the mold after cooling, thus hardening, and detachment from the mold;
   - injection molding compounder is similar to the previous process, but this time compounding and injection molding are performed in concomitance, combining the advantages of both activities;
   - water injection technology is another injection process, which uses water as the pressing agent. The liquid is inserted in the center of the molten resin, pushing the plastic to the boundaries of the mold and leaving the middle of the part void;
   - blanks compression is a molding process that uses a hot compression mold to make pressure on the material, usually in the form of fabrics, obtaining the final part once the matrix has cooled down.

b) production processes for thermosets:
   - resin transfer molding refers to placing semi-finished fibers or a bundle of these in pre-fabricated matching molds, to which the resin is injected using vacuum until it fully embeds the fibers. The use of this technique enables wall thickness precision and high-quality surfaces on both sides of the piece generated;
   - infusion process uses a vacuum bag involving the mold to disperse the resin on the fibers, which were previously laid up dry in between the mold and the vacuum bag;
   - continuous lamination enables the production of panels and sheeting by making fiber fabrics cross a resin bath, after which they are compressed by covering sheets, cured, and controlled for thickness and resin content;

- hand or spray layup can be performed in many forms, and traditionally consists in manually pouring or spraying the resin on the fiber reinforcement fabrics, producing the composite material once the matrix dries.

Fiber-reinforced plastics find several fields of application, including in aerospace, automotive, wind energy, sports and leisure equipment, construction and furniture industries, among many others. 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 [8].

2.2.5. 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 ***Table 1***, 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 most 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 [8].

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 in the categories [8]:

a) landfilling;
b) incineration and co-incineration;
c) thermal or chemical recycling;
d) mechanical recycling.

In Landfilling, products are sent to landfills, in which they are properly buried in an area prepared to receive waste after taken a number of environmental precautions. 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 goal 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 [8].

There are some studies tackling the recycling problem. La Rosa et al. [15] 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. [17] 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 on properties. Therefore, they state there is a need of fiber reclaiming process optimization in order 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. [30] analyze the recovery and disposal pathways for CFRP management and reach interesting conclusions. They claim without regulation, landfill and incineration will continue to be dominant economic choices in CFRP waste management, and continue to suggest there is an economic and environmental conflict in CFRP recycling when techniques with 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[7] during the 1950’s at Massachusetts Institute of Technology, addressing the investigation of complex, non-linear, dynamic systems by means of formal mathematical modeling and computer simulations. 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 often are misled by their mental models to wrong inferences about these dynamics, regardless of the simplicity of the system [25].

Because of the limitations of their mental models, people’s actions do not take into consideration all the possible outcomes, and the efforts applied to solve specific problems frequently create unpredicted side effects. In turn, those side effects generate new problems in the near future, hence, the instruments applied as 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 prior to decision-making [25].

Sterman [25] points that complex systems’ behavior in which the system’s 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:

a) constantly changing: change is always happening inside systems, yet in different speeds, and the distinct time scales can interact as well;
b) tight coupling: all elements inside a system are interconnected even though they may not seem, either among themselves or with the environment, and they all strongly interact;
c) feedback governance: the tight couplings result in subjects’ actions feeding back to themselves, since their decisions change the state of the environment, making others

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[7] FORRESTER, J. W. Industrial Dynamics. Cambridge: MIT Press, 1961

react, which produces further disturbances that will in turn shape the first group's next decisions; feedbacks are the source of dynamics;

d) non-linearity: cause and effect usually are not proportional, local behavior seldom is applicable to distant regions of the system and the system's components can have boundaries;

e) history-dependence: the present state of the system depends on the previous actions taken, and these can be irreversible;

f) self-organization: the internal structure of the system gives birth to its dynamics, in which the feedback structures determine the behavior following any disturbance;

g) adaptation: agent's decision criteria and capabilities evolve over time, some being replicated and others extinguished, and the evolution is not necessarily for the best;

h) trade-off characterized: long-run and short-run responses are different, and usually short-run and long-run benefits occur in antagonism;

i) counterintuitive: cause and effect are distant in time and space, and frequently attention is not directed to root causes but rather to gleaming evidences close to the problem;

j) policy resistant: system's complexity is too great for mental models to handle, thus they are oversimplified by people's minds, resulting in possibly-threatening obviosities.

The reasons behind erroneous decision making in complex, dynamic systems is the misinterpretation of causal relations, commonly built from heuristics incapable of coping with the main sources of dynamic complexity, namely feedbacks, stocks and flows, and time delays, the principal components of SD thinking [25].

2.3.2. Components

The henceforth presentation of System Dynamics' main components is mainly based on the work by Sterman [24], unless stated otherwise.

2.3.2.1. Feedbacks

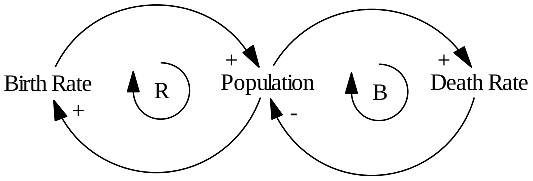
When approaching real word problems, people tend to use an event-oriented view. Observed behaviors are assumed to have a cause, which in turn is the effect of another event that originates from some other fact, in a never-ending, linear, open-loop view of the world. From the recognition of a problem, for example, the mismatch between the state of a given parameter and the goal for it, a number of different actions to solve it can be taken, and after the assessment, selection and implementation of measures, the results achieved are expected to solve the issue. Nonetheless, the previous view assumes the system state remains static after agents' interferences; however, it reacts to the interventions. The system responds to the actions taken, and the results obtained shape the future state, to which agents will be exposed, that will serve as base for the future decisions, in a behavior that constitutes the systems' feedbacks. These responses are not only those planned, but also unexpected ones, which arise as side effects of the measures in place. Moreover, by producing changes in the environment, one agent's actions trigger actions from other agents that will feed back in the state of the system, leading to further moves, and so on, ultimately with the potential to render policies ineffective and to produce unpredicted results. This view of the world, in which events originate from the loops of feedbacks arising as interactions of the agents, can foster the understanding of systems' behavior, changing its image of being unpredictable and uncontrollable.

There are only two types of feedback loops that can shape the dynamics of every 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 own 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 the 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 by variables that are interconnected by arrows with defined polarities, which can be positive or negative. The arrows represent the causal links (cause-effect relations) between the variables, while their polarity displays if they vary in the same direction, defined by the positive sign, or in the contrary, shown by the negative sign. In other words, if when a variable grows the one linked to it grows above what it would otherwise have been, this characterizes a positive link; if it shrinks below what it would have been under different circumstances, this means the polarity is negative. The first variable is called independent variable, whilst the second is referred to as dependent variable. If following a sequence of causal links the variable of origin can be reached as 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 3*** it is possible to observe a simple example of Causal Loop diagram representing the dynamics of population, birth and death rates, which contains both reinforcing and balancing feedbacks. Georgiadis and Vlachos [12] state causal loop diagrams play two main roles in SD, by serving as preliminary drafts of causal hypotheses and by allowing the simplified representation of a model.

Figure 3 – Example of a Causal Loop diagram



Source: Adapted from Sterman [24]

Behind the graphical representations of polarity, there is a mathematical background. Positive links mean the derivative of the dependent variable with respect to the independent is positive, or that the independent adds to the dependent, if the case is an accumulation. Instead, negative links disclose the derivative is negative or that the independent variable subtracts the dependent. Equations ***(1)*** and ***(2)*** show the mathematics behind respectively, positive and negative link polarity, in which the independent variable is denoted by *x* and the dependent by *y*.

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

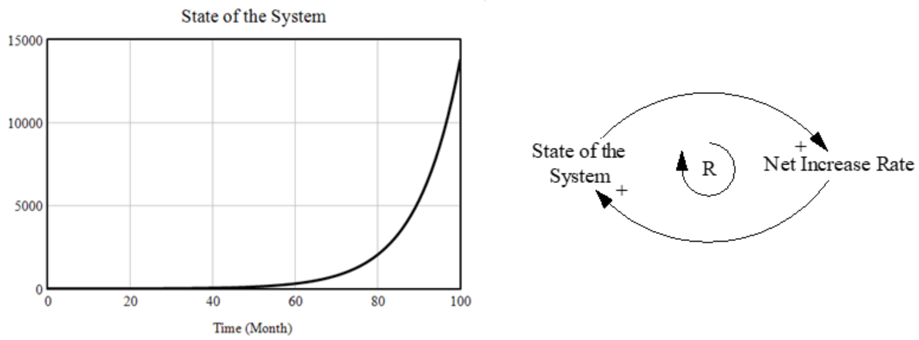
$$\frac{\partial y}{\partial x} < 0 \; or \; y = \int_{t_0}^{t} (-x + \cdots) ds + y_{t_0} \tag{2}$$

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. Additional patterns with higher complexity also derive from these structures, but in such cases, the interactions usually entangle non-linearity.

Exponential growth behavior is a result of self-reinforcing feedbacks, and occurs when the higher (lower) the value of a variable, the greater its net increase (decrease), thus the growth in a quantity leads to an additional rise in its value, boosting even more the pace of its gains, or the contrary. In exponential growth systems, the time interval between two points determines the percentage change of the variable, no matter its absolute value. As clarification, it takes the same time for the variable to double its value, being the change from one to two or from one thousand to two thousands. If observed over short time horizons in respect to its dynamics' pace, exponential growth systems can resemble linear, however, linear growth is rare and only occurs when the state of the system has no influence over its change ratio. Additionally, systems exhibiting exponential growth are usually path dependent, meaning the events that occur during its early history are paramount for determining the end-state they achieve.

There are many real situations that can be represented by exponential growth, such as population growth, investment gains, technological performance, GDP growth, among many others, considered the systems' growth factors only. ***Figure 4*** shows a graphical representation for an exponential growth behavior together with its characteristic feedback loop.

Figure 4 – Exponential Growth behavior graph and feedback structure

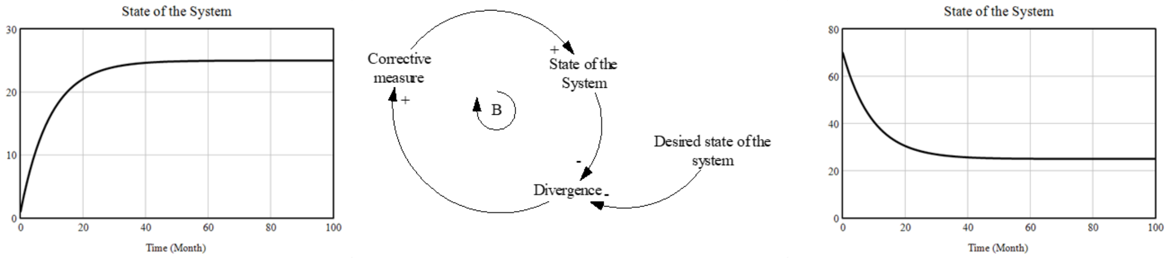


Source: Adapted from Sterman [24]

<u>Goal seeking</u> behavior arises as a combination of positive and negative feedback loops. While the reinforcing ones push increases and changes, and amplify discrepancies, the balancing others steer the system to a desired level. The current state is compared continuously to the goal for it, and if a disparity is identified, corrective actions are implemented until the equilibrium condition is achieved. Normally, the rate of change of the system's state moves in a gradual approach, decreasing when it gets closer to the goal, which can be either explicit or implicit, thus lie or not under the controller's responsibility. The gradual approach is a result of the impact of the size of the gap on the reaction, since huge gaps lead to stronger responses in comparison to smaller gaps. Goal seeking behaviors are observed in both increasing and decreasing forms, in situations such as hunger and eating, tiredness and sleeping, inventory control, coffee cup cooling process etc.

A particular case of goal seeking behavior is exponential decay, which occurs if the corrective response relates linearly to the size of the mismatch. If the latter diminishes, the first follows and is reduced as well. Similarly to exponential growth, in this particular scenario the time between equal percentage variations does not depend on the absolute value of the variable. ***Figure 5*** exhibits an example of a goal seeking behavior feedback structure and its graphical representation, both when the initial state is below (left) and above (right) the desired level.

Figure 5 – Goal seeking behavior graphs and feedback structure



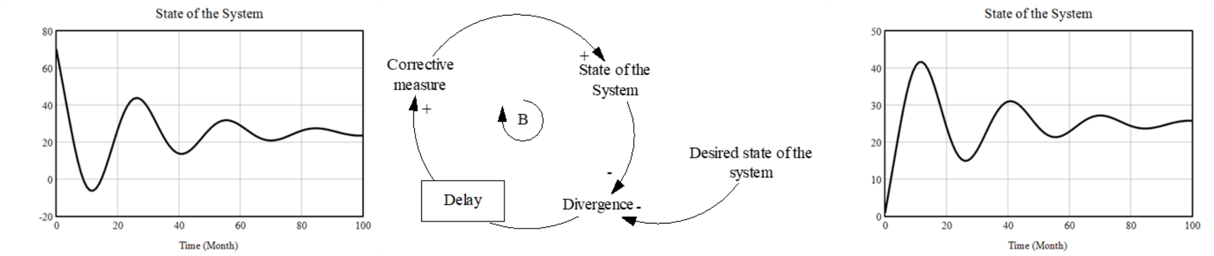
Source: Adapted from Sterman [24]

<u>Oscillation</u> arises due to negative feedback loops containing significant time delays. The functioning of this behavior is very similar to goal seeking systems, however, given the time delays in the negative loops, the corrective measures continue effective for an excessive period, thus the state of the system repeatedly goes above (overshoots) the goal, then reverses and goes below (undershoots) the desired level, only to switch another time, characterizing the oscillation. The feedback structure and its strength, as well as the length of time delays and in which part of the structure they are located determine the kind of oscillatory behavior that will be observed in the system.

It is very common to verify oscillations in real systems, and many of the mentioned cases of the previous behaviors, when observed in the real world, in fact disclose oscillations. Frequently, it is possible to recognize some oscillatory pattern, characterized by a given amplitude, which is the amount of overshooting or undershooting, and certain period, the time it takes to observe a full oscillation cycle. However, these parameters do not render oscillation cycles predictable; they only offer further insights on the system’s behavior. ***Figure 6*** displays a sample of oscillation system’s graph and feedback structure, again, when the initial state is above (left) and below (right) of the desired level.

The three fundamental modes of behavior presented before 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. Sterman [24] provides more details on the mentioned patterns.

Figure 6 – Oscillation behavior graphs and feedback structure



Source: Adapted from Sterman [24]

2.3.2.2. Stocks and Flows

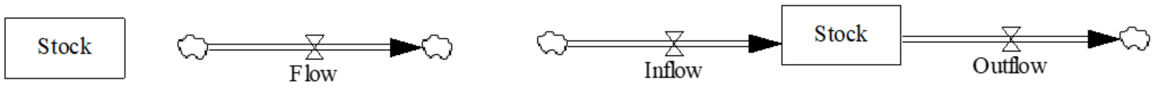
Stocks and flows are, together with feedbacks, key concepts in SD theory. Stocks are defined as accumulations, which describe the state of the system and provide the information base used in decision-making. They grant systems with inertia, memory, and delays, arising as the difference between inflows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

In dynamic systems theory, stocks and flows can be represented by either diagramming or 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 systems, they contain a cloud in their beginning or in their end to disclose this information. Additionally, flows contain valves to highlight the presence of regulators that provide control over them. In ***Figure 7***, 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, stocks are defined as being integrations over time of their flows, which are thus represented as the derivative of stocks over time. Hence, the stock and flow structure can be represented mathematically in two ways, either by an Integral equation or by a Differential equation, respectively shown in ***(3)*** and ***(4)***.

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

$$\frac{d\,Stock(t)}{dt} = Inflow(t) - Outflow(t) = Net\;Flow\;Rate \tag{4}$$

Figure 7 – Diagrammatic representation of Stocks, Flows, and Stocks and Flows structures

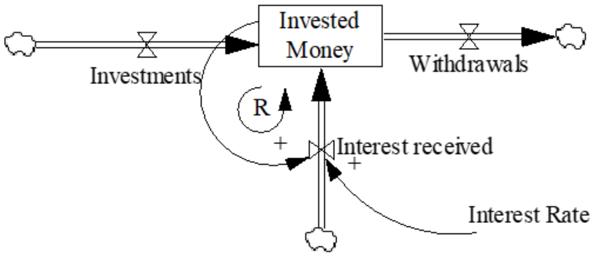


Source: Adapted from Sterman [24]

The distinction between stocks and flows can be facilitated by taking into account the units of measure of these elements. Normally, stocks are measured in quantities, using units such as pieces, people, kilograms, and currencies, while the related flows are expressed in the same units, or in its multiples/submultiples, per time-period arbitrarily defined. Another manner to differentiate between them is to recognize that stocks can be measured without the need of further variables, whilst flows necessarily require additional information, a time interval, for their mensuration.

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 Networks, also Stock and Flow Map. Such 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, thus it should be applied to describe the elements whose patterns are important to the assessed dynamics, in combination with the feedback structure. ***Figure 8*** displays an example of a simple Stock and Flow Network.

Figure 8 – Example of Stock and Flow Network



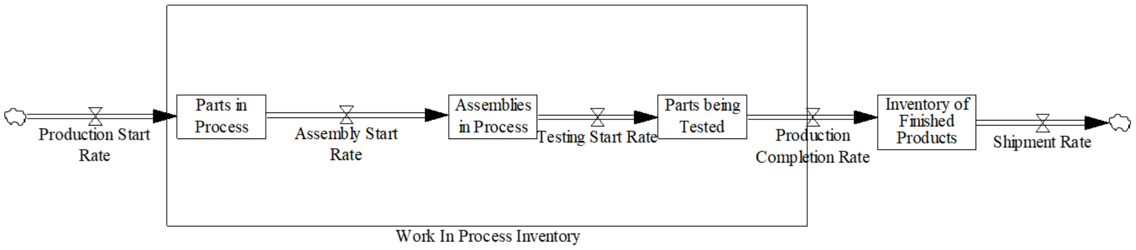
Source: Author's elaboration

The approach taken in SD is called state variable approach or 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, both stocks as well. Constants are state variables that change over time horizons much greater than the one assessed in the model, so their increase is barely noticed, thus enabling their representation with 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. In ***Figure 8***, the variable *Interest Rate* is an example of an auxiliary variable, which is function of an exogenous input, in this case the decisions of the economy's Central Bank. 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 it 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: all inflows and outflows are zero, which is called static equilibrium, or the sum of every inflow and that of every outflow have exactly 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. The amount of change of a stock over time is the integration of the net flow rate, and this is the stock level's derivative with respect to time. Consequently, if the patterns of flows over time are available, it is possible to discover the stocks' behaviors (Equation ***(3)***), and conversely, if the stock levels are known, the net flow rates can be obtained (Equation ***(4)***).

