Impact of Policy Actions on the Deployment of the Circular Value-Chain for Composites

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Abstract The effect of legislation on composites recycling can be both a driving force, such as in the case of End-of-Life Vehicle legislation, that is making it mandatory to reuse the materials used in vehicle manufacturing, or a boundary, increasing the burden to manufacturers reusing composite materials. As a consequence, a deep study on the impact of policies on the reuse of composites is fundamental to promote those actions boosting the deployment of circular value-chains. In this Chapter, a model based on System Dynamics theory, representing the entire industrial environment of composite materials, has been developed, leading to a prioritization of most impacting legislations, providing conclusions and recommendations derived from data.

Keywords System dynamics · Causal loop diagram · Stock and flow map · Legislation · Policies · Policy actions · Prioritization

1 Introduction

One of the major issues of the implementation of Circular Economy in the composites sector 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. 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

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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. 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 Circular Economy business models, and there is no alignment across the sector regarding the search for funds and pricing methodologies. 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 is evident, from the FiberEUse project, that integration and information exchange in the supply chain could boost circular practices on the market.

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 in 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 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 model evolution since recycled products may face resistance in their uptake, there are also present trends of increased environmental responsibility, which boost the development of circular solutions, opposing the belief.

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. Hence, establishing communication mechanisms between players involved in composites' recycling is foremost. Stakeholders' appeals regarding composites policy hold a lack of priority in legislators' agendas even though plastics are at the spotlight of discussions, a scenario that discourages agents from engaging in composite de-manufacturing activities.

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. For example, we see changes in legislations regarding the cost of landfilling (which can be quite cheap in some countries in Europe and beyond) which constitutes a barrier towards widescale adoption of CE. 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 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.

In terms of 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 above-mentioned directives are eventually complemented by country- and region-specific rules, as previously mentioned, with varying level of enforcement. These complementary rulings vary across countries and regions according to the specific circumstances within their territories. Consequently, there is a misalignment between regional regulations concerning FRP, yielding intricacies and inconsistency, which imply stakeholders in different locations must comply with divergent standards. Once more, the complexity related to the establishment of composites 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 composite materials waste management would be helpful, as it would define the practices to be adopted to handle waste at the time of their generation, possibly after the creation of standards for residues and offering waste generators information on such materials' pathways (for example Material Passports). 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, thus changing their perceptions about EoL materials and about the products they originate too.

2 State of the Art

System Dynamics (SD) is a field of study initially developed by Forrester [1] 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 [2].

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 [2].

Sterman [2] 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 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 evidence 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 [2].

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 [3] 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. [4] 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 [5] 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 [2, 6] 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. [7] 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 [8] models remanufacturing under System Dynamics to evaluate strategies aimed at improving a production system. Zamudio-Ramirez [9] investigates the economic aspects related to automobile recycling in the United States of America using SD, the same country analyzed by Taylor [10], 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. [11] 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 et al. [13] they adopt it for studying remanufacturing capacity planning in a closed-loop supply chain situation.

3 Rationale of the Work

The quantitative model is used to assess the effect of different scenarios of policy intervention on the adoption of recycled composites. The problem definition lies in the untapped value of disposed composites, while a circular alternative exists in the de-manufacturing of scrap and end-of-life (EoL) composites to produce recycled composites (rComposites). Perusing and promoting the circular route entails savings in raw materials and energy. To achieve a higher market share of rComposites, the SD model should capture the market dynamics of the composites sector while scenarios are built to showcase the long-term effects of different policies. In this section, the Causal Loop Diagram (CLD) is presented as a method of visualizing the interrelations between different variables in the system, embodying the mental model of causal relations. Next, the Stock and Flow map is presented and elements within are elaborated. The map depicts the dynamics of the technical system, while scenarios are simulated by manipulating proxy parameters that disturb the technical system in accordance with the CLD connections.

Causal Loop Diagram

The CLD, captured in Fig. 1, illustrates the causal relations between the technical system and the regulatory environment. CLDs are composed of variables that are interconnected by arrows with defined polarities that can be positive or negative. The arrows represent the causal links (cause-effect relations) between variables, while their polarity displays whether they vary in the same direction. Positive links mean the derivative of the dependent variable (effect) with respect to the independent (cause) is positive, or that the independent adds to the dependent. Negative links, on the other hand, means that the derivative is negative or that the independent variable subtracts from the dependent.