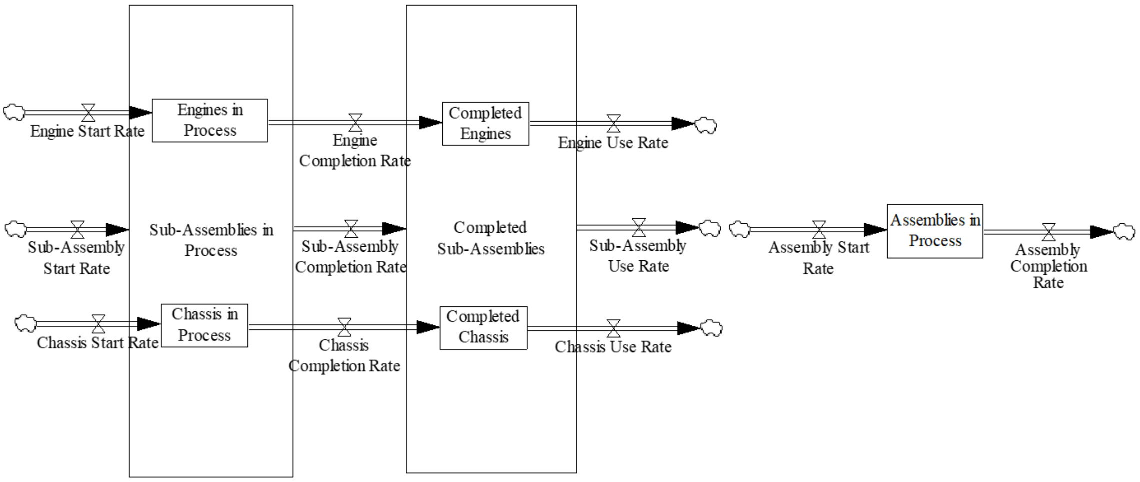
When mapping stocks and flows, the decision regarding their aggregation, both sequential and parallel, must be taken in accordance to the purpose of the model. If the objective is satisfied with the aggregated, higher-level picture, further detailing effort can be saved. Notwithstanding, if the purpose demands a thorough analysis, disaggregation shall be necessary. The choice of aggregation involves mainly two elements: the level of aggregation, which is the number of internal categories or stocks aggregated; and the boundaries for these internal stocks and flows, representing the comprehensiveness of the aggregation over the supply chain. ***Figure 9*** and ***Figure 10*** contain examples of different possible aggregations.

Figure 9 – Example of Sequential Aggregation



Source: Adapted from Sterman [24]

Figure 10 – Example of Parallel Aggregation



Source: Adapted from Sterman [24]

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 by only one stock (thus first-order) and flows whose equations are linear combinations of the state variables and exogenous inputs (linear), that is, weighted sums of these variables. 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 is goal seeking or exponential decay. If multiple loops are combined and non-linearity is present, behaviors that are more complex can be observed, such as S-shaped growth. Worth of note that oscillation behavior cannot happen in first-order systems, just from second-order ones onwards, given the need of the net flow rate to alternate between positive and negative values for it to occur, which only is possible if the system involves more than one state variable.

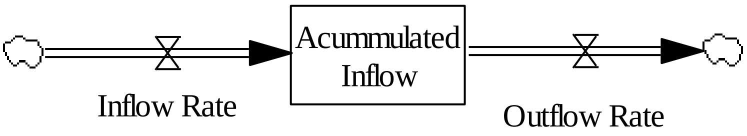
2.3.2.3. Time delays

Time delays are one major source of dynamics in almost every system, and can be either threatening, when creating oscillation and instability, or fruitful, when filtering out noise, for the assessment of the system's behavior. They are frequently observed in real processes, since it takes time not only to decide about actions to be taken and implement them, but also for the system to respond to the interferences. Time delays are procedures whose output laggardly trails the input in 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, hence physical units move through the delay so it must conserve the flow, since the items leaving the delay stock can only do so if they have previously entered it. 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 11***. 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, the capacity of a delay can be considerably greater than the inflow up to a point in which 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 the awareness about the processes' average residence time (or average delay time), defined as the average time a unit spends inside the delay, and how the output is distributed around it.

Figure 11 – Stock and Flow Structure of a Material Delay



Source: Adapted from Sterman [24]

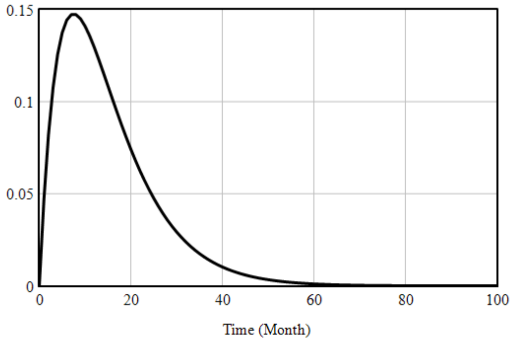
The output's distribution around the average residence time is influenced by the specific activities originating the time delay. The order of the units leaving the stock, which can affect their residence time, is determined by the service rule adopted for the processing of items by these activities, for example, a First-In First-Out or a Last-In First-Out discipline. Even though service rules are applied, the processing of multiple items by many operators along different stages often results in mistakes in the order of items, introducing a degree of mixing between the units that affects their average residence time as well. Not only the changes in order can affect the average residence time, but also the processing times of the activities may do so, since they can differ across individual units, altering the time these spend inside the delay, once again introducing mixing.

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 does not distinguish between the units' residence time to determine their exit, but only on the amount 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, however continuing to be respected, classified as Higher-Order material delays, frequently arising when delays involve many sequential processing stages, each introducing some degree of mixing. The order of these delays is defined by the approximation of the number of stages involved in the processing, each one represented by a first-order material delay. Hence, a third-order material delay, for example, represents the delay of a three-stage process and is defined as the sequential combination of three first-order material delays, in which the input of the delay next in the sequence is the output of the previous one. This cascaded combination produces results in which the output is distributed around the average residence time in a curve that initially rises up to a peak, falling after that, as shown by the example in ***Figure 12***.

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

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

Figure 12 – Output distribution of a Second-Order Material Delay following a pulse input

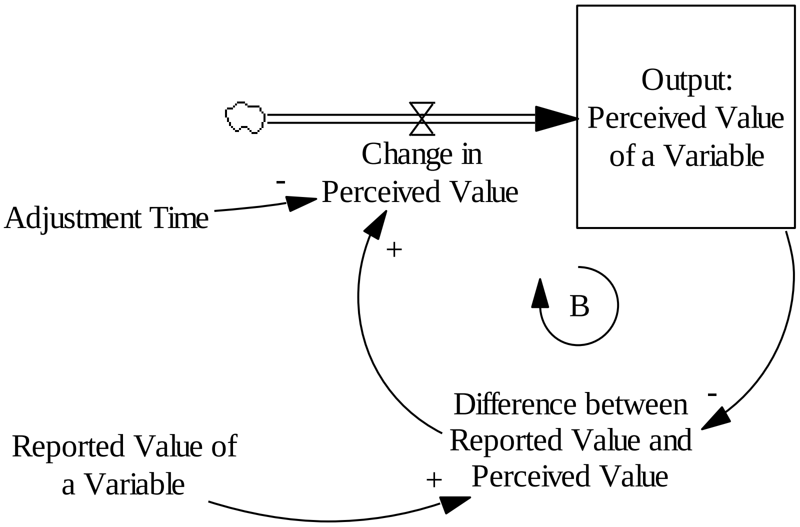


Source: Adapted from Sterman [24]

Regarding information delays, the stock and flow structure used in their description, depicted in ***Figure 13***, is different from that of material delays, since the firsts involve flows of information rather than materials and thus conservation of the inflow to the delay is not applicable. The simplest and one of the most widespread information delay structure used to model the refinement of assumptions given the availability of new information is Exponential smoothing or 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.

Differently from material delays, in which the delay's stock was the accumulation of input and its output a flow, in information delays the output is the stock itself, considering that an opinion or perception is already a state of a system, in this case a state of mind. 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 introduces delays in systems because the error between the inference and the real value is corrected over a period of time, not immediately, smoothening temporary changes and avoiding overreacting to them; its mathematical expression is the one in ***(7)***.

Figure 13 – Stock and Flow Structure of Adaptive Expectations



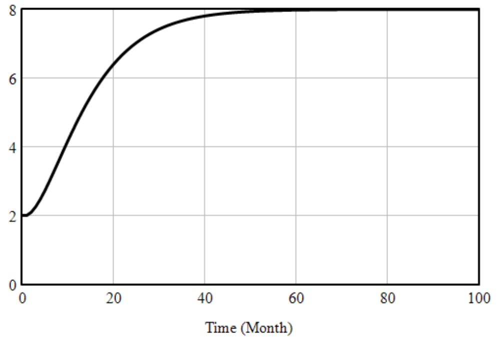
Source: Adapted from Sterman [24]

$$Change\ in\ Perceived\ Value = \frac{Reported\ Value - Perceived\ Value}{Adjustment\ time} \tag{7}$$

Similarly 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, additional ways of modeling information delays may be used, including pipeline and higher-order information delays. In a pipeline delay structure, the output, or the reported value, is the observed value lagged the reporting delay; it is described by the expression in ***(8)***. Moreover, reporting procedures are generally composed by multiple stages, each introducing a certain degree of smoothing. Consequently, higher-order information delays, which contain a cascade of first-order structures, one for each stage, 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 14*** shows an example of it.

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

Figure 14 – Output distribution of a Second-Order Information Delay following a Permanent Change in the Observed Value



Source: Adapted from Sterman [24]

An additional aspect that should be considered when modeling delays regards the delay time, which can be constant or variable. In case delay times vary, this can happen endogenously, when the delay time depends on the state of the system, or exogenously, if it responds to exogenous factors. The response of material and information delays to a variation in delay times 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 cases assessment and policy interaction effects observation. Although it seems a cascaded process, modeling is iterative. Therefore, downstream steps may generate the need of upstream changes in the model, a loop fed by additional knowledge and information about the system.

System Dynamics' models find innumerous applications in the real world and are used in many different contexts. Nassehi and Colledani [19] 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 amount 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. [22] 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 high-level of aggregation. In their study, Trailer and Garsson [28] 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 [24], [25] presents a series of practical applications of SD theory in occasions such as vehicle leasing, epidemics spreading, and technology adoption, among many others.

Regarding elements within the Circular Economy's perspective, Wang et al. [31] 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 to the conclusion that combining different policies provides better results to the system under analysis. Poles [21] models remanufacturing under System Dynamics to evaluate strategies aimed at improving a production system. Zamudio-Ramirez [33] investigates the economic aspects related to automobile recycling in the United States of America using SD, the same country analyzed by Taylor [26], 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. [3] develop a model to comprehend the impacts generated by regulations focused on cleaner production in the context of the Chinese electroplating industry. At last, Georgiadis and Vlachos [12] use System Dynamics to assess decision making in the context of reverse logistics, and in Vlachos, Georgiadis and Iakovou [29] they adopt it for studying remanufacturing capacity planning in a closed-loop supply chain situation.

CHAPTER 3: METHODOLOGY

This chapter provides a deeper description of the Composite Industry’s current scenario, covering its characteristics, practices and trends, with the spotlight on the present CE context. The inquiry’s information bases mainly on the findings displayed by project FiberEUse [7], [8], [9], [10] or develops from them, unless differently indicated, and is segmented in six different sections: Industry Overview; Waste Source Sectors; Processes; Market Opportunities; Barriers; and Regulatory Aspects.

3.1. Industry Overview

As previously mentioned, two types of fibers – glass and carbon – mainly dominate the FRP market. GFRP are 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 around 2%. However, it may be only a regional issue, since the causes behind it are mainly production migration, thus in the worldwide aggregation the trend may have continued. The main consumers of GFRP in Europe are the sectors of Construction and Infrastructure, with a 36% market share, Transport, representing 34% of the market, Electro and Electronic, detaining 15% of market’s figures, and Sports and Leisure, destination of 14% of the production. Regarding the fabrication methods employed, the most widely adopted processes is 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-pace growth trend, and continuous processes as well, of approximately the same 12% [2].

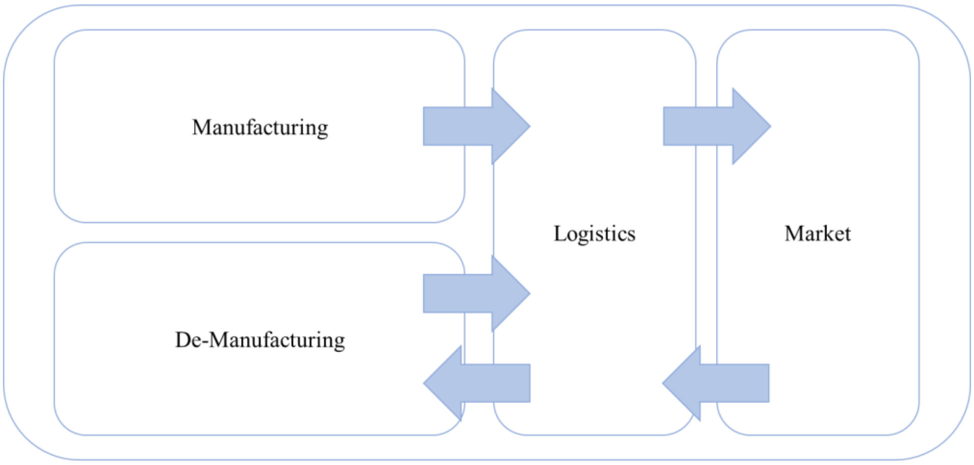
Regarding CFRP, global demand in 2019 was forecasted at 141.500 tons, a 10,1% expansion in comparison to the previous year, representing between 1-2% of the global market for FRP. Europe accounted for approximately 27% of the market in terms of demand, but regarding production capacity its stake falls 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 [1], [2], [7], [8], [14].

Composites are adopted in many different components particularly because of their combination of low weight and great mechanical properties, which positions these materials as great substitutes for metals in applications requiring mechanical resistance, replacement that is even intensified by their resistance to corrosion. Furthermore, FRP are durable materials, 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.

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 latters 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. With reference to recovered fibers, the figures for those made of glass and of carbon are, respectively, 1,35€/kg and 6€/kg.

The players operating in the industry can be classified as members of one of the groups contained in ***Figure 15***, which provides an overview of its major activities, with the arrows symbolizing the flows of material between them, thus linkages. 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. Some examples of companies operating in each of the activities may be useful for the understanding; not necessarily all the mentioned enterprises 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, 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 Market [9].

Figure 15 – Overview of the industry's stakeholders and material links



Source: Author's elaboration

3.2. Waste Source Sectors

Predictably, the sectors configuring the main clients of the Composite Industry's forward activities are also the main sources of waste flows for its reverse processes. The Transport sector, embracing automotive, aviation and marine industries, to mention a few, 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 by fibers, content expected to double by 2020, and the 2016 European production of cars reached 16 million units. This numbers show a current market potential of around 128.000 tons/year of composites disregarding the growth, or 256.000 tons/year if the predictions of expansion are true; 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.

Another important source of composite waste lies in the Construction and Infrastructure sector, whose refuses 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 include landfilling and incineration with energy recovery. In 2020, the volume expectation is around 50.000 tons of these materials, with shares of 70% for glass fibers and 30% for carbon fibers.

Moreover, there are additional inflow possibilities for de-manufacturing processes coming not from EoL materials, but from industrial waste and production scrap. In an internal survey among the partners of the consortium, FiberEUse [8] 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 its 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.

3.3. Processes

The establishment of a supply chain for composite materials under Circular Economy's perspectives provides 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. The great mixing level in these flows, characterized by containing different materials with different characteristics, generates additional problems, as the most adequate methods to apply for processing distinct materials may vary from one another. Hence, the present organization of the collection activity increases the need of sorting in the system and can make it more intricate, though sorting is always necessary in 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 having a significant influence on the price of the final regenerated product.

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 in the near future. 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.

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

Reiterating, in mechanical recycling the flow is submitted to size-reduction procedures, including crushing, milling, shredding, in order to obtain fine grains or a powder than can be reused in other applications. Yet, before that, it can go through additional sorting procedures for the separation and extraction of specific constituents. Such particles can find different destinations, for example, one possibility is their introduction in cement kilns, especially if dealing with glass fibers, which is also the recommendation of the European Composite Industry Association for that case. In this way, the mineral components of the fibers are absorbed into the cement clinker, and the energy recovery procedure helps in reducing the CO_2 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 powder makes it a potential reinforcing agent to insert in other composites, which is normally done by adding it as filler in compounds used in 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.

Thermal recycling in mainly performed by means of 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 the new matrix.

In relation to 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. 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 normally the route for carbon fiber composites because of the better preservation state of fibers' properties achieved by these processes, which provides the output of the recycling process higher commercial value.

Concerning repair and remanufacturing, there is still the need of further technology improvement and validation if they are to compete against other pathways. Both activities could leverage a lot on advancements in inspection operations, since nowadays 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.

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 of raw materials, succeeded by those arising from de-manufacturing, avoiding the purchase and thus the related capital requirements. In addition, without the need of the same quantity of virgin materials, there is a predicted reduction up to 70% in the energy consumption associated to 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%.

3.4. 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, which consists in FRP waste from industries characterized by high standards for composites’ mechanical properties be used, after de-manufacturing processes, in different sectors for applications that require an inferior level of mechanical resistance. In this way, materials once considered as 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 must shift their positioning in stakeholders’ mindsets from an incurred cost to a company’s asset.

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 those business are created, firms can use them for their own benefit and yet become a service provider for the market. In this way, they would be able to increase the processing flows thus compensate 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 generating 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 its 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.

3.5. Barriers

The former sections already glimpsed some of the existing barriers regarding the institution 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 may 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. They would have to change their behaviors adapting to the new circumstances, not to mention eventual training efforts, which would represent additional costs to the enterprise. 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, and the related boundaries and limitations are still unclear, factor that limits leadership and definition of integrated strategies for innovation, and raises the risk the investor must bear thus inhibiting their 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 sector regarding the search for funds and pricing methodologies. The latter aspect force players to compete against each other for the scarce resources under undefined basis, a combat that is detrimental for the whole sector advancement.

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. 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 and 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 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. 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, which boost the development of circular solutions, opposing the belief.

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 the prosperity of these chains, hence, establishing communication mechanisms is foremost. Stakeholders' appeals regarding composites must loom amid of a lack of priority in legislators' agendas even though plastics are in the spotlight of discussions, a scenario that discourages agents from engaging in composite de-manufacturing activities.

3.6. 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 are general legislations on waste handling that must be followed by stakeholders operating in the industry within the block's territory.

The main standard currently in place is the European Directive on Waste (2008/98/EC) that provides fundamental concepts and definitions regarding the management of waste flows. It offers definitions for waste, discerning it from by-products, and for processes related to its processing, as recycling and recovery. However, it poorly embraces remanufacturing activities and does not go in depth on technical aspects with the provision of 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 than can be landfilled as an EoL option 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 of 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 the low margins.

The abovementioned directives are eventually complemented by country- and region-specific rules, the levels enforcing the employed 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 concurrently 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. This could lead to higher availability of flows to de-manufacturing systems and better sorting, increasing their efficiency, as well as educate people on opportunities arising from waste, maybe changing their perceptions about EoL materials and about the products they originate.

CHAPTER 4: MODEL DEVELOPMENT

This chapter 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 on 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 in two sections, namely Model Structure and Simulation Scenarios.

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 cancelled by adopting 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 variation in input parameters between the two simulations.

4.1. 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 materials are disposed after their use phase despite the possibility to reenter the market if processed by de-manufacturing supply chains within Circular Economy business models. The trouble around this practice, which allows classifying it as problematic, rests on the loss of all the value embedded in these materials once adopted the disposal pathways, on the generation of waste and on the need to commit additional resources, such as raw fibers, resins and energy, on the fabrication of new composites, otherwise spared.

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 the listing of 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 FRP lifecycle, started. Since usual composite's use life does not exceed 25 years, the time horizon decided for a model's run was 30 years.