The technical system is composed of two subsystems: production and demand. Starting with the *demand subsystem* (Fig. 2), the expected demand of composites effects the production of virgin composites which satisfies the bulk of said demand. Yet, an increase in composites demand -an exogenous factor- also triggers the adoption of rComposites, which causes a positive effect on the rComposites demand and consequently reduces the production of virgin composites. The demand subsystem is not only connected to the production subsystem through the *production of virgin composites* variable, but also through connecting the demand of rCompositets to the de-manufacturing rate, creating the *demand feedback loop*. Feedback loops can either be reinforcing i.e., nurturing a certain behavior, or balancing i.e., halting a behavior. Demand feedback loop is a reinforcing one, meaning an increase in the de-manufacturing rate of rComposites will cause an increase of in-use rComposites thus higher expectations of rComposites demand which, after a time delay, leads to higher de-manufacturing rate.

Going into more details in the production system, depicted in Fig. 3, two more reinforcing feedback loops are noticed; namely: *composites circularity loop* and *scrap recycling loop*. The former captures the life cycle of recycled composites, since in-use composites after their useful life become EoL composites that in turn are collected and enter de-manufacturing process to become in-use composites once again. Collected composite materials have two pathways, either entering de-manufacturing processes or being controllably disposed. *Scrap recycling loop* tackles the other input source to de-manufacturing route, that is scrap from the production of both virgin and recycled composites. Collection of scrap composites reinforces collected composites which after processing and adoption become in-use composites. If the quality requirements are fulfilled, these reinforcing feedback loops sustain the input to de-manufacturing.

Production rates for both virgin and recycled composites are governed by resource constraints represented in lead times. While scrap rates are dependent on production