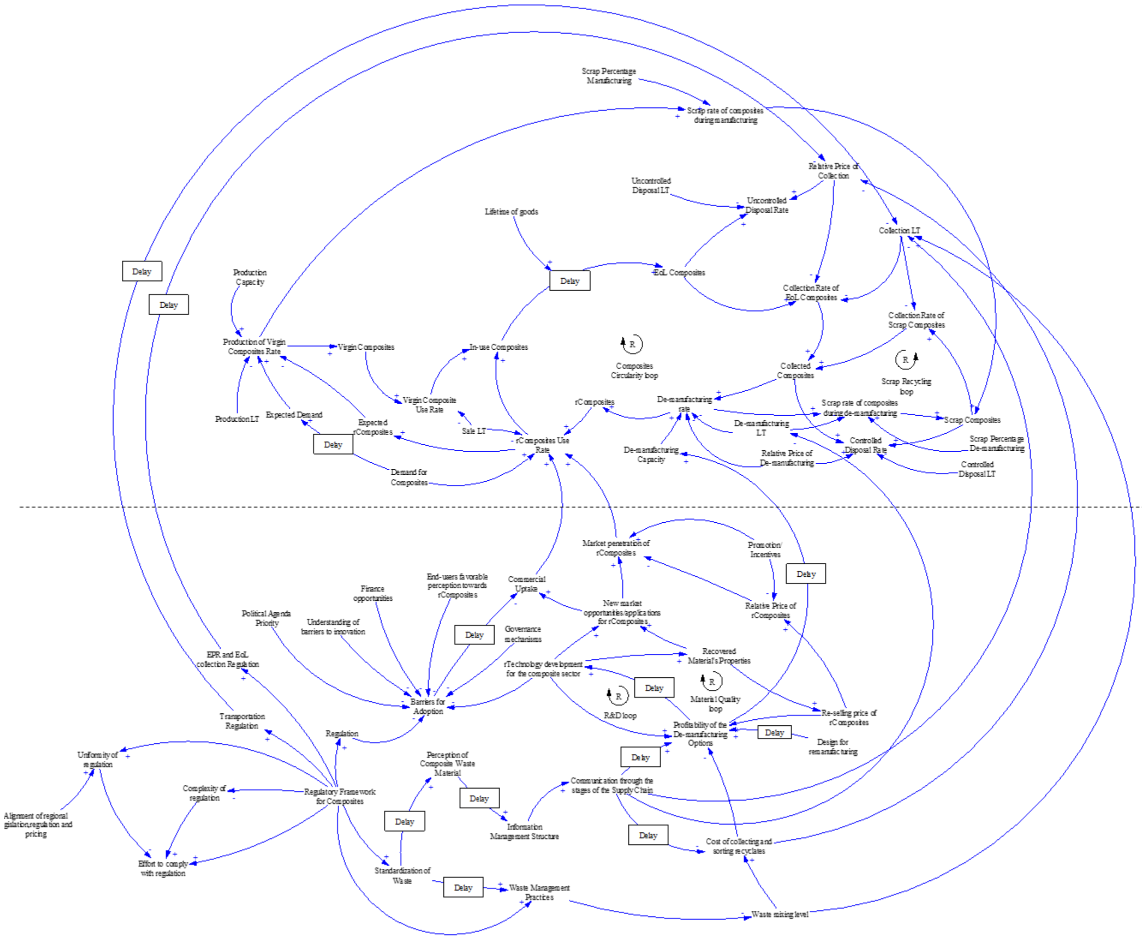
The increase in knowledge about the system's modes of operation and characteristics enabled the beginning of the representation of the verified actual causal relations and feedback loops. In parallel, as the causal structure became clearer it allowed the formulation of initial explanations for the undesired behavior, based on the information about the industry. Maybe, composite materials do not enter de-manufacturing chains because producers and the agents who get these products prior do their disposal are unaware of this opportunity for this kind of waste. If not the case, perhaps these goods follow other pathways because Circular Economy business models for their processing are economically unviable or unattractive given the related costs. It might be that the issue is not on manufacturers but on the recycled product itself, which may not be fit for the applications it had before reaching the EoL phase, or even that the customers are the ones to blame given their unwillingness to consume recycled composites. Broader approaches can attribute accountability to current legislation, which complicates the handling of waste materials thus delaying the processes required for de-manufacturing to occur, or still to the lack of regulation and incentives in some areas critical to the prosperity of Circular Economy business models.

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, whose many aspects shall be thoroughly discussed, was developed with the help of *Vensim® PLE* software and can be seen in ***Figure 16***.

4.1.1. Causal Loop diagram

One of the first elements grabbing the viewer's attention is the traced line that divides the diagram in 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 scrutiny, starting by the technical system's components and then moving on to the regulatory environment's elements. ***Appendix A*** shows the two parts of the diagram separately to increase their comprehension.

Figure 16 – Causal Loop diagram

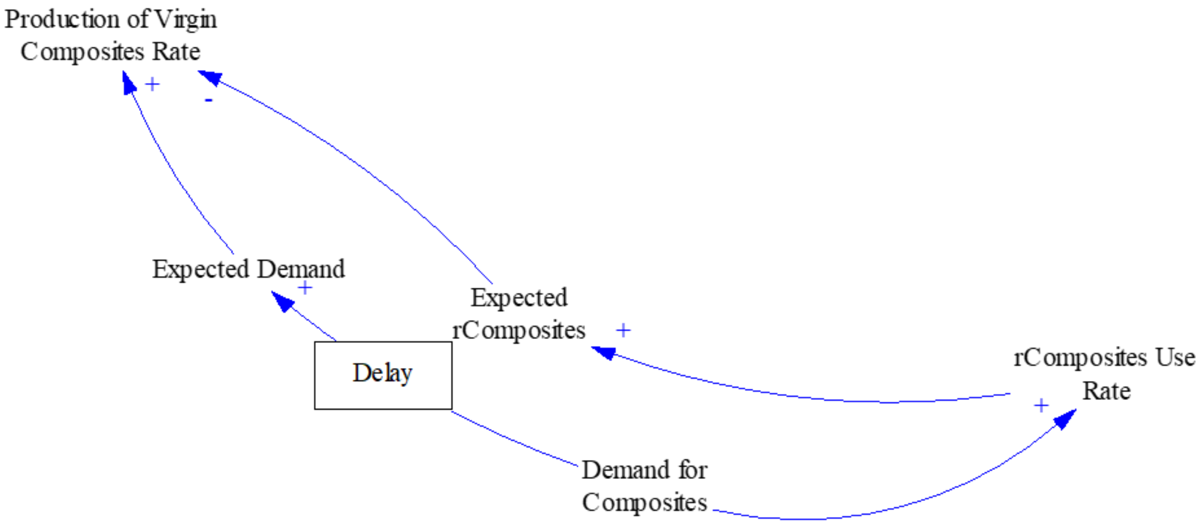


Source: Author's elaboration

The technical system part of the model can be divided in two smaller subsystems that interact with each other. The first is the demand subsystem, shown in ***Figure 17***, which aims to represent the effect demand has on the other variables present and how it shapes the dynamics observed.

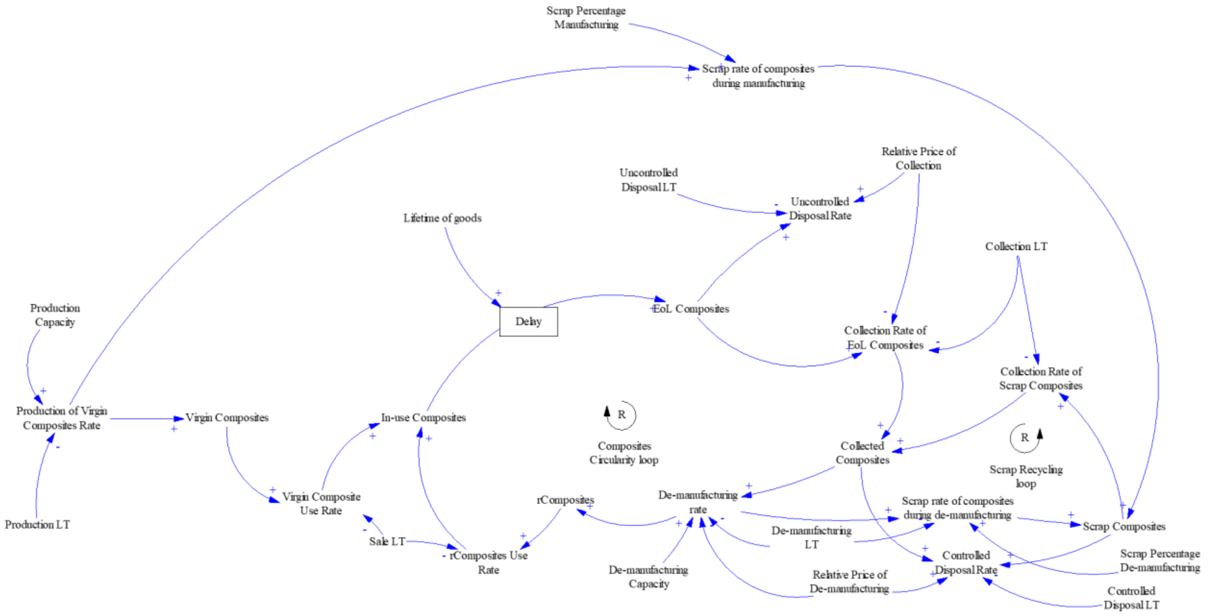
The second subsystem, depicted in ***Figure 18***, displays the composite's entire production chain, in which there are the parameters and elements that integrate both linear and circular perspectives and the identified causal relations between them, in an attempt to elucidate the system's ways of working and thus enable the understanding of the behaviors it demonstrates.

Figure 17 – Demand Subsystem



Source: Author's elaboration

Figure 18 – Production Subsystem



Source: Author's elaboration

In the demand subsystem, the demand for composites over time, *Demand for Composites*, was considered an exogenous factor. In turn, the demand influences manufacturers' expectations of demand, illustrated in *Expected Demand*; however, as expectations do not change immediately upon new demand figures, this effect embeds a delay. Additionally, *Demand for Composites* also affects the rate of use of recycled composites, shown in *rComposites Use Rate*, which alters agents' expectations regarding the speed at which recycled composites enter the market, captured by *Expected rComposites*. When deciding how much of new composites to produce at a time, manufacturers base their choices on these expectations not to exceed market's capacity of absorption and hence remain with stocks; thus *Expected Demand* and *Expected rComposites* affect *Production of Virgin Composites Rate*. The links between this subsystem and its production peer lie in the relations of the demand subsystem with the rates of production of either recycled or virgin FRP.

Regarding the production subsystem, the *Production of Virgin Composites Rate* also responds to the *Production Capacity* and to the lead-time required for manufacturing, expressed by *Production LT*, apart from its responses to the previous factors. This rate of production will affect the amount of newly fabricated composites available, shown by *Virgin Composites*, as well as the rate of scrap material originating from manufacturing activities, represented by *Scrap rate of composites during manufacturing*, which given the average scrap loss during manufacturing, *Scrap Percentage Manufacturing*, alters the quantity of scrap composites in the market, depicted by *Scrap Composites*. The availability of virgin composites allows their use in the fabrication of goods, thus there is a link from this variable to the one expressing the usage of these materials, *Virgin Composite Use Rate*, which is also affected by the lead-time taken to organize the transfer, named *Sale LT*. The rate at which these goods enter the market alters the amount of composites currently employed in the many fields of applications possible, symbolized by *In-use Composites*, which after their use life, represented by a delay affected by their lifetime, *Lifetime of goods*, reach their EoL state, represented in *EoL Composites*.

The presence of composites in the end-of-life phase favors both their uncontrolled disposal and their collection. Normally, the first is practiced by end users who do not know the proper destination for FRP and was included in the diagram under the name of *Uncontrolled Disposal Rate*, which reacts to the lead-time required for that activity, *Uncontrolled Disposal LT*. Collection, represented by *Collection Rate of EoL Composites*, reacts as well to an activity-specific lead-time, *Collection LT*. The option for one or another depends mainly on the price comparison of the two alternatives, thus the relative price between them, represented in *Relative*

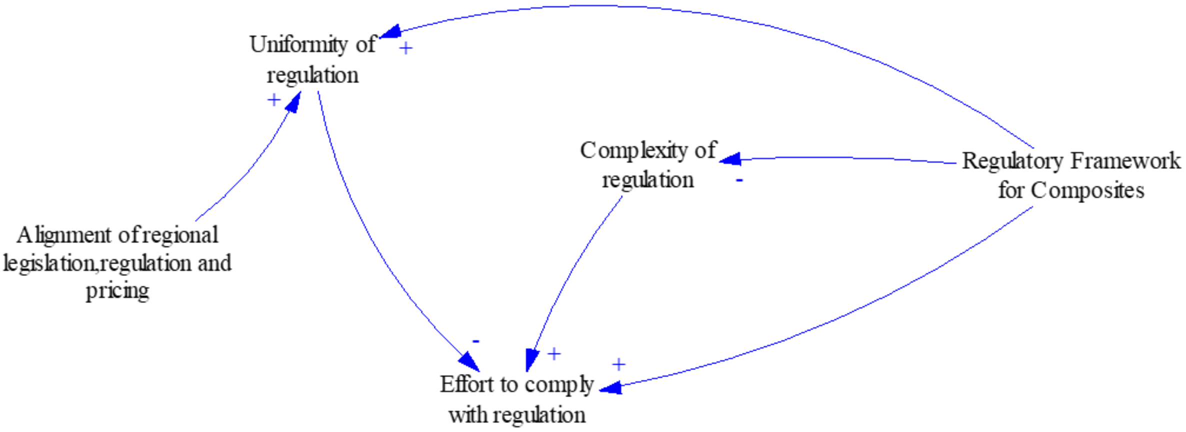
Price of Collection, impacts on these practices. The pace at which goods are collected affects the amount of collected items, *Collected Composites*, which is also influenced by the collection of scraps, *Collection Rate of Scrap Composites,* that in turn depend on the amount of scrap composites, mentioned before.

Once collected, composite materials can trace two different pathways: either being controllably disposed, pictured by *Controlled Disposal Rate,* or entering de-manufacturing processes, captured in *De-manufacturing rate*, that aggregates all the activities within de-manufacturing; the availability of materials interferes in the quantity they process. Another time, the choice is governed by the difference in the prices of these activities, hence the two variables respond to *Relative Price of De-manufacturing*. Both activities, again, are impacted by lead-times, respectively *Controlled Disposal LT* and *De-manufacturing LT*. The introduction of de- and remanufacturing activities, alike manufacturing, incur in losses of material while operating, which generates a new scrap flow that adds to the levels of scrap composites present in the market. To represent the flow the diagram uses *Scrap rate of composites during de-manufacturing*, which has its speed regulated by the de-manufacturing lead-time and depends on a specific scrap percentage, *Scrap Percentage De-manufacturing*, representing the ratio of materials rejected by de-manufacturing processes as leftovers or because of poor quality. Analogously to collected composites, scrapped composites can follow controlled disposal or collection routes, previously explained, and thus has links to these elements. If they are collected, there is the formation of a loop regarding scrap recycling/de-manufacturing, evidenced in the diagram as *Scrap Recycling loop*.

In addition to the relative price and the lead-time, the de-manufacturing activity rate is constrained by, thus depends on, the capacity of de-manufacturing systems, considered in *De-manufacturing Capacity*. Undergoing the previous step modifies the quantity of recycled composites available in the market, *rComposites,* since they originate from these activities; this availability has impacts on the rate at which they are employed in applications by the market, represented by *rComposites Use Rate,* that adds to the total quantity of FRP being used, *In-use Composites*. This last link closes a second loop in the system, representing the path of a composite that underwent use, collection, and de-manufacturing stages, gaining a further use cycle after these procedures; the highlighted circular loop in the composite's production subsystem received the name *Composites Circularity loop*.

In relation to the second part of the Causal Loop diagram, which refers to the regulatory environment, it also contains subsystems inside its structure, particularly, policy compliance, barriers for adoption, and regulatory frameworks and their effects subsystems. Concerning the policy compliance subsystem, shown in ***Figure 19***, it describes the implications of rules for the stakeholders that must adhere to them. Once there is a regulatory framework regarding a specific subject, in the case composite materials, represented in the diagram by *Regulatory Framework for Composites*, it consolidates the management of the target aspect with a specific set of rules contained in the document's clauses, which combines the current enforceable norms, spread over different decrees, and new ones under an unified scheme. Thus, the presence of regulatory frameworks decreases the complexity of regulation since it consolidates all the necessary aspects related to the subject, so there is a causal link between *Regulatory Framework for Composites* and *Complexity of regulation*. Moreover, as such scheme also aggregates the existing dispersed rules, they contribute to an increase in the uniformity of regulation over a given territory; therefore, these frameworks are linked to *Uniformity of regulation* in the diagram. Nonetheless, by pursuing alignment efforts when designing regional legislation, regulation and pricing standards, it is also possible to achieve a higher degree of consistency between distinct regions' regulatory systems; representing this feature is the link between *Alignment of regional legislation, regulation and pricing* and *Uniformity of regulation*. In order to comply with the enforced rules, stakeholders have to devote resources and time, thus there is an effort associated to the process of compliance, illustrated by *Effort to comply with regulation*, which is influenced by the previous elements, namely the existence of regulation schemes, their uniformity and their complexity, which justifies the presence of causal relations connecting them. This subsystem unites with the rest of the system in the element *Regulatory Framework for Composites*.

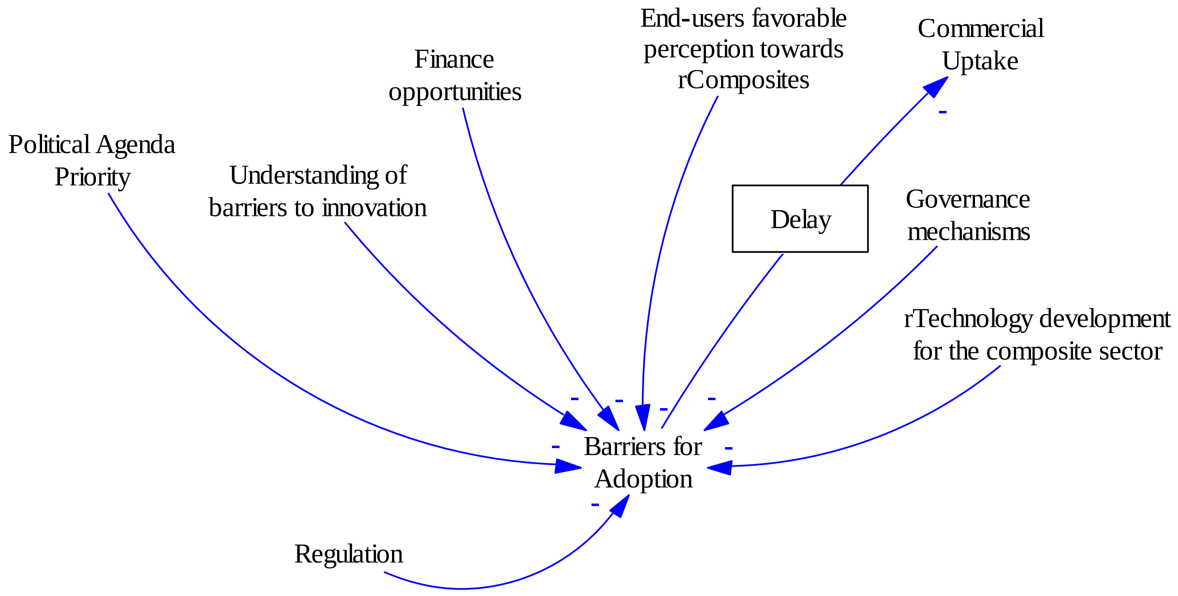
Figure 19 – Policy Compliance Subsystem



Source: Author's elaboration

With reference to the barriers for adoption subsystem, displayed in ***Figure 20***, 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. Specifically, it shows that *Barriers for Adoption* arise because of a list of aspects that were included in the diagram under the labels *Regulation*, *Political Agenda Priority*, *Understanding of barriers to innovation*, *Finance opportunities*, *End-users favorable perception towards rComposites*, *Governance mechanisms*, *rTechnology development for the composite sector*. When present, barriers for adoption interfere in the market's uptake of the goods; however, even if removed the impact on consumption would not be immediate, as the improvements may take some time to manifest. Consequently, the link between *Barriers for Adoption* and *Commercial Uptake* comprises a delay. The boundaries of this subsystem connecting it to the rest of the diagram are the elements *Regulation*, *rTechnology development for the composite sector* and *Commercial Uptake*.

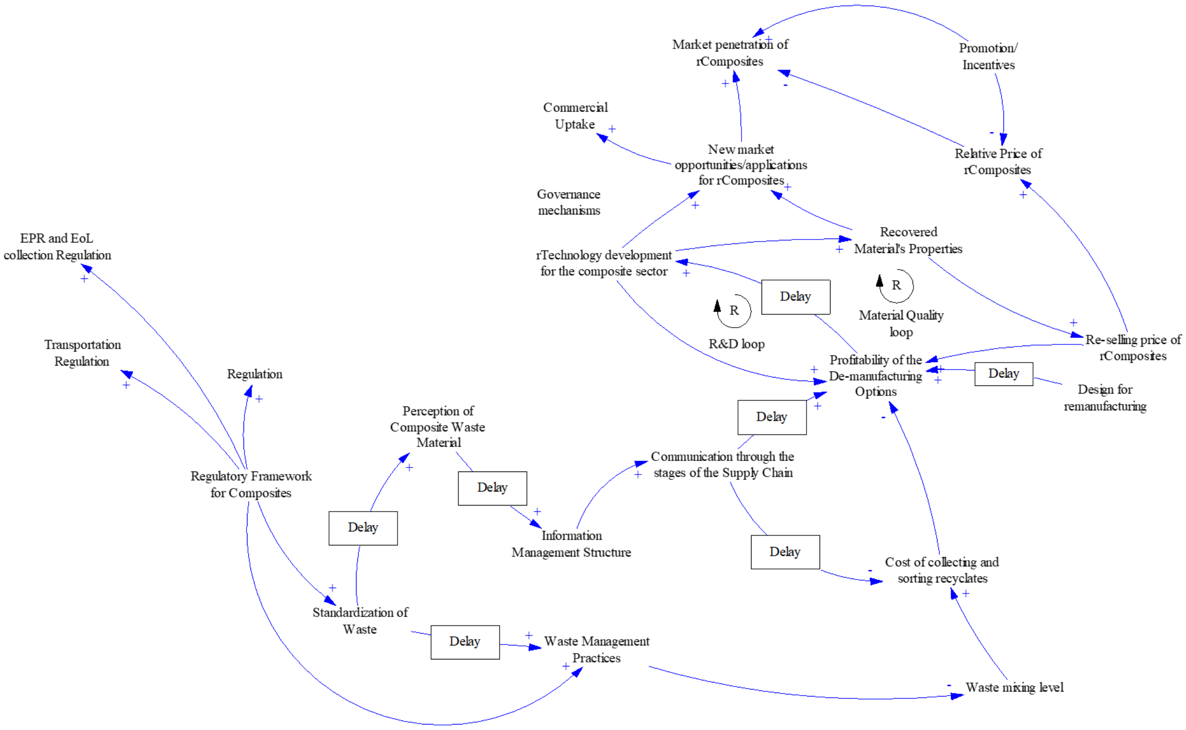
Figure 20 – Barriers for Adoption Subsystem



Source: Author's elaboration

The remaining subsystem, pictured in ***Figure 21***, 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 21 – Regulatory Frameworks and their Effects Subsystem



Source: Author’s elaboration

Standardizing waste aids the development of other processes in the course of time. First, by having standards for classifying residues, it benefits procedures related to their management. Second, defining sorting criteria carries the hidden message of materials’ utility even in their EoL state, because of the value entrenched in them. Hence, if there are waste guidelines people are informed implicitly about the importance of that flow, which can alter the perception they hold about it. Both effects are not immediate, as is takes time for perceptions and practices to modify; therefore, the causal relations between *Standardization of Waste* and *Perception of Composite Waste Material* and *Waste Management Practices* incorporate delays. The main effect of established waste management practices is on waste mixing level, that normally decreases when these activities are in place, and with the inferior mixing it is possible to obtain cost reductions in collection and sorting procedures, which raises the profitability of the de-manufacturing supply chain. The former relations are expressed by the causal links between *Waste Management Practices* and *Waste mixing level*, between the latter with *Cost of collecting* *and sorting recyclates*, and by the one from *Cost of collecting and sorting recyclates* to *Profitability of the De-manufacturing Options*. Still, better impressions of composite waste allied to the desire to explore their embedded value may lead to the emergence of structures for managing the information flows within the supply chain. By exploiting them, such structures can produce an increase in the communication and integration of stakeholders over different stages of the supply chain, which in turn increases efficiency, affecting the profitability of de-manufacturing, and over time, with higher integration and information sharing, reduces costs in collection and sorting since arrangements can be made based on the information available. On these grounds, the map shows causal connections between *Perception of Composite Waste Material* and *Information Management Structure*, which encompasses a delay, *Information Management Structure* and *Communication through the stages of the Supply Chain* and from the last to both *Cost of collecting and sorting recyclates* and *Profitability of the De-manufacturing Options*, the two characterized by delays as well.

The profits generated by de-manufacturing systems respond to some additional factors. In case the conception of the product adopted design for de-manufacturing approaches, the activities at the end of the loop benefit from the design choices and become easier to perform, which reflects in the overall chain’s economic results. Moreover, if the re-selling price of the composite subject to de-manufacturing processes increases, the returns from incurring these activities accompany. Furthermore, if new technology is introduced in the sector, it may also boost productivity and efficiency, thus raising the gains players get from circular supply chains. For these reasons, the diagram contains causal relations from *Design for remanufacturing*, *Re-selling price of rComposites* and *rTechnology development for the composite sector* to *Profitability of the De-manufacturing Options*.

Nonetheless, the increase in profits represents additional capital available to companies, which can become a source of finance for investments. These resources can end in different areas, being used for distinct purposes, for example, they may fund the expansion of the sector’s productive capacity by the enlargement of current players or the entry of new ones attracted by the profitability, or to pursue research and development activities. Whenever the profits allow the development of technology within the sector, it is possible to verify an additional loop in the system, as technology advancements can foster more profits. In the map, this loop received the label *R&D loop* and the causal link from *Profitability of the De-manufacturing Options* to *rTechnology development for the composite sector*, as well as the one from the same starting point to *De-manufacturing capacity*, comprise delays since the investments' results linger to manifest.

Technological advancements contribute to the enhancement of the recovered material's properties, achieved after de-manufacturing processes, by introducing new methods or machinery capable of treating waste flows more effectively, either preserving material's characteristics or restoring them more than current procedures. As already discussed, the price of the recycled composite depends on the properties it displays, hence, if higher standards can be achieved they will affect the re-selling value companies can charge for these products, influencing the operation's profitability. This sequence of effects represents another loop in the system, denoted *Material Quality loop* in the diagram, which is closed by the causal relations linking *rTechnology development for the composite sector*, *Recovered Material's Properties*, *Re-selling price of rComposites* and *Profitability of De-manufacturing Options*. Notwithstanding, the enhancement of properties and novel outcomes of de-manufacturing processes because of the introduction of modern technology modify the range of applications that can incorporate rFRP, generating new market opportunities for them either previously inexistent in the market or in areas to which their access had been denied. This represents the background of the links reaching *New market opportunities/applications for rComposites*, whose origins are *rTechnology development for the composite sector* and *Recovered Material Properties*.

Reasonably, the price at which recycled composites are sold in the market is key in the economic comparison against the virgin FRP that it substitutes, represented by *Relative Price of rComposites*. Such variable, at the core of the evaluation between alternatives, alters the degree of substitution rFRP have considering the applications of virgin composites, that is to say, to what extent recycled composites are in fact viable substitutes for their virgin peers given economic factors and quality standards, evidenced by *Market penetration of rComposites*. Still, there is one element capable of shaping both the relative price and market penetration, namely *Promotion/Incentives*. If there is the promotion of or there are incentives to foment the adoption of recycled FRP, for example tax reliefs or subsidies, they could produce an artificial change in the absorption of these materials by either modifying relative prices or stimulating their attractiveness in the market, both actions represented in the Causal loop map.

The referred penetration of recovered composites have additional biases related to former elements discussed, namely, *New market opportunities/applications for rComposites*. Provided there is the possibility to use these materials in areas before unexplored, indeed their market penetration is impacted. The new utilizations contribute to propagate recycled FRP in the market and can translate into greater awareness about the availability of Circular Economy solutions for this type of materials. Successively, this may produce changes in the market's consumption propensity regarding such products, which explains the causal relation between *New market opportunities/applications for rComposites* and *Commercial Uptake* present in the diagram.

Rigorous observation of ***Figure 16*** reveals there are still some causal links missing in the scrutiny, left behind on purpose since they represent the joints between the technical system and the regulatory environment parts of the diagram. Policies interfere in the system's behavior through these mechanisms, thus, they are extremely relevant for this work to fulfill its objective and therefore deserve special attention. To begin, the implementation of EPR and EoL collection regulation introduces obligations for manufacturers after the use phase of the goods they have provided to the market, for instance securing compliance to defined EoL pathways, establishing the division of roles between stakeholders in the end-of-life phase of the product or defining fines for non-conformity. After introduced, it may take some time for the enforcement of these measures to materialize, thus there is a delay in their effect. However, once in operation, they directly affect the costs of the procedures involved in the EoL management of materials, normally penalizing the non-circular route. As consequence, *EPR and EoL collection Regulation*, in the bottom part of the diagram, has a delayed causal relation to the top-part element *Relative Price of Collection*, uniting the two spheres of the system. Moreover, a similar effect is seen in the causal link between *Transportation Regulation* and *Collection LT*, in this case regarding rules for the transportation of composite waste. The relation is subject to a lag whose origins are the same as the one before, but this time the consequences are on the time taken to comply with all the requirements for moving this type of material and the movements themselves, constituting another connection between the technical system and the regulatory environment.

In addition, the level of mixing in waste flows produces difficulties in the sorting and collection procedures, an effect already discussed that in consequence lengthens the duration of these activities; hence, the waste mixing level interferes in the lead-time of collection operations. Such relation illustrates a further attachment of the spheres the system contains, which the diagram depicts with the causal link between *Waste mixing level* and *Collection LT*. Besides, these two procedures detain a predominant share in the total costs of the collection activity, so changes in their costs figures will reflect on the decisive price comparison during the selection of the option for retrieval. Accordingly, this relation is described by the link from *Cost of collecting and sorting recyclates* and *Relative Price of Collection*, another interconnection of the system's two parts.

Adding to the joining mechanisms are the causal relations from *Communication through the stages of the Supply Chain* to *De-manufacturing LT* and *Collection LT*. Recalling previous chapters, information sharing can facilitate the organization of both collection and de-manufacturing processes. As it potentially reduces the variability embedded in waste flows or at least details its content, it supports and accelerates the definition of the best alternative for these activities. The increased knowledge about the flows to threat allow de-manufacturers to better prepare their processes for receiving the waste stream and handling it more effectively, boosting productivity and thus affecting the time needed to execute the activities in the value chain.

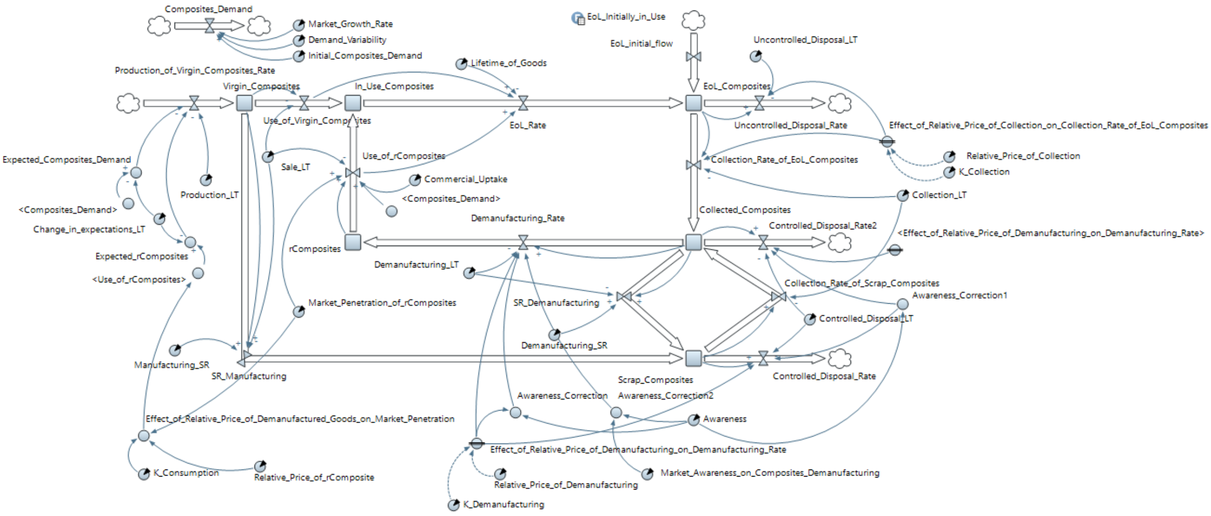
Proceeding, it is important to stress that a formerly presented causal link between *Profitability of the De-manufacturing Options* and *De-manufacturing Capacity* is also a connection between the two parts of the system. Part of the same group of joints, the relations between *Market penetration of rComposites* and *rComposites Use Rate*, as well as the one from *Commercial Uptake* to the latter element, describe the influence both variables have on the rate at which recycled composites enter the market, either pushing or halting the consumption of these materials.

4.1.2. Stock and Flow map

Following the completion of the Causal Loop diagram representing the system, the detailing of the elements within its structure started, differentiating 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, thus it was already developed under the simulation environment offered by *AnyLogic*© software.

During the modeling activity, translating the regulatory environment portion of the system in quantitative terms proved to be challenging, especially 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 [28]. 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, alike in the study by Georgiadis and Vlachos [12]. Moreover, both production and de-manufacturing capacity are unconstrained since the representation comprises the overall sector and not just single firms, thus there is greater flexibility in capacity. Also supporting this decision, the studies by Tailor [26], and Georgiadis, and Vlachos [12] already evidenced the need to ensure de-manufacturing capacity is sufficient to cope with an increase in 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 22*** and also enlarged in ***Appendix B***; ***Table 2*** lists its stock and flow components.

Figure 22 – Model of Composite Materials' Value Chain under Circular Economy



Source: Author's elaboration

Table 2 – List of the Model's Stock and Flow Elements

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]	Represent 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

Table 2 – List of the Model's Stock and Flow Elements (concluded)

	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

Source: Author's elaboration

Notwithstanding, a Stock and Flow Network was said to contain additional elements apart from the stocks and flows, including constants, exogenous variables and additional variables, which help in the comprehension of the systems' behavior. Indeed, the structure in ***Figure 22*** 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 3***.

Table 3 – 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 [29], [31]
Demand	Demand was modeled subject to an overall growth trend over the period of assessment with induced local disturbances
Production	The flow of de-manufacturing-originated products to the market depends only on their availability but is bounded by demand
Production	Production related outflows from stocks depend only on stock level and the activity's lead time [12]
Production	Stakeholders' decisions regarding the path of waste flows is represented by an effect of the relative price of the activity on its corresponding flow [12]

Source: Author's elaboration

In the software adopted, the way to include exogenous variables, auxiliary variables and constants is by using either *Dynamic Variables* or *Parameters*. Their main difference lies in the latter being exclusively static, while the previous can be constant or dynamic. The elements of these types included in the model are reported in ***Table 4***, in which N/A denotes the cases of dimensionless components. Worth of note that a *Table Function* is an element composed by a pair of data, one argument and one value, that upon called and offered a number, this is used as the argument of which the function returns the correspondent value.

Table 4 – Model's Additional Elements

Type of Element	Name	Unit of measure	Description
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

Table 4 – Model's Additional Elements (continued)

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

Table 4 – Model's Additional Elements (continued)

	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

Table 4 – Model's Additional Elements (concluded)

	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

Source: Author's elaboration

4.1.3. 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***; nonetheless, this section will explain in detail the overriding formulations.

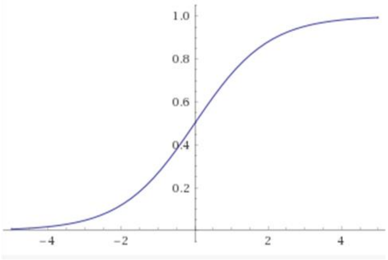
4.1.3.1. Sigmoid functions

As already presented, the model functions based on a decision making process that happens in two different points of the system. To represent this procedure mathematically, it employs sigmoid functions, which produce sigmoid curves, also referred to as S-shaped curves. In ***Figure 23***, it is possible to see an example of a sigmoid curve together with its equation.

Georgiadis and Vlachos [12] 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 in three occasions, two of them regarding the reverse logistics function and the third involving market penetration.

Figure 23 - Sigmoid function and curve example

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



Source: Author's elaboration

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 in monetary terms, for example time, by considering person-hour of effort. The expression in ***(9)*** describes the sigmoid equation representing the decision rule governing the collection of EoL composite materials.

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

In which

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 the decision whether to send collected FRP materials to de-manufacturing processes or dispose them by means of 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)***.

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

In which

K_Demanufacturing is a parameter alike *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)***.

$$Relative\_Price\_of\_Demanufacturing = \frac{Cost\_of\_Disposal - Cost\_of\_Demanufacturing}{Cost\_of\_Production} \tag{12}$$

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 price of newly manufactured FRP. If these materials are cheaper than their virgin counterparts are, there will be an incentive for their adoption and thus additional applications might be found, whilst if the contrary were true, there would be a setback to their utilization. Such effect was described using the equation in ***(13)***.

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

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.

4.1.3.2. Time Delays

Previously, *Chapter 2* presented the theoretical background of time delays and their specificities, however, the mathematics behind them still lack a disclosure. As presented before, the output of a delay depends on its past input, and can be generalized as the expression ***(14)*** for continuous time and constant delay times, in which *p(s)* is the probability of exit from the delay after *s* time units of entry, given by a continuous distribution; hence, *t-s* is the time of entry. Since the delay time was considered as fixed, the delay's behavior is equivalent for both material and information delays, provided this remains unchanged [24].

$$Output(t) = \int_0^\infty p(s) * Input(t - s)ds \tag{14}$$

In which

$$\int_0^\infty p(s)dS = 1 \tag{15}$$

According to the order of the delay, the probability function characterizing it will vary. In the case of first-order material delays, the probability of departure from the delay is defined by the exponential distribution, seen in ***(16)***, with D being the average delay. Nonetheless, referring to higher-order delays, since they are a cascaded combination of first-order delays, the probability of exit from the delay is given by the Erlang distribution of n^th^-order, in which *n* corresponds to the order of the delay and whose expression is depicted in ***(17)***; once again, D stands for the average delay [24].

$$p(t) = (\frac{1}{D})\exp(-\frac{t}{D}) \tag{16}$$

$$p(t) = \frac{\left(\frac{n}{D}\right)^n}{(n-1)!} t^{n-1} \exp\left[-\left(\frac{n}{D}\right)t\right]; t > 0 \tag{17}$$

The two types of delays have been employed in the model in different occasions. Fortunately, the software environment contains embedded functions for modeling delays that were applied accordingly. Regarding information delays, these structures were inserted in the model in order 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 amount of virgin composites to manufacture [24].