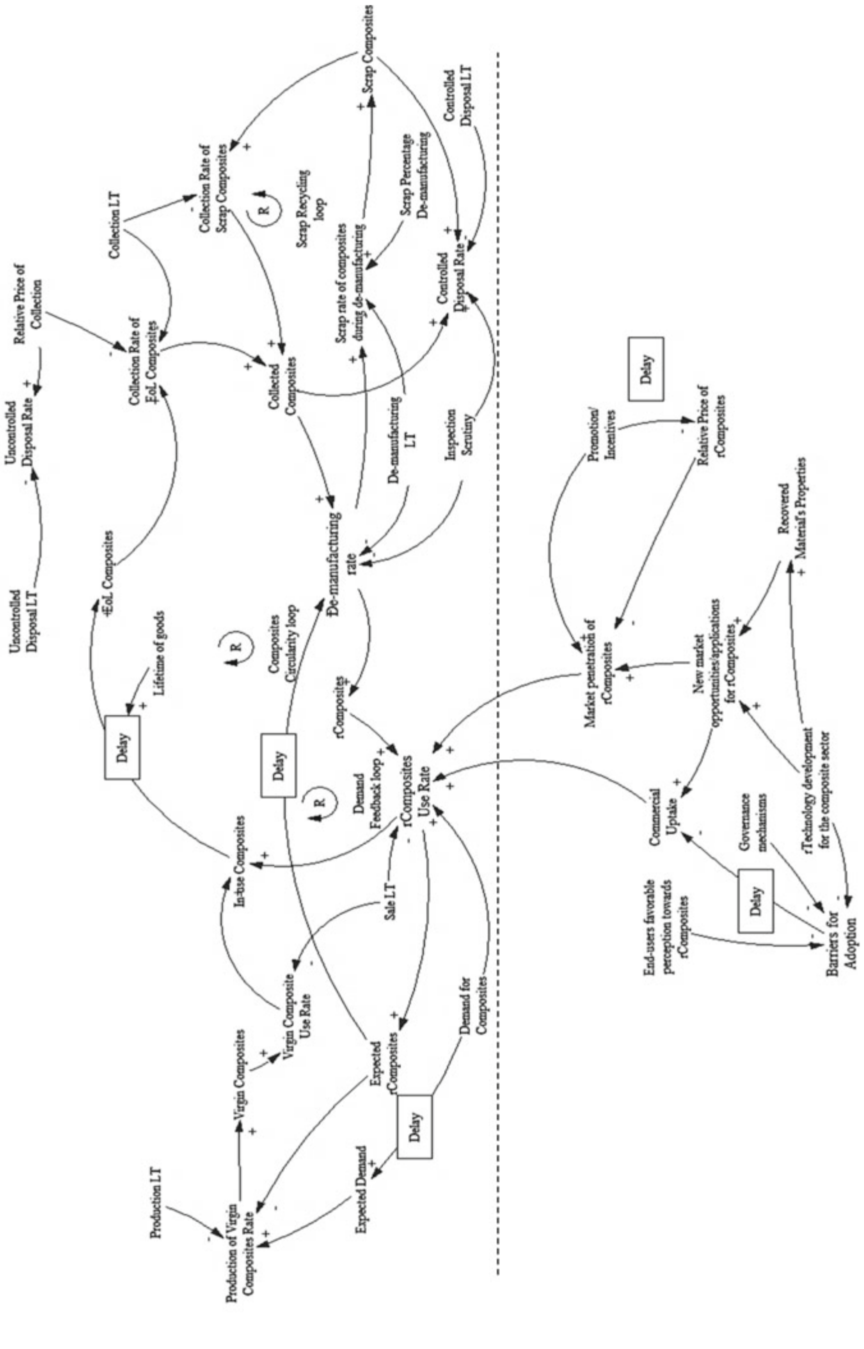

Fig. 1 Simplified causal loop diagram. Technical system upper half and regulatory environment bottom half. Developed using Vensim®

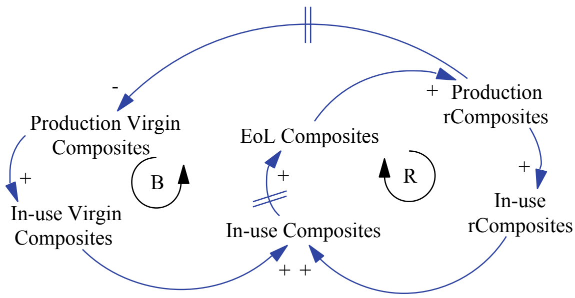

Fig. 2 Demand subsystem simplified causal loop within the technical system

rates by considering the average rate of material scrapped during manufacturing and de-manufacturing activities represented by scrap percentage. Collection and disposal rates also respond to lead times, but as they present alternative routes, they depend also on a price comparison between the options captured *in relative price of collection.* Composite materials that are not collected are uncontrollably disposed, meaning they do not enter any circular route.

The second part of the CLD refers to the regulatory environment, which influences the technical system across different levels of analysis. Starting with the notable interlinks between policies and the technical system, these links serve two goals (1) setting the baseline for how the sector operates now, and (2) instigating disturbances to the technical system to create scenarios. Stand alone, the regulatory environment contains the subsystems *barriers for adoption, regulatory framework,* and *profitability of operations.* Barriers for adoption are affected by a set of different variables to paint a complete picture of the hurdles facing rComposite adoption, the effect is seen after a delay in the variable *commercial uptake.* This variable influences the technical system, particularly in the interlink with *rComposite use rate* in accordance with goal 2. While in the *regulatory framework* the effects are more related to goal 1, that is controlling the lead-times of different operations i.e., collection, disposal, and (de)manufacturing. For example, transportation regulations affect the collection lead times in the technical system, while EoL and extended producer responsibility (EPR) regulations influence the decision point where flow diverges into disposal and collection, i.e., *relative price of collection.* As for the profitability of operations, the subsystem captures the effect of technological advancement on the resource constraints of rComposite production, as well as connecting the different policies to *relative price of rComposites* variable.

Elaborating on the proxy variables rooting from the regulatory environment and influencing the technical system, Fig. 4 demonstrates the causes tree of *market penetration of rComposites* variable. The variable can be directly influenced by promotion activities, yet it is also subject to the available applications for rComposites, as well as the price difference between recycled and virgin composites. Each of these two causes have their own causes tree. For example, *relative price of rComposite* is influenced by a policy that affects the price of virgin composites, as well as another policy that affects the price of rComposites. While applications of rComposites are constrained by the quality of collected composites, and the recycling technology

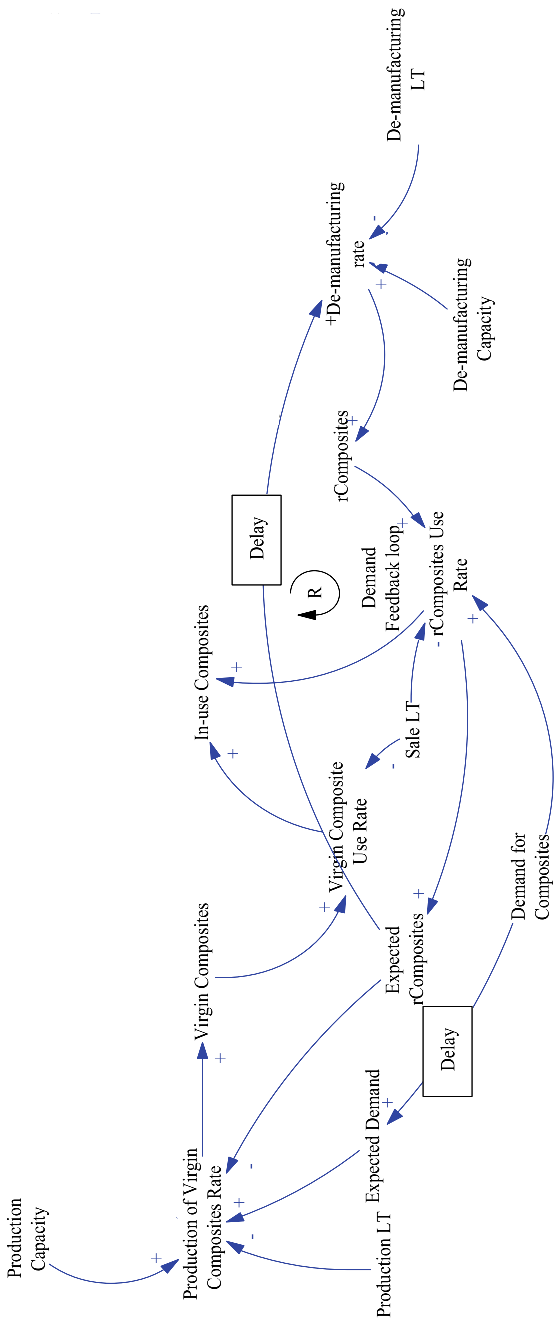

Fig. 3 Production subsystem causal loop in the technical system

used. Different causes that lead to changes in these proxy variables are formalized in the scenarios' definition section.

Stock and flow map

The stock and flow map provides the detailing of the model structure. In this subsection, elements are differentiated between stocks, flows, and other parameters. This map constitutes the quantitative model proposed. To capture policy effects, the time frame of the simulation needs to be higher than the lifecycle of composites. Since the composites use phase does not exceed 25 years, the model was assigned a time frame of 30 years. As previously mentioned, the logic behind this model is based on the existence of decision points which directs the flow of waste, along with proxy variables that mimic the effects of particular policies on the system. To capture realistic dynamics of the system, certain assumptions were necessary to narrow the focus of data collection and later on scenarios' definition. Particularly, the model tackles the carbon fiber market as a representative of FRP sector, and recycling as a representative of de-manufacturing activities. Detailing the assumptions will be discussed in the methodology section. Figure 5 captures the stock and flow model developed using AnyLogic software.

Systems are a network of stocks, flows and the information exchanged between them, through which stocks alter the flows. Stocks and flows can be represented by either diagramming or mathematics. Mathematically, stocks are the integrations over

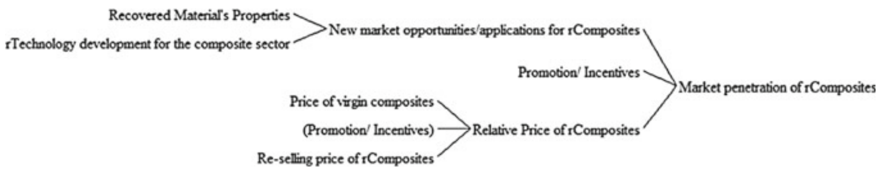

Fig. 4 Market penetration causes tree

Fig. 5 Stock and flow map. Developed using AnyLogic®

time of their flows, consequently flows are represented as the derivative of stocks over time. In diagramming, convention dictates that stocks are described with rectangles, while arrows, or pipes, depict flows. Additionally, flows contain valves to highlight the presence of regulators that provide control over them. Table 1 details the stock and flow elements within the simulation environment. The distinction between stocks and flows can be noticed by checking the unit of measurement. Since stocks represent cumulation of flow, the measurement is done in quantities such as [tons]. While flows require additional information to convey their meaning, such as time. Thus, flows' measurement can be quantities per time unit such as [tons/week].