Recalling the dynamics described in *Chapter 4*, there were two different expectations to be modeled, the first about 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 ***(18)*** and ***(19)***.

$$Expected\_Composites\_Demand \\ = smooth3(Composites\_Demand, Change\_in\_Expectations\_LT) \tag{18}$$

$$Expected\_rComposites = \\ delayInformation(Use\_of\_rComposites, Change\_in\_Expectations\_LT) \tag{19}$$

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 in exponential decays of the stock level over the average delay time for the activity. The only exception is the rate at which FRP reach their EoL phase, described by a third-order delay of the rate at which they enter the market. Georgiadis and Vlachos [12] adopted the same representations of first-order material delays. Alike in their study, the initial values of all the stocks was set to zero; the third-order material delay of sales was also used in a similar context by Vlachos, Georgiadis and Iakovou [29], being common in the examples of Sterman [24] 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, which would reach end-of-life during the simulation period thus being the major input for de-manufacturing activities for most of the simulation time, 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 afterwards. The expressions for both EoL rates and an example of a first-order material delay are provided in ***(20)***, ***(21)*** and ***(22)***. Note that the expression *year()* is a translation of an year in model time units, specifically weeks.

$$EoL\_Rate = delay3(Use\_of\_Virgin\_Composites + Use\_of\_rComposites, Lifetime\_of\_Goods * year()) \tag{20}$$

$$EoL\_flow\_initial\_stock = \frac{EoL\_Initially\_in\_Use(getYear())}{year()} \tag{21}$$

$$Use\_of\_Virgin\_Composites = \frac{Virgin\_Composites}{Sale\_LT} \tag{22}$$

4.1.3.3. Parameters

After adding the expressions to the model, the next step involved the estimation of the parameters embedded inside it, which served as the basis for its functioning and ignited the dynamics of the system. Their values were mainly defined having literature research on the topics and industry's technical documents as data sources; for the sake of information availability, they come primarily from the case of CFRP used by the aerospace industry, and can be found in ***Table 5***.

Table 5 – Parameters' base values

Parameter	Value	Unit of measure	Remarks
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 [7]
Cost_of_Demanufacturing Mechanical Recycling Thermal Recycling Chemical Recycling (SCW treatment)	 248 1800 5430	[€/ton]	Source: Vo Dong et al. [30] The cost of the recycling process was used as a proxy for the cost of de-manufacturing
Cost_of_Disposal	125	[£/ton]	Source: FiberEUse [7]
Cost_of_Production	20130	[€/ton]	Source: FiberEUse [10] This value corresponds to the selling price of virgin carbon fibers, used as a proxy of production costs

Table 5 – Parameters' base values (concluded)

Demand_Variability	5%	N/A	Low variation assumed based on the study of Vlachos, Georgiadis and Iakovou [29]
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 [10]
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. [16]
Manufacturing_SR	15%	N/A	Source: FiberEUse [7]
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 contained in FiberEUse [9]
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 [29]
Relative_Price_of_rComposite	0,6	N/A	Source: FiberEUse [10]
Sale_LT	0,5	[weeks]	No remarks
Uncontrolled_Disposal_LT	0,2	[weeks]	No remarks

Source: Author’s elaboration

The calculation of the relative prices used the data contained in the previous table, applying expressions ***(10)*** and ***(12)***, which yielded the results shown next; the negative sign of the de-manufacturing relative price means this pathway is more expensive than the disposal option.

a) Relative Price of De-manufacturing;
   - CFRP Mechanical Recycling: -0,00487;
   - CFRP Thermal Recycling: -0,08197;
   - CFRP Chemical Recycling: -0,2623.

b) Relative Price of Collection: 0,32.

The values set for the EoL annual flow of FRP already in the market are shown in ***Table* 6**. For the intermediate years, the model used linear interpolation in order to seize the annual amount of the flow.

Table 6 – Annual EoL flow of composites initially in use

Year	Annual EoL flow [tons/year]
2020	1290
2035	2618
2040	6410

Source: Adapted from Lefeuvre et al. [16]

Having defined and loaded in the software the values of the previous elements, the model validation step took place, during which the aim was at verifying its reasonability. To fulfill this objective, the evaluation consisted of tests such as boundary adequacy, structure assessment, dimensional consistency and extreme conditions, carried out iteratively since their results provoked minor adjustments that then demanded reassessment, until they achieved satisfactory outcomes, which approved the model for experimenting.

4.2. Simulation Scenarios

In parallel to the completion of the model occurred the specification of the scenarios and policies to undergo evaluation. This process produced twelve different runs, each one assessing either a different context or the effects of the implementation and enforcement of a policy, the latter following the causal relations contained in ***Figure 16***, the system's Causal Loop diagram; the various runs, all of them reproduced for a 30 years period, are detailed next. The collection can be divided in two categories: the first, which encompasses runs *4.2.1.1* to *4.2.1.4*, analyzes current and hypothetical scenarios in the industry's present context, mainly to observe behavior reproduction and consistency, whist the second, containing runs from *4.2.2.1* to *4.2.2.8*, simulates the effects of modifications in the regulatory context by means of the establishment of policies.

4.2.1. Scenarios considering the industry's present context

4.2.1.1. Baseline: CFRP Thermal Recycling

The first run, also the baseline for the assessment, 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 material's properties, characteristics already discussed by previous chapters, which makes it a typical market choice. In ***Table 7***, it is possible to observe the parameters' values used for the simulation of the scenario of reference.

Table 7 – Parameters' values used in the simulation of the CFRP Thermal Recycling case

Parameter	Value
Awareness	True
Change_in_expectations_LT	1
Collection_LT	0,5
Commercial_Uptake	60%
Controlled_Disposal_LT	0,5
Demand_Variability	5%
Demanufacturing_LT	1
Demanufacturing_SR	15%
Initial_Composites_Demand	48488
K_Collection	2,5
K_Consumption	2,5
K_Demanufacturing	10
Lifetime_of_Goods	20
Manufacturing_SR	15%
Market_Growth_Rate	4%
Market_Penetration_of_rComposites	25%
Producer_Awareness_on_Composites_Demanufacturing	100%
Production_LT	1
Relative_Price_of_Collection	0,32
Relative_Price_of_Demanufacturing	-0,08197
Relative_Price_of_rComposite	0,6
Sale_LT	0,5
Uncontrolled_Disposal_LT	0,2

Source: Author's elaboration

4.2.1.2. CFRP Mechanical Recycling

The second 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; ***Table 8*** depicts the figures used for the complete set of parameters in this run.

Table 8 – Parameters' values used in the simulation of the CFRP Mechanical Recycling case

Parameter	Value
Awareness	True
Change_in_expectations_LT	1
Collection_LT	0,5
Commercial_Uptake	60%
Controlled_Disposal_LT	0,5
Demand_Variability	5%
Demanufacturing_LT	1
Demanufacturing_SR	15%
Initial_Composites_Demand	48488
K_Collection	2,5
K_Consumption	2,5
K_Demanufacturing	10
Lifetime_of_Goods	20
Manufacturing_SR	15%
Market_Growth_Rate	4%
Market_Penetration_of_rComposites	15%
Producer_Awareness_on_Composites_Demanufacturing	100%
Production_LT	1
Relative_Price_of_Collection	0,32
Relative_Price_of_Demanufacturing	-0,00487
Relative_Price_of_rComposite	0,6
Sale_LT	0,5
Uncontrolled_Disposal_LT	0,2

Source: Author's elaboration

4.2.1.3. CFRP Chemical Recycling

The third run refers to the occasion in which chemical recycling, specifically 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, alike in the previous experiment, the divergence from the baseline lies on the parameters *Relative_Price_of_Demanufacturing* and *Market_Penetration_of_rComposites*, whose values, together with those for the rest of the parameters, are shown in ***Table 9***.

Table 9 – Parameters' values used in the simulation of the CFRP Chemical Recycling case

Parameter	Value
Awareness	True
Change_in_expectations_LT	1
Collection_LT	0,5
Commercial_Uptake	60%
Controlled_Disposal_LT	0,5
Demand_Variability	5%
Demanufacturing_LT	1
Demanufacturing_SR	15%
Initial_Composites_Demand	48488
K_Collection	2,5
K_Consumption	2,5
K_Demanufacturing	10
Lifetime_of_Goods	20
Manufacturing_SR	15%
Market_Growth_Rate	4%
Market_Penetration_of_rComposites	75%
Producer_Awareness_on_Composites_Demanufacturing	100%
Production_LT	1
Relative_Price_of_Collection	0,32
Relative_Price_of_Demanufacturing	-0,2623
Relative_Price_of_rComposite	0,6
Sale_LT	0,5
Uncontrolled_Disposal_LT	0,2

Source: Author's elaboration

4.2.1.4. Fixed Demand

The fourth 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, a 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's values for this simulation is only on the *Market_Growth_Rate*, set to zero, whereas the remaining elements maintain their values, as can be perceived by the observation of ***Table 10***.

Table 10 – Parameters' values used in the simulation of the Fixed Demand case

Parameter	Value
Awareness	True
Change_in_expectations_LT	1
Collection_LT	0,5
Commercial_Uptake	60%
Controlled_Disposal_LT	0,5
Demand_Variability	5%
Demanufacturing_LT	1
Demanufacturing_SR	15%
Initial_Composites_Demand	48488
K_Collection	2,5
K_Consumption	2,5
K_Demanufacturing	10
Lifetime_of_Goods	20
Manufacturing_SR	15%
Market_Growth_Rate	0%
Market_Penetration_of_rComposites	25%
Producer_Awareness_on_Composites_Demanufacturing	100%
Production_LT	1
Relative_Price_of_Collection	0,32
Relative_Price_of_Demanufacturing	-0,08197
Relative_Price_of_rComposite	0,6
Sale_LT	0,5
Uncontrolled_Disposal_LT	0,2

Source: Author's elaboration

4.2.2. Scenarios considering changes in the regulatory context

4.2.2.1. Promotion of De-manufacturing among Producers

The fifth run analyzes the effect of implementing policies promoting actions that make producers aware about the possibility to send 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 composite waste. In order to attain its objective, the run conducts different experiments by gradually varying the value of the parameter *Producer_Awareness_on_Composites_Demanufacturing* according to a defined step variation within a predetermined range of values. 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. In ***Table 11***, it is possible to see the values used for the parameters in this run.

Table 11 – Parameters' values used in the simulation of the Dissemination of De-manufacturing among producers case

Parameter	**Value**	**Step Variation**
Awareness	True	N/A
Change_in_expectations_LT	1	N/A
Collection_LT	0,5	N/A
Commercial_Uptake	60%	N/A
Controlled_Disposal_LT	0,5	N/A
Demand_Variability	5%	N/A
Demanufacturing_LT	1	N/A
Demanufacturing_SR	15%	N/A
Initial_Composites_Demand	48488	N/A
K_Collection	2,5	N/A
K_Consumption	2,5	N/A
K_Demanufacturing	10	N/A
Lifetime_of_Goods	20	N/A
Manufacturing_SR	15%	N/A
Market_Growth_Rate	4%	N/A

Table 11 – Parameters' values used in the simulation of the Dissemination of De-manufacturing among producers case (concluded)

Market_Penetration_of_rComposites	25%	N/A
Producer_Awareness_on_Composites_Demanufacturing	From 50% to 100%	10%
Production_LT	1	N/A
Relative_Price_of_Collection	0,32	N/A
Relative_Price_of_Demanufacturing	-0,08197	N/A
Relative_Price_of_rComposite	0,6	N/A
Sale_LT	0,5	N/A
Uncontrolled_Disposal_LT	0,2	N/A

Source: Author's elaboration

4.2.2.2. EPR and EoL Regulation

The sixth 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 tax related to 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. The values for the parameters adopted in this case are disclosed in ***Table 12***.

Table 12 – Parameters' values used in the simulation of the EPR and EoL regulation case

Parameter	Value	Step Variation
Awareness	True	N/A
Change_in_expectations_LT	1	N/A
Collection_LT	0,5	N/A
Commercial_Uptake	60%	N/A
Controlled_Disposal_LT	0,5	N/A
Demand_Variability	5%	N/A
Demanufacturing_LT	1	N/A

Table 12 – Parameters' values used in the simulation of the EPR and EoL regulation case (concluded)

Demanufacturing_SR	15%	N/A
Initial_Composites_Demand	48488	N/A
K_Collection	2,5	N/A
K_Consumption	2,5	N/A
K_Demanufacturing	10	N/A
Lifetime_of_Goods	20	N/A
Manufacturing_SR	15%	N/A
Market_Growth_Rate	4%	N/A
Market_Penetration_of_rComposites	25%	N/A
Producer_Awareness_on_Composites_Demanufacturing	100%	N/A
Production_LT	1	N/A
Relative_Price_of_Collection	From 0,32 to 0,16	-0,032
Relative_Price_of_Demanufacturing	From -0,08197 to 0	0,016394
Relative_Price_of_rComposite	0,6	N/A
Sale_LT	0,5	N/A
Uncontrolled_Disposal_LT	0,2	N/A

Source: Author’s elaboration

4.2.2.3. Customer Education Activities

The seventh 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 characteristic. The values of the parameters used for performing the considered run can be seen in ***Table 13***.

Table 13 – Parameters' values used in the simulation of the Customer Education Activities case

Parameter	Value	Step Variation
Awareness	True	N/A
Change_in_expectations_LT	1	N/A
Collection_LT	0,5	N/A
Commercial_Uptake	From 60% to 100%	20%
Controlled_Disposal_LT	0,5	N/A
Demand_Variability	5%	N/A
Demanufacturing_LT	1	N/A
Demanufacturing_SR	15%	N/A
Initial_Composites_Demand	48488	N/A
K_Collection	2,5	N/A
K_Consumption	2,5	N/A
K_Demanufacturing	10	N/A
Lifetime_of_Goods	20	N/A
Manufacturing_SR	15%	N/A
Market_Growth_Rate	4%	N/A
Market_Penetration_of_rComposites	25%	N/A
Producer_Awareness_on_Composites_Demanufacturing	100%	N/A
Production_LT	1	N/A
Relative_Price_of_Collection	0,32	N/A
Relative_Price_of_Demanufacturing	-0,08197	N/A
Relative_Price_of_rComposite	0,6	N/A
Sale_LT	0,5	N/A
Uncontrolled_Disposal_LT	0,2	N/A

Source: Author’s elaboration

4.2.2.4. Information Exchange along the Supply Chain

The eighth 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 the treatment of the 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; the values for the parameters in this run are presented in ***Table 14***.

Table 14 – Parameters' values used in the simulation of the Information Exchange along the Supply Chain case

Parameter	Value	Step Variation
Awareness	True	N/A
Change_in_expectations_LT	1	N/A
Collection_LT	From 0,5 to 0,3	-0,05
Commercial_Uptake	60%	N/A
Controlled_Disposal_LT	0,5	N/A
Demand_Variability	5%	N/A
Demanufacturing_LT	From 1 to 0,6	-0,1
Demanufacturing_SR	15%	N/A
Initial_Composites_Demand	48488	N/A
K_Collection	2,5	N/A
K_Consumption	2,5	N/A
K_Demanufacturing	10	N/A
Lifetime_of_Goods	20	N/A
Manufacturing_SR	15%	N/A
Market_Growth_Rate	4%	N/A
Market_Penetration_of_rComposites	25%	N/A
Producer_Awareness_on_Composites_Demanufacturing	100%	N/A
Production_LT	1	N/A
Relative_Price_of_Collection	0,32	N/A
Relative_Price_of_Demanufacturing	-0,08197	N/A
Relative_Price_of_rComposite	0,6	N/A
Sale_LT	0,5	N/A
Uncontrolled_Disposal_LT	0,2	N/A

Source: Author's elaboration

4.2.2.5. Discovery of New Applications

The ninth 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 utilizations either 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 the parameter *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. The values for the parameters set in order to execute the present simulation are displayed in ***Table 15***.

Table 15 – Parameters' values used in the simulation of the Discovery of new applications case

Parameter	Value	Step Variation
Awareness	True	N/A
Change_in_expectations_LT	1	N/A
Collection_LT	0,5	N/A
Commercial_Uptake	60%	N/A
Controlled_Disposal_LT	0,5	N/A
Demand_Variability	5%	N/A
Demanufacturing_LT	1	N/A
Demanufacturing_SR	15%	N/A
Initial_Composites_Demand	48488	N/A
K_Collection	2,5	N/A
K_Consumption	2,5	N/A
K_Demanufacturing	10	N/A
Lifetime_of_Goods	20	N/A
Manufacturing_SR	15%	N/A
Market_Growth_Rate	4%	N/A
Market_Penetration_of_rComposites	From 30% to 75%	15%
Producer_Awareness_on_Composites_Demanufacturing	100%	N/A
Production_LT	1	N/A
Relative_Price_of_Collection	0,32	N/A
Relative_Price_of_Demanufacturing	-0,08197	N/A
Relative_Price_of_rComposite	0,6	N/A
Sale_LT	0,5	N/A
Uncontrolled_Disposal_LT	0,2	N/A

Source: Author's elaboration

4.2.2.6. De-manufacturing Technology Improvement

The tenth 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 parameters *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. The ranges of values for these parameters and the step variations adopted, as well as the figures for the remaining elements can be seen in ***Table 16***.

Table 16 – Parameters' values used in the simulation of the De-manufacturing Technology improvement case

Parameter	Value	Step Variation
Awareness	True	N/A
Change_in_expectations_LT	1	N/A
Collection_LT	0,5	N/A
Commercial_Uptake	60%	N/A
Controlled_Disposal_LT	0,5	N/A
Demand_Variability	5%	N/A
Demanufacturing_LT	From 1 to 0,6	-0,1
Demanufacturing_SR	15%	N/A
Initial_Composites_Demand	48488	N/A
K_Collection	2,5	N/A
K_Consumption	2,5	N/A
K_Demanufacturing	10	N/A
Lifetime_of_Goods	20	N/A
Manufacturing_SR	15%	N/A
Market_Growth_Rate	4%	N/A
Market_Penetration_of_rComposites	From 25% to 50%	12,5%
Producer_Awareness_on_Composites_Demanufacturing	100%	N/A
Production_LT	1	N/A
Relative_Price_of_Collection	0,32	N/A

Table 16 – Parameters' values used in the simulation of the De-manufacturing Technology improvement case (concluded)

Relative_Price_of_Demanufacturing	From -0,08197 to 0	0,016394
Relative_Price_of_rComposite	0,6	N/A
Sale_LT	0,5	N/A
Uncontrolled_Disposal_LT	0,2	N/A

Source: Author's elaboration

4.2.2.7. Transportation Regulation

The eleventh 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 the aggregation of 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%. The details about the parameters in this run are portrayed in ***Table 17***.

Table 17 – Parameters' values used in the simulation of the Transportation Regulation case

Parameter	**Value**	**Step Variation**
Awareness	True	N/A
Change_in_expectations_LT	1	N/A
Collection_LT	From 0,5 to 0,3	-0,05
Commercial_Uptake	60%	N/A
Controlled_Disposal_LT	0,5	N/A
Demand_Variability	5%	N/A
Demanufacturing_LT	1	N/A
Demanufacturing_SR	15%	N/A
Initial_Composites_Demand	48488	N/A
K_Collection	2,5	N/A
K_Consumption	2,5	N/A
K_Demanufacturing	10	N/A

Table 17 – Parameters' values used in the simulation of the Transportation Regulation case (concluded)

Lifetime_of_Goods	20	N/A
Manufacturing_SR	15%	N/A
Market_Growth_Rate	4%	N/A
Market_Penetration_of_rComposites	25%	N/A
Producer_Awareness_on_Composites_Demanufacturing	100%	N/A
Production_LT	1	N/A
Relative_Price_of_Collection	0,32	N/A
Relative_Price_of_Demanufacturing	-0,08197	N/A
Relative_Price_of_rComposite	0,6	N/A
Sale_LT	0,5	N/A
Uncontrolled_Disposal_LT	0,2	N/A

Source: Author’s elaboration

4.2.2.8. Waste Management Practices

The twelfth 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 to their execution. Since sorting is responsible for a great 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, the parameters *Relative_Price_of_Collection*, *Relative_Price_of_rComposite* and *Relative_Price_of_Demanufacturing* experimented variations in their values, which can be seen in ***Table 18***, together with those corresponding to the remaining elements.

Table 18 – Parameters' values used in the simulation of the Waste Management Practices case

Parameter	**Value**	**Step Variation**
Awareness	True	N/A
Change_in_expectations_LT	1	N/A
Collection_LT	0,5	N/A
Commercial_Uptake	60%	N/A
Controlled_Disposal_LT	0,5	N/A
Demand_Variability	5%	N/A

Table 18 – Parameters' values used in the simulation of the Waste Management Practices case (concluded)

Demanufacturing_LT	1	N/A
Demanufacturing_SR	15%	N/A
Initial_Composites_Demand	48488	N/A
K_Collection	2,5	N/A
K_Consumption	2,5	N/A
K_Demanufacturing	10	N/A
Lifetime_of_Goods	20	N/A
Manufacturing_SR	15%	N/A
Market_Growth_Rate	4%	N/A
Market_Penetration_of_rComposites	25%	N/A
Producer_Awareness_on_Composites_Demanufacturing	100%	N/A
Production_LT	1	N/A
Relative_Price_of_Collection	From 0,32 to 0,16	-0,032
Relative_Price_of_Demanufacturing	From -0,08197 to -0,040985	0,008197
Relative_Price_of_rComposite	From 0,6 to 0,36	-0,06
Sale_LT	0,5	N/A
Uncontrolled_Disposal_LT	0,2	N/A

Source: Author's elaboration

4.2.3. Evaluation of the different 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 ***(23)***. 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 an additional use phase. 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.

$$Used\_rComposites = \int_0^t Use\_of\_rComposites(t)\,dt \tag{23}$$

For comparison reasons, the same accumulated quantity of virgin composites used by the market was calculated using expression ***(24)***, called *Used_Virgin_Composites*. These two variables allow the obtainment of a third value used for the assessment of the scenarios, which represents the share of recovered composites in the total market's use of FRP, arising from equation ***(25)***.

$$Used\_Virgin\_Composites = \int_0^t Use\_of\_Virgin\_Composites(t)\,dt \tag{24}$$

$$Share\_of\_rComposites = \frac{Used\_rComposites}{Used\_rComposites + Used\_Virgin\_Composites} \tag{25}$$

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 in 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.

CHAPTER 5: RESULTS AND DISCUSSION

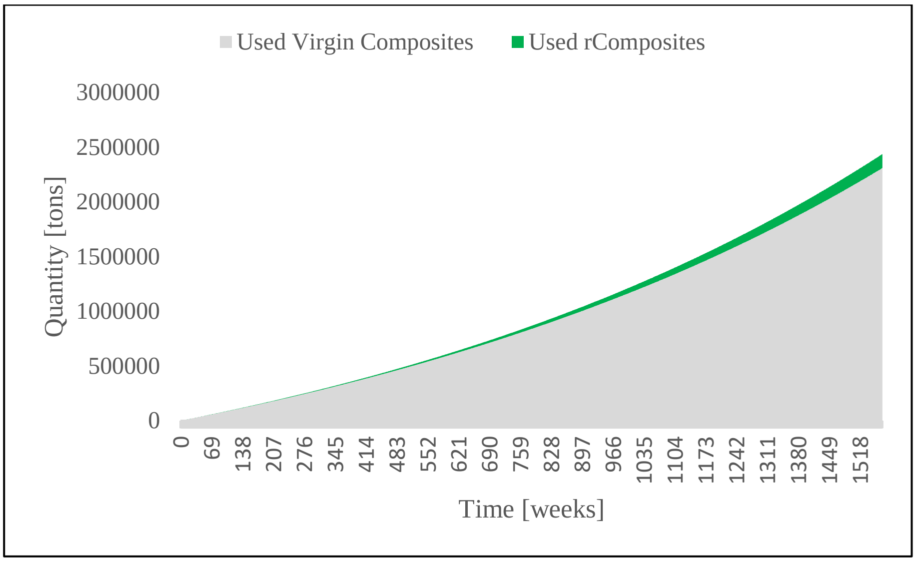
This chapter presents and discusses the results obtained by the simulations of the scenarios previously introduced, exhibiting the final appraisal of the decision variable *Used_rComposites* in the different runs performed with the aid of the model; in some occasions, the variable *Used_Virgin_Composites* is represented as well. From the presentation, the chapter reviews and explores the outcomes reached, seeking their interpretation and the derivation of conclusions based on the findings. To achieve its goal, the structure of the chapter contains two sections, the first displaying the results and the second reasoning about them.

5.1. Results from the simulations

5.1.1. Baseline: CFRP Thermal Recycling

The simulation of the baseline, comprising the case in which thermal recycling of CFRP is performed within de-manufacturing activities, produced the results that represent the benchmark for the assessment of the different alternative policy scenarios evaluated, illustrated by ***Figure 24***. In this run, over the simulation period, the variable *Used_rComposites* amounted around 127.810 tons, which represented 5,24% of the total volume of composite material consumed by the market in the same time horizon.

Figure 24 – Results from the run Baseline: CFRP Thermal Recycling

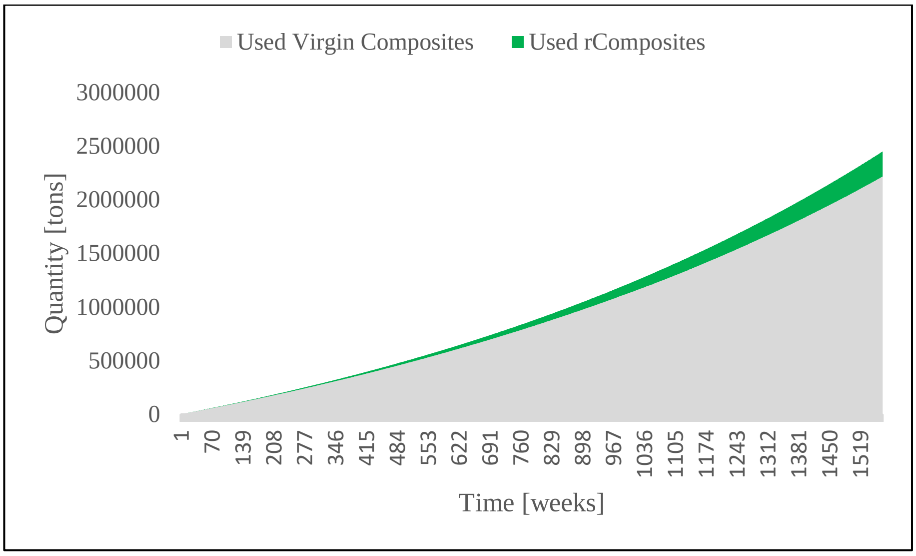


Source: Author’s elaboration

5.1.2. CFRP Mechanical Recycling

The results of the second run, representing the use of mechanical recycling to treat FRP waste instead of thermal processes as in the baseline, are exposed in ***Figure 25***. In this case, the variable *Used_rComposites* ended the simulation totaling approximately 233.951 tons, which represented a share of 9,55% of the total market demand in the period. It is interesting to observe that the combination of a smaller relative price of de-manufacturing and an inferior property degree of the recyclate leaving the process, in comparison to the baseline, increased the use of de-manufactured composites.

Figure 25 – Results from the run CFRP Mechanical Recycling

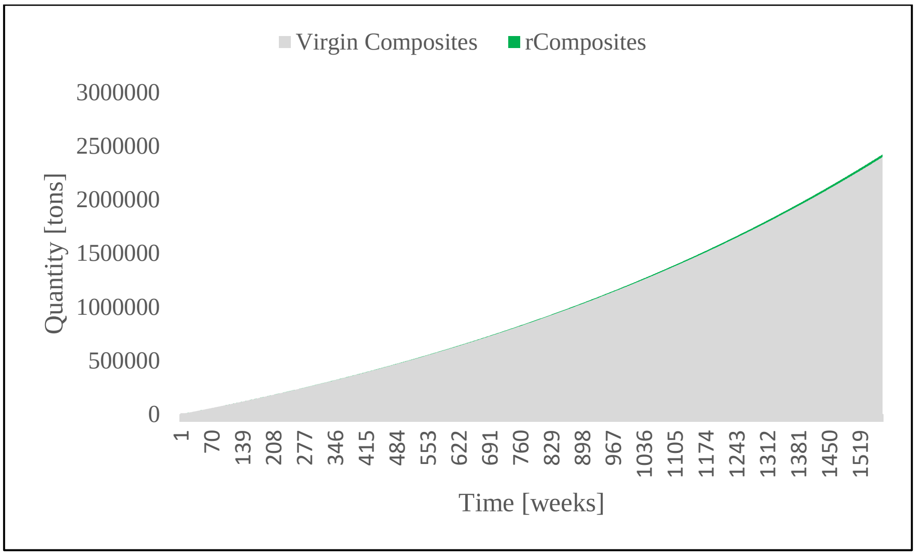


Source: Author's elaboration

5.1.3. CFRP Chemical Recycling

The third run's outcomes, depicted in ***Figure 26***, refer to the case using chemical recycling within de-manufacturing activities. In this occasion, the variable *Used_rComposites* reached the value of 24.141 tons, which constituted a share of 1% in the total quantity of FRP employed by the market during the simulated period. Contrarily to the previous run's aftermath, an increase in the relative price of de-manufacturing activities allied with a higher level of properties of the final recyclate diminished the adoption of rFRP by the clients of the industry, compared to the baseline.

Figure 26 – Results from the run CFRP Chemical Recycling

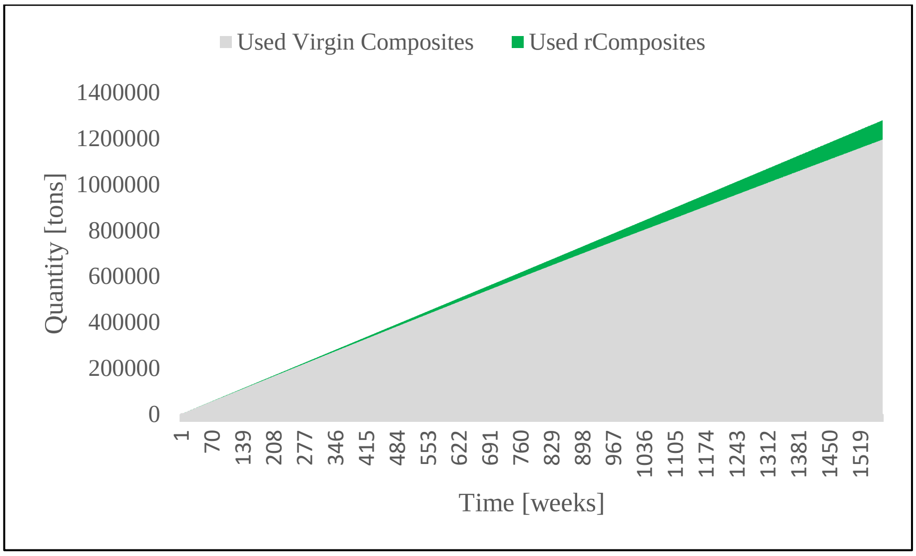


Source: Author’s elaboration

5.1.4. Fixed Demand

The fourth run, which tested the baseline process, that is, CFRP treated by thermal recycling, but under a context of devoid growth in the demand for composites, has its results displayed by ***Figure 27***. Customers in the market, within this scenario, used close to 84.111 tons of composite material originated from de-manufacturing activities, which represented 6,58% of the total market intake of FRP during the simulation time. Confronting the results to those of the baseline, the fixed demand engendered a smaller final quantity of recovered composites entering the market, although higher in relative terms of the total volume of FRP used.

Figure 27 – Results from the run Fixed Demand



Source: Author's elaboration

5.1.5. Promotion of De-manufacturing among Producers

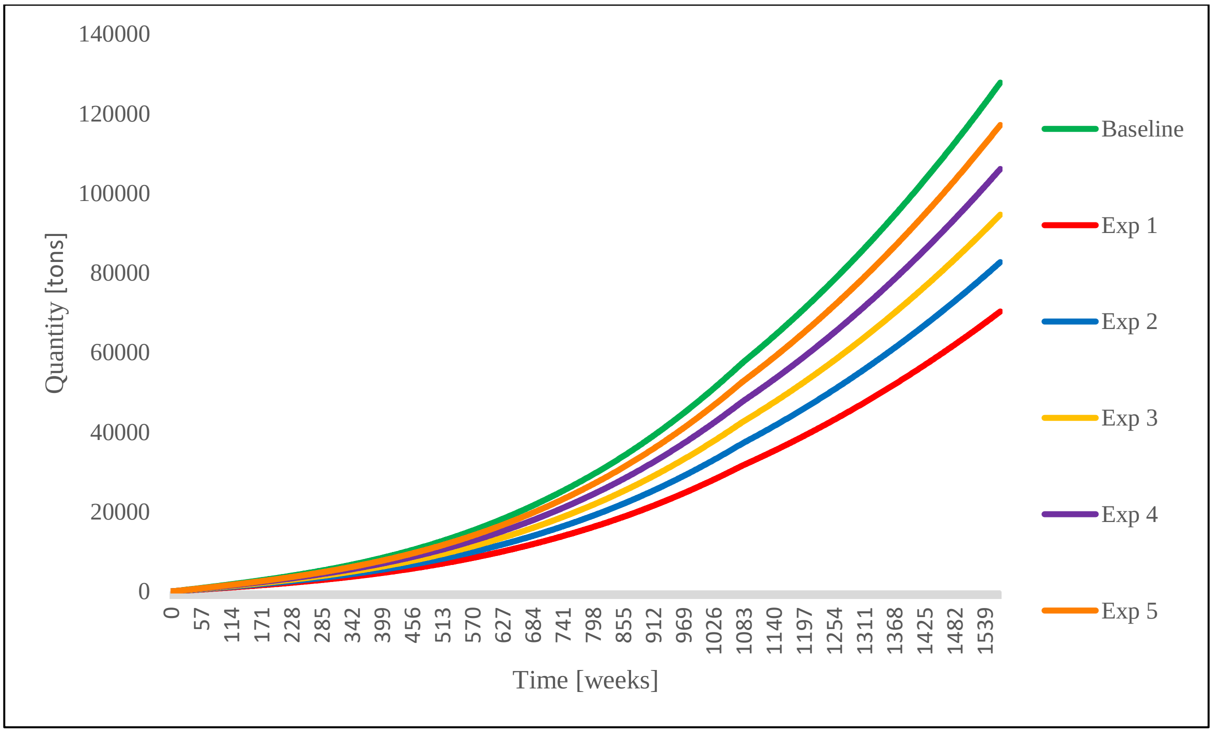
The results from the fifth run are shown in ***Figure 28***, in a different manner than those displayed so far. For this and the subsequent runs, since they involved experiments in which the values of the parameters changed, the figures disclose only the value of *Used_rComposites* in the different experiments, directly allowing their comparison to the baseline. The details about the experiments within this run are provided by ***Table 19***. The observation of the figure reveals there was a progressive reduction in the quantity of rFRP entering the market accompanying the decrease in the value of *Producer_Awareness_on_Composites_Demanufacturing*. In the worst performing case in terms of the decision variable, namely experiment 1, in which the awareness parameter was halted, the final amount of de-manufactured composites employed by the market decreased by almost 45%, and the share of the total they represented dropped to 2,89%.

Table 19 – Experiments' characteristics

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

Source: Author's elaboration

Figure 28 – Results from the run Promotion of De-manufacturing among Producers



Source: Author's elaboration

5.1.6. EPR and EoL Regulation

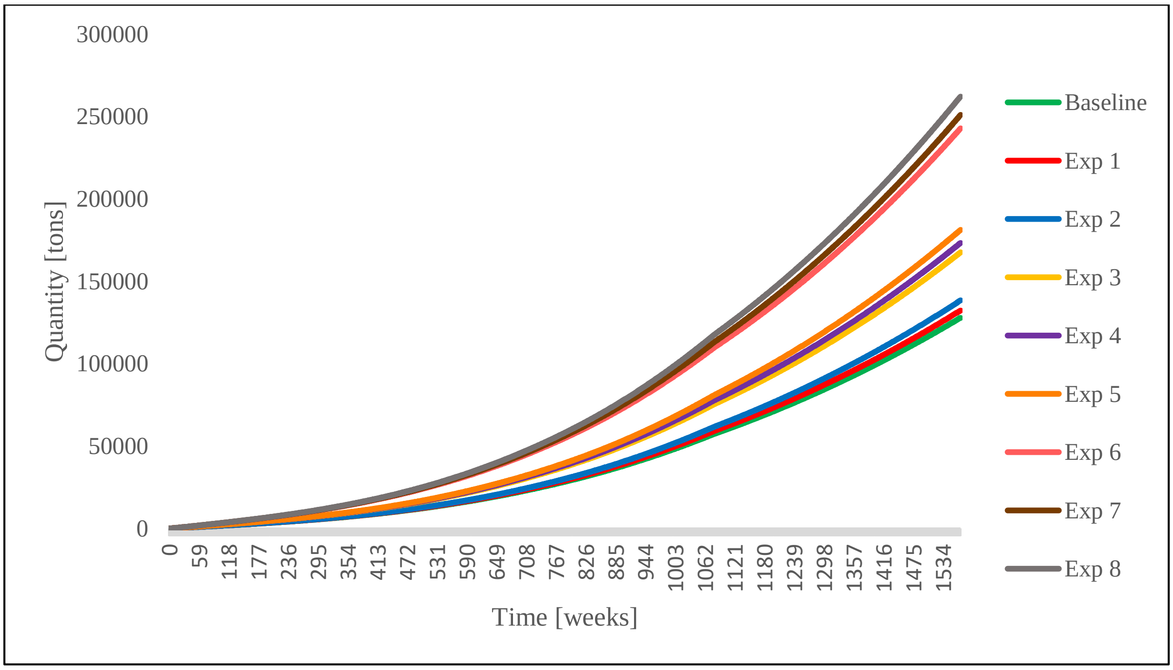
The outcomes of the run studying the introduction of EPR and EoL policies are exposed by ***Figure 29***, while the experiments' characteristics are shown by ***Table 20***. The results describe the flow of recovered composites to the market, measured by the decision variable, increased along the reduction in one or in both of the parameters *Relative_Price_of_Demanufacturing* and *Relative_Price_of_Collection*. More precisely, in the figure, it is possible to observe three clusters containing three curves each; the clusters corresponds to the three values tested for the first parameter, whereas the variations in the second's value confer the distinction between the curves within a cluster. In experiment 8, the most favorable case, in which the cost of disposal equaled that of de-manufacturing and the relative price of the collection activity halted, the value of *Used_rComposites* more than doubled compared to the baseline, reaching a 10,68% share of the market's total FRP intake.