This model mostly relies on a state dependent system approach, which means changes in the state of stocks depends on inflows and outflows. However, other exogenous variables and constants can play a role in altering the interactions between stocks and flows. Including these additional parameters in the modelling environment is done by using the elements *dynamic variables* and *parameters*. *Dynamic variables* can be constant or dynamic, while *parameters* are strictly static. Table 2 lists these elements, along with one instance of a *table function* that serves as an input to the model by returning argument of composites demand values per year.

4 Methodology

Following the introduction to the model and explanation of elements within, this section focuses on the applied methodology. Since the output is a rank-order of scenarios, it is important to highlight the assumptions and mathematical formulation of the model. Scenarios are run as experiments with the response representing the market share of recycled composites. The metric *used_rcomposites* calculates the cumulation of in-use recycled composites circulating the system with a weekly instance. This is done by assigning a stock to the flow *use_of_rComposites*, the series is stored for each experiment. This approach is replicated for the *use_of_virgin_composites*. Market share is calculated by dividing the *used_rComposites* at the end of the simulation run by the total used composites. Equations (1–3) elaborate the formulation of the Market share of rComposites dependent variable.

$$\text{Market Share} = \frac{\text{Used rComposites}}{Used\ Virgin\ composites + \text{Used rComposites}} \tag{1}$$

$$Used\_Virgin\_Composites = \int_0^t Use\_of\_Virgin\_Composites \tag{2}$$

$$Used\_rComposites = \int_0^t Use\_of\_rComposites \tag{3}$$

Table 1 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 end-of-life stage
	In_Use_Composites	[tons]	Represents the amount of composite material currently being used in applications by the market
	Scrap_Composites	[tons]	Represents the amount of composite material rejected either prior to or during processing
	Used_rComposites	[tons]	Represents the accumulated amount of recovered composites used by the system
	Used_Virgin_Composites	[tons]	Represents the accumulated amount of virgin composites used by the system
	Virgin_Composites	[tons]	Represents the amount of virgin composites available for the market
	rComposites	[tons]	Represents the quantity 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 materials are 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

(continued)

Table 1 (continued)

Type of element	Name	Unit of measure	Description
	Controlled_Disposal_Rate2	[tons/week]	Represents the rateatwhich collected composites are sent to disposal pathways
	Demanufacturing_Rate	[tons/week]	Represents the processing rate of de-manufacturing activities
	EoL_flow_initial_stock	[tons/week]	Represents the rate of composite material known to be already in use and reaching EoL state
	EoL_Rate	[tons/week]	Represents the rate of composite material entering 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 scrapped duringde-manufacturing processes
	SR_Manufacturing	[tons/week]	Represents the rate of composite material scrapped during virgin manufacturing
	Uncontrolled_Disposal_Rate	[tons/week]	Represents the rate at which EoL composite material is discarded incorrectly
	Use_of_rComposites	[tons/week]	Represents therateatwhich 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

Table 2 Dynamic variables and additional parameters

Type of element	Name	Unit of measure	Description
Dynamic variable	Effect_of_Relative_Price_of_Collection_on_Collection_Rate_of_EoL_Composites	N/A	Represents the impact of the relative price of collection on the rate of collection of EoL composites
	Effect_of_Inspection_Scrutiny_on_Demanufacturing_Rate	N/A	Represents the impact of the inspection scrutiny on the flow of collected composites into the de-manufacturing route
	Effect_of_Relative_Price_of_Demanufactured_Goods_on_Market_Penetration	N/A	Represents the impact of the relative price of the de-manufactured goods on their utilization by the market
	Expected_Composites_Demand	[tons/week]	Represents the volume of composites players expected to be demanded at a given moment
	Expected_rComposites	[tons/week]	Represents the volume of recovered composites expected to be entering the market at a given moment
Parameter	Awareness	N/A	Element that determines whether there is awareness aboutde-manufacturing pathways
	Change_in_expectations_LT	[weeks]	Represents the average delay for expectations to change in the face of new evidence