Table 20 – Experiments' characteristics

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

Source: Author's elaboration

Figure 29 – Results from the run EPR and EoL Regulation



Source: Author's elaboration

5.1.7. Customer Education Activities

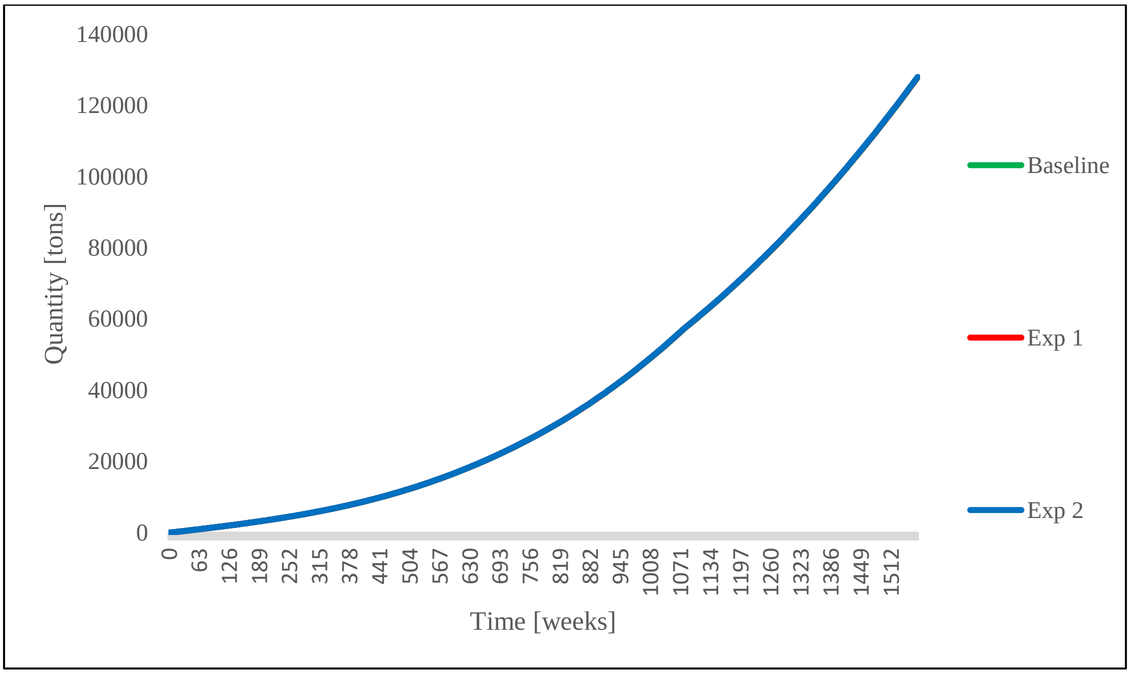
The seventh run, investigating policies that target the education of customers about the benefits of products arising from de-manufacturing value chains produced the results depicted in ***Figure 30***, whilst the details of the experiments are presented in ***Table 21***. The image appears to show only one curve, but in fact, it contains all the three experiments' outcomes, implying that the variations in the parameter *Commercial_Uptake* had slight impacts in the flow of rFRP to the market during the simulation's time horizon. Taking the example of experiment 2, in which the model assumed all consumers were willing to buy de-manufactured composites, the increase in the accumulated quantity represented by *Used_rComposites*, in relation to the baseline, was only of 0,13%, with the share of the demand remaining at the same 5,25%, despite the increase in customer's perception about the recovered materials.

Table 21 – Experiments' characteristics

Experiment	Commercial_Uptake
Baseline	60%
1	80%
2	100%

Source: Author's elaboration

Figure 30 – Results from the run Customer Education Activities



Source: Author's elaboration

5.1.8. Information Exchange along the Supply Chain

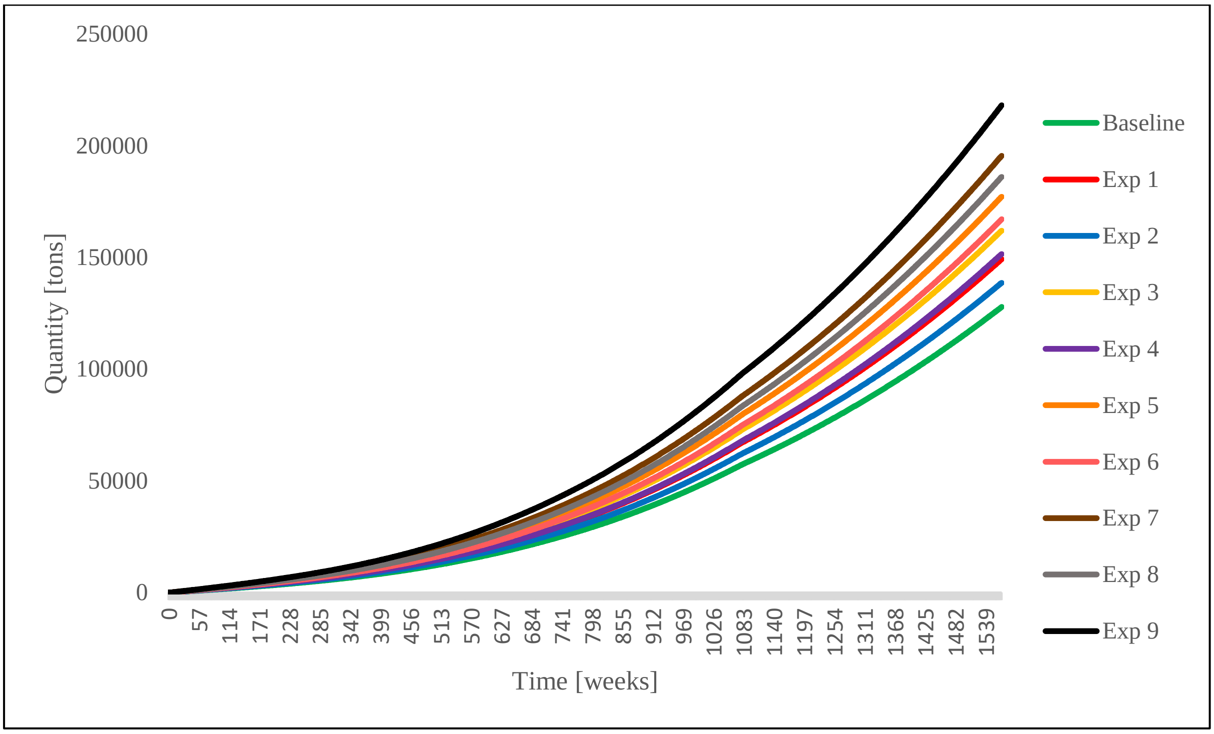
The run testing the establishment of policy actions to foster the exchange of information about waste flows along the supply chain gave rise to the upshots illustrated by ***Figure 31***, whose curves are further characterized by the information contained in ***Table 22***. In this scenario, decreases in the lead-times of collection and de-manufacturing activities, represented by the parameters *Collection_LT* and *Demanufacturing_LT*, caused an increase in the final value of the decision variable. The figure shows only a selection of the experiments conducted in the scope of this scenario, so it stays comprehensible though insightful. It is observable that some experiments, although with different characteristics assessed, produced results close to each other, for instance tests 1 and 4 or 3 and 6. Notwithstanding, between the two parameters, *Demanufacturing_LT* demonstrated a greater influence over the decision variable in comparison to its collection counterpart if considered equal proportional variations. In the best performing experiment, in which the two lead-times shrank 40%, the effect on the value of *Used_rComposites* in the end of the simulation was an increase of more than 70% in the quantity of de-manufactured FRP employed by the market, which accounted for 8,91% of the market's total demand for composites in the period.

Table 22 – Experiments' characteristics

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

Source: Author's elaboration

Figure 31 – Results from the run Information Exchange along the Supply Chain



Source: Author's elaboration

5.1.9. Discovery of New Applications

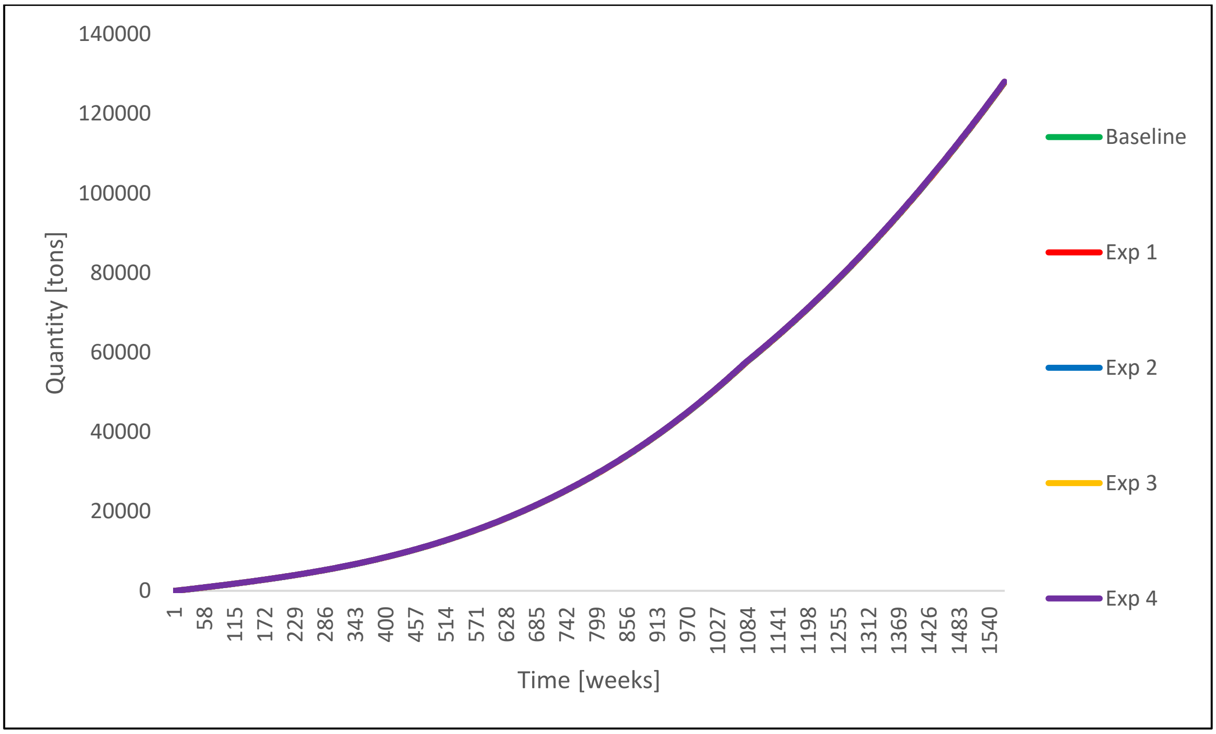
The ninth run executed, which targeted the investigation of the effects of policies promoting the search and discovery of additional applications for rFRP, achieved the results exposed in ***Figure 32*** and specified by ***Table 23***. The modifications in the value of the parameter *Market_Penetration_of_rComposites* did not generate significant effects in the decision variable *Used_rComposites*; as consequence, the curves in the figure are overlapping, being practically impossible to distinguish one from another. In experiment 4, whose outcome is the most preeminent among the tests, the volume of composite materials stemming from de-manufacturing processes that fulfilled market's demand was 0,43% bigger than that of the baseline, representing a stake of 5,26% in the total consumption of FRP over the period of simulation.

Table 23 – Experiments' characteristics

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

Source: Author's elaboration

Figure 32 – Results from the run Discovery of New Applications



Source: Author's elaboration

5.1.10. De-manufacturing Technology Improvement

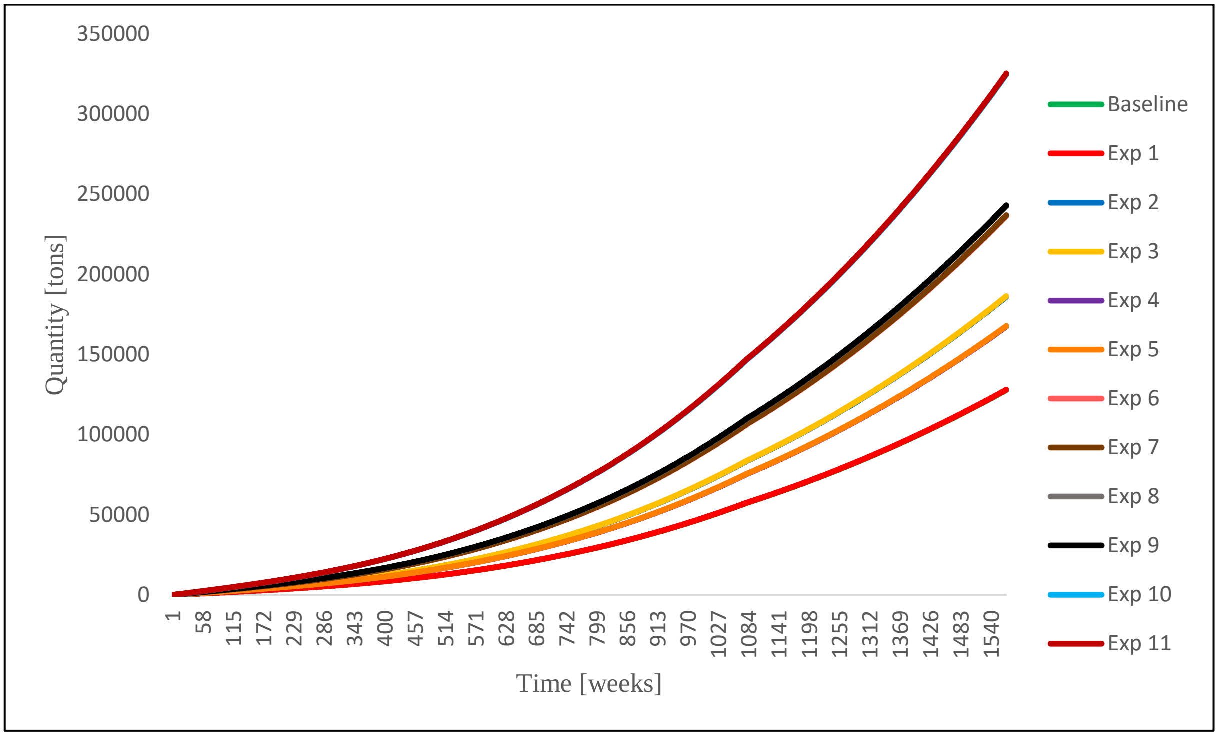
The tenth run, focused on the effects of policies inciting the improvement of de-manufacturing methods and technology, generated the results described by ***Figure 33***, which ***Table 24*** complements with further information about the experiments. In this scenario, despite a great number of parameters experiencing variation in their values, specifically *Relative_Price_of_Demanufacturing*, *Demanufacturing_LT* and *Market_Penetration_of_* *rComposites*, it is possible to observe the overlapping of different experiments' curves. Once again, the figure exhibits only a collection of the experiments performed due to clarity issues, although it still provides acumens arising from the simulation's outcome. It is possible to visualize that *Used_rComposites* grew along the experiments, accompanying specially the reductions is the parameters *Relative_Price_of_Demanufacturing* and *Demanufacturing_LT*. In experiment 11, holder of the run's best result, the decision variable at the end of the test added more than 2,54 times the baseline's supply of composites originated from de-manufacturing chains to the market, and the share of the demand they served represented 13,21% of the total demand of FRP.

Table 24 – Experiments' characteristics

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

Source: Author's elaboration

Figure 33 – Results from the run De-manufacturing Technology Improvement



Source: Author's elaboration

5.1.11. Transportation Regulation

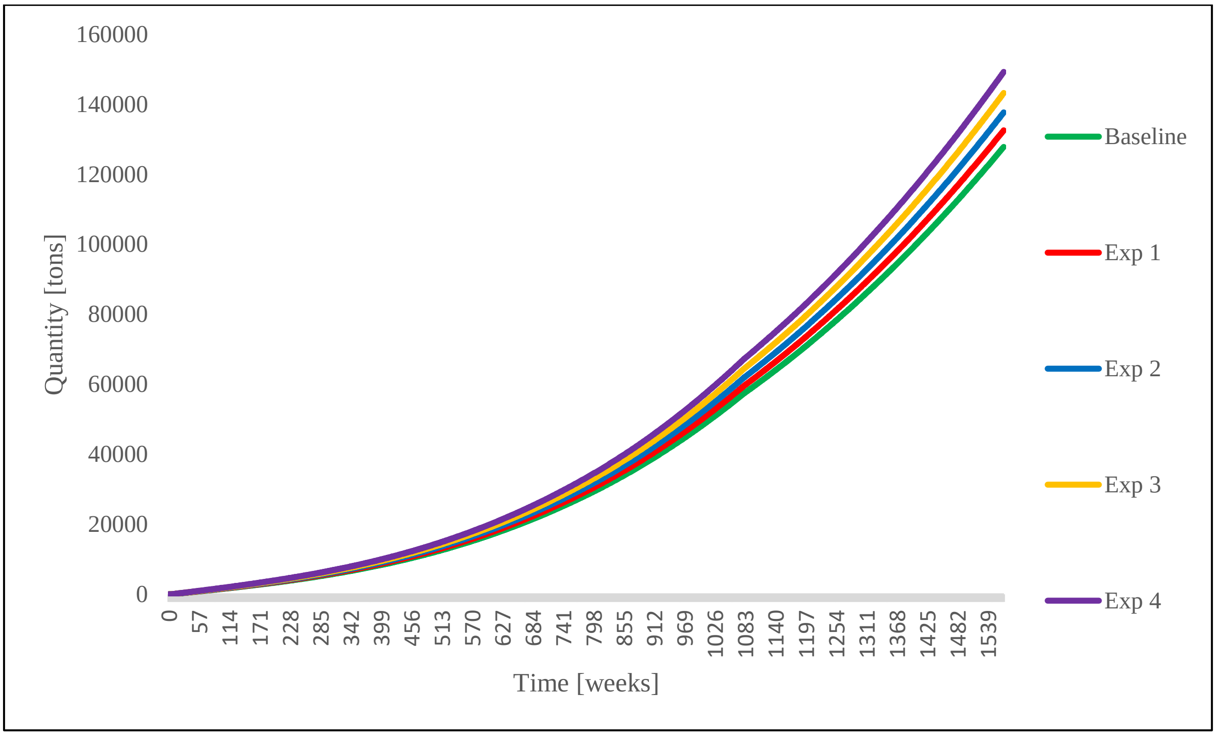
The results from the eleventh run, experimenting changes in the regulation of composites' transportation, are depicted in ***Figure 34*** and further characterized by ***Table 25***. In this case, the value of *Used_rComposites* increased, in comparison to the baseline, the more the value of the parameter *Collection_LT* diminished. Experiment 4, to which the most superior curve in the figure refers, achieved an outcome for the decision variable 16,77% greater than the one from the baseline, and the share of the total demand held by rFRP reached the mark of 6,12%.

Table 25 – Experiments' characteristics

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

Source: Author’s elaboration

Figure 34 – Results from the run Transportation Regulation



Source: Author’s elaboration

5.1.12. Waste Management Practices

The run simulating the establishment of policies that introduce the obligation to follow waste management practices for composite materials originated the results presented in ***Figure 35***, whose details are contained in ***Table 26***. The image contains part of the experiments performed in the scope of the present scenario, as reporting the entire set of curves would hamper its comprehension and thus the interpretation of the results. It is possible to observe that a gradual reduction in the value of the parameters *Relative_Price_of_Demanufacturing*, *Relative_Price_of_Collection* and *Relative_Price_of_rComposite* led to a rise in the accumulated quantity of recovered composites used by the market, measured by *Used_rComposites* and whose values are represented by the curves. The best performing experiment in terms of the decision variable was Experiment 26, in which the relative prices of de-manufacturing and collection are half of their baseline's value and the relative price of the rFRP had a 40% cut. The combination of these values for the parameters produced an increase in the market's consumption of de-manufacturing-originated composites in the period of simulation that reached 51,24%; this quantity represented 7,91% of the total demand for fiber-reinforced plastics. An attentive scrutiny in the figure may reveal the curves can be grouped in three clusters, each for one value of *Relative_Price_of_Demanufacturing*, and inside them there are additional clusters as well, this time distinguished on the basis of the parameter *Relative_Price_of_Collection*.

Table 26 – Experiments' characteristics

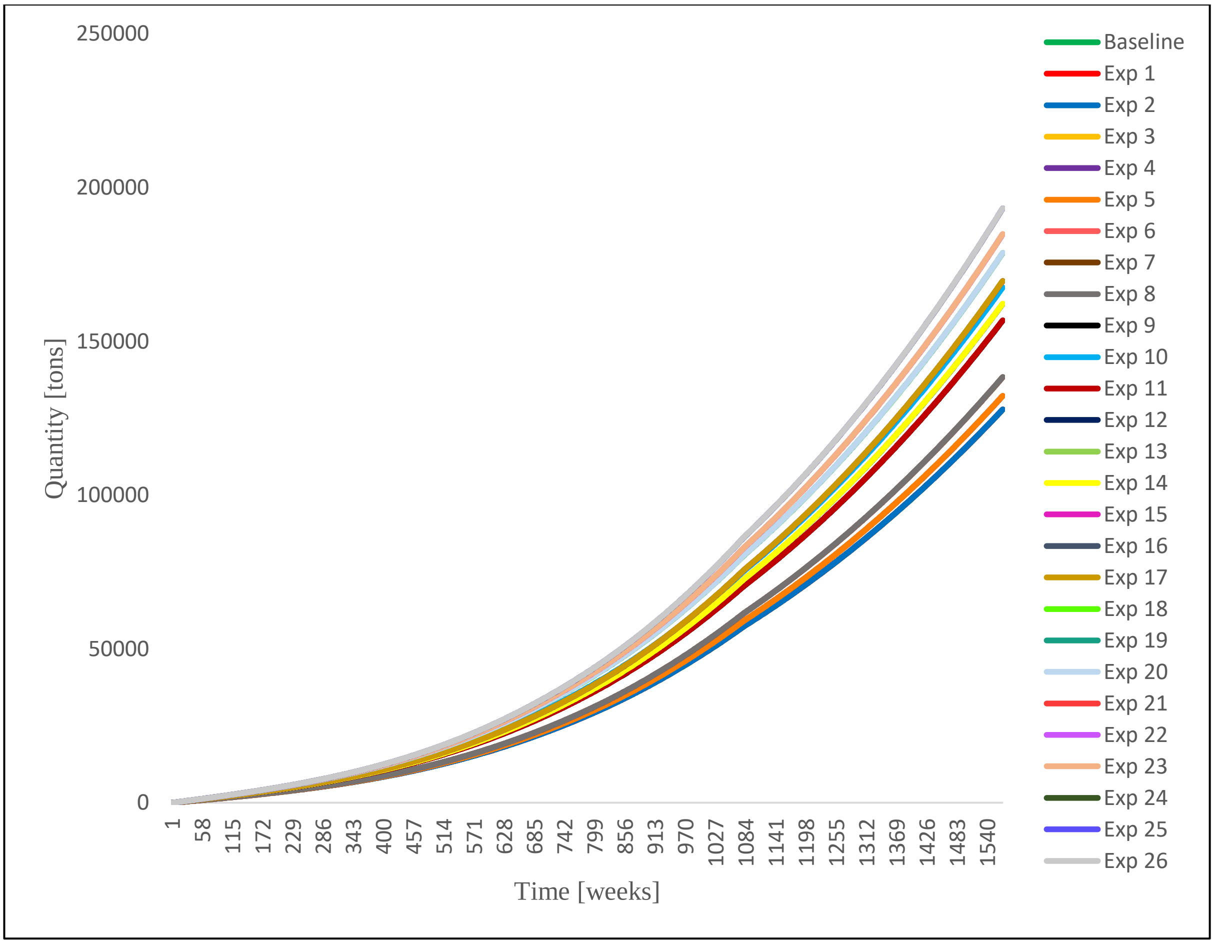
Experiment	**Relative_Price_of_ Demanufacturing**	**Relative_price_of _Collection**	**Relative_Price_of _rComposite**
Baseline	-0,08197	0,32	0,6
1	-0,08197	0,32	0,48
2	-0,08197	0,32	0,36
3	-0,08197	0,256	0,6
4	-0,08197	0,256	0,48
5	-0,08197	0,256	0,36
6	-0,08197	0,16	0,6
7	-0,08197	0,16	0,48
8	-0,08197	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

Table 26 – Experiments' characteristics (concluded)

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

Source: Author's elaboration

Figure 35 – Results from the run Waste Management Practices



Source: Author's elaboration

5.2. Discussion

The results achieved by the simulation of the model under different contexts are able to reveal relevant aspects about the dynamics of the rCFRP industry, which can be largely extended to the situation of the rFRP sector in general. This section deepens the analysis of the outcomes exhibited previously and reasons about them, in an attempt to derive conclusions from the insights that emerged from the simulations executed with the model.

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 disposal, which is also the amount of composites de-manufacturing business are able to 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 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. This might be the case as the values were estimated based on data from 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 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 in order to make the usage of rFRP evolve, the results from the simulations assessing the different regulatory modifications that can be enacted by means of policies offer the opportunity to prioritize between the alternatives and focus the efforts to 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 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 being on the availability of inputs, in this case ready-for-use-rFRP. Therefore, the evidence led to the conclusion the current bottleneck for the adoption of de-manufactured composites does not locate 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 by the analysis of the collection wing, the run that assesses the enforcement of policies whose scopes affect 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 a significant 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 a greater availability of inputs for composite 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 clusters in isolation, the increments in the value of *Used_rComposites* are consequence of the reduction in the *Relative_Price_of_Collection*. In case the collection of composite waste becomes cheaper, the pathway should gain more of the stakeholders' preference, hence 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 process and its 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 to decreases in *Relative_Price_of_Demanufacturing*. This indicates that if the costs of de-manufacturing activities are closer to those of their alternative, market's adoption of recovered composites should increase. Indeed, the finding must be the development of the higher predilection for de-manufacturing pathways once their costs decline, which results in a greater 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 is destined 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 in the discussion 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 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 proceed 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 a room for maneuver depending on their goals, though targets that are more ambitious 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.

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 later 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 indicated: the more comprehensive the policy, with effects on a greater number of parameters, the better the 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 run.

Concisely, the results showed that modifications in the regulatory environment to which the composite industry is subject to, 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 collection and de-manufacturing stages, since the impacts generated by changes in distribution elements were limited comparing 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. Finally, the results signaled that policies with effects spanning more elements are more effective, but the finding still requires careful investigation about its veracity.

CHAPTER 6: CONCLUSIONS 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. Hoping to become a tool to support policymakers in their regulatory decisions, it envisioned the creation of a model, representing 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 the development of business models for composite materials under Circular Economy.

Based on this perspective, the study revised the scientific literature on the topics of interest. This allowed the discussion to deepen on the concept of Circular Economy, offering an overview of its main pillars and historical background, with special attention given to de-manufacturing, 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 main utilization cases. Consecutively, the work presented the theory of System Dynamics, dated from the 1950s, and its principles, which represent the modeling technique selected to assist the investigation of the FRP industry.

Once the scientific research ended, the study devoted its attention to the market, discussing the main elements relevant to the sector, for example the demand for composites and its trends, which are certainly significant. Nevertheless, the focus of the investigation lay on the industry's situation regarding reverse activities, thus the scenario for the establishment of business models embodying the concept of Circular Economy. It covered aspects such as existing waste sources, applicable de-manufacturing processes, foreseen market opportunities, the main barriers and the regulatory environment. Hence, the analysis provided the knowledge fundamental for the development of the proposed model, helping in the comprehension of the industry's dynamics.

In possession of the necessary information, the construction of the model began, first with the execution of the system's Causal Loop diagram, followed by its Stock and Flow map, the latter already created in *AnyLogic*$^{©}$ software, the environment chosen to host the simulations. Later, the model received the mathematical expressions and parameters necessary to the reproduction of the dynamics of the system, with their respective estimated values. In parallel, the design of the potential policies proposed the evaluation of twelve different scenarios. Following the experimentation, the work disclosed and discussed the results obtained, deriving conclusions from the findings.

6.1. Conclusions

To begin, the work proved the feasibility of the decoupling of the technical system from the regulatory context. By 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 ambience 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. 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 on 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.

Finally, the high-level responses achieved allow the establishment of a priority agenda for the policies regarding the composite sector. 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. In a second moment should follow those that also affect 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 the introduction of information exchange mechanisms in the supply chain. Ultimately, after the development of the reverse loop, the focus should go to the issues related to customers and the demand.

6.2. Limitations of the study and future research

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 that occasional modelling deviations from reality lose their strength as 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 the observation of 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, but these were out of the scope of the study.

Finally, the work considered a flexible capacity in all of the stages part of the supply chain as it operated in the industry level. However, since individual companies have a constraint for the quantity of composites they are able to process, and the industry aggregates individual 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 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 elements 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. This could shift the efforts towards the establishment of more comprehensive regulations, tackling a multitude of the industry's issues at once, or to the introduction of small, incremental modifications at a time.

To conclude, the model produced offers a high-level characterization of the FRP industry that can be generalized and applied to the case of other Circular Economy business, 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 Circular Economy.

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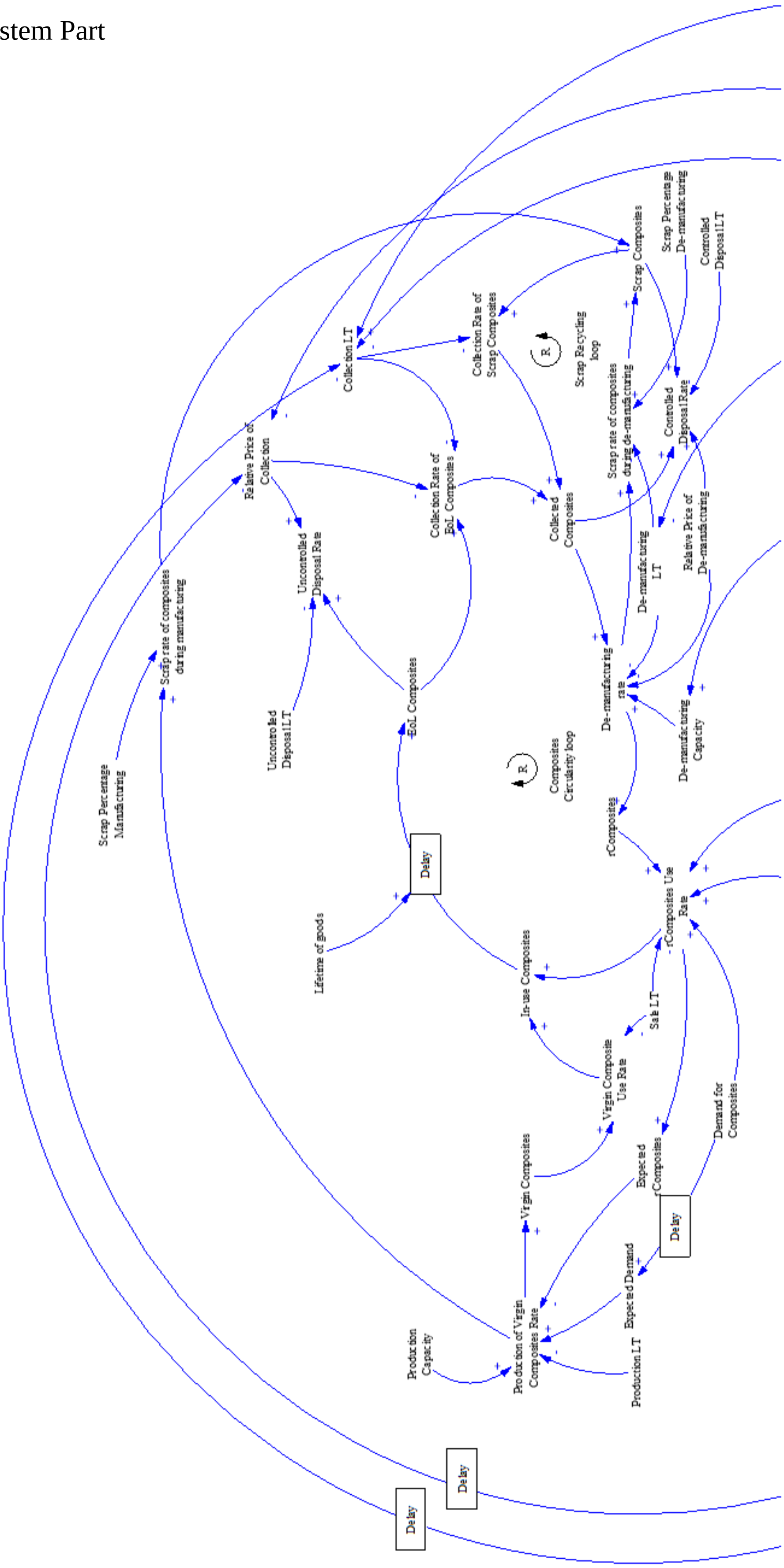
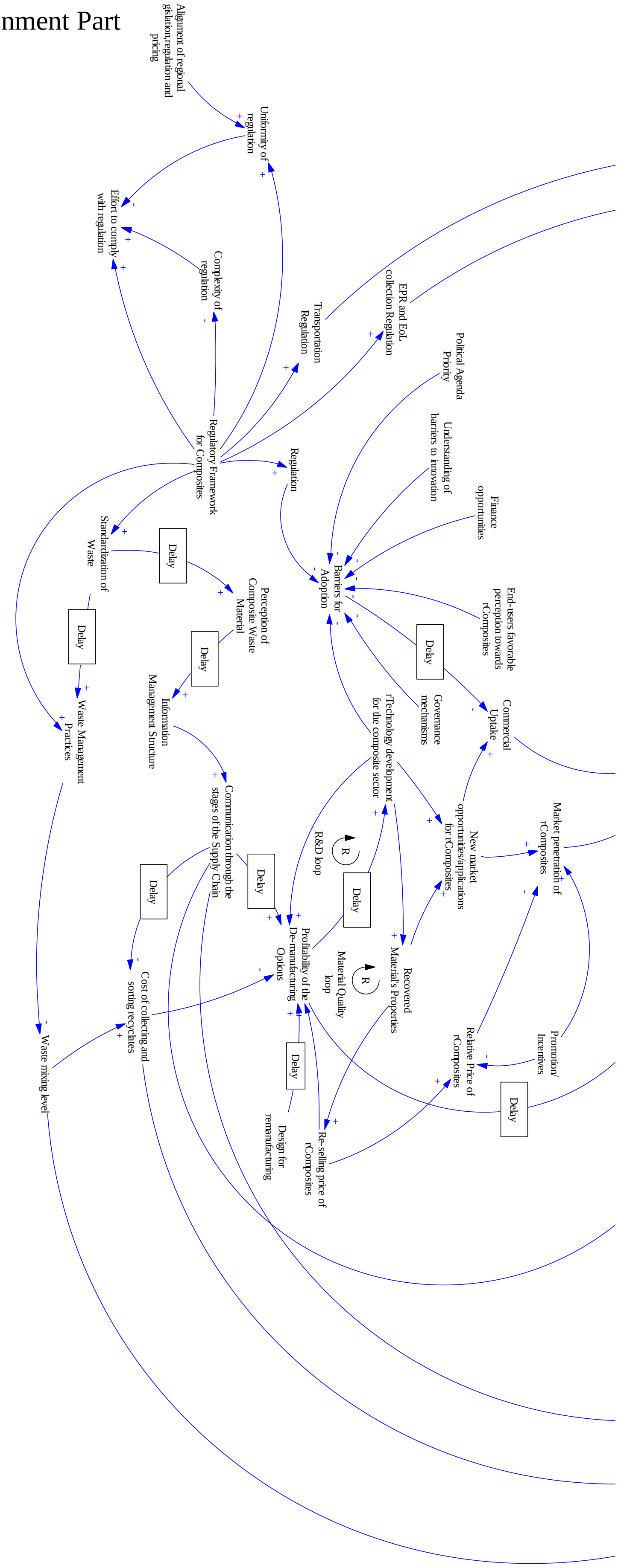
APPENDIX A: SEGMENTED CAUSAL LOOP DIAGRAM

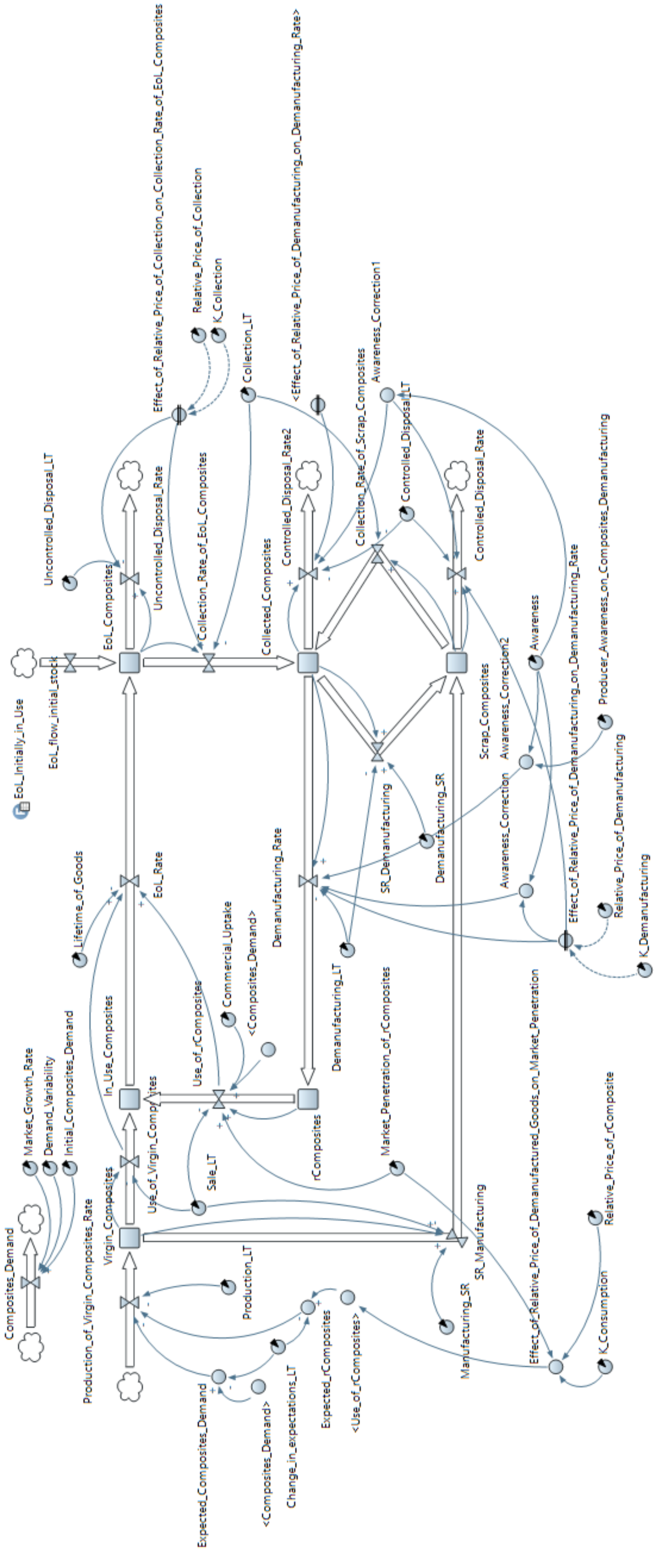
Technical System Part



Regulatory Environment Part



APPENDIX B: ENLARGED STOCK AND FLOW MAP



APPENDIX C: LIST OF THE MODEL'S EQUATIONS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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