(continued)

Table 2 (continued)

Type of element	Name	Unit of measure	Description
	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
	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 activities

(continued)

Table 2 (continued)

Type of element	Name	Unit of measure	Description
	K_Consumption	N/A	Measure of stakeholders' price sensitivity on the consumption of FRP
	K_Technology	N/A	Represents the sensitivity to the input scrap to the recycling technology used
	Lifetime_of_Goods	[years]	Representstheaverage duration of a single 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 composites
	Accepted_EoL_Composites	N/A	Represents the percentage of collected composites that enter the de-manufacturing route

(continued)

Table 2 (continued)

Type of element	Name	Unit of measure	Description
	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_rComposite	N/A	Represents the ratio between the price of a recovered and that of a virgin composite
	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

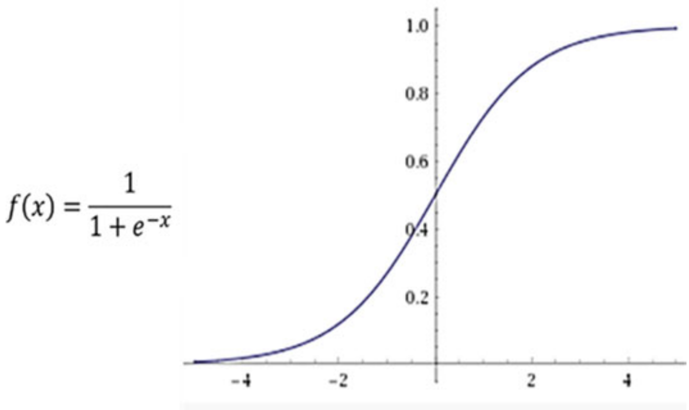

Fig. 6 Sigmoid function and curve

As previously mentioned, the model depends on decision points that direct the flow of waste material either towards de-manufacturing activities or outside the system. The mathematical representation chosen for these decision rules is the sigmoid function, or S-shape curve, Fig. 6 shows the typical equation and corresponding sigmoid curve. The use of sigmoid function for decision rules is common in literature, Vlachos et al. [13] utilized it for reverse logistics decisions.

In this work, sigmoid functions are employed on 3 instances. (A) reverse logistics decision point of EoL composites collection, (B) reverse logistics decision point of waste disposal, and (C) market penetration decision point for rComposites. The regulation of flows out of the decision points in the stock and flow map is performed by adding an effect variable. This can be seen in the sigmoid formulation of dynamic variables:

A. *Effect_of_Relative_Price_of_Collection_on_Collection_Rate_of_EoL _Composites* represents the end user's decision whether to send the EoL composites to collection routes or just discard them by sending them to landfills. The model assumes consumers base their choice on economic factors, with a proxy of relative price of collection. The effect is adjusted by including a price sensitivity parameter (*K_Collection*), Eqs. (4) and (5) show this mathematical formulation.

$$\text{Effect\_of\_Relative\_Price\_of\_Collection\_on\_Collection\_Rate} \\ \text{\_of\_EoL\_Composites} = \frac{1}{(1 + e^{-K\_\text{Collection} * \text{Relative\_Price\_of\_Collection}})} \quad (4)$$

$$\text{Relative\_Price\_of\_Collection} = \frac{\text{Cost\_of\_Collection}}{\text{Cost\_of\_Disposal}} \quad (5)$$

B. *Effect_of_Inspection_Scrutiny_on_Demanufacturing_Rate* represents the de-manufacturers decision whether to accept the collected composites and allow them to enter de-manufacturing processing or reject them to be sent to appropriate disposal. Like the previous variable, the effect is adjusted by a sensitivity parameter (*K_Technology*) that signifies the sensitivity of the recycling technology used to the input waste mix.
C. *Effect_of_Relative_Price_of_Demanufactured_Goods_on_Market_Penetration* presents composites exiting de-manufacturing processes with 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, there will be an incentive for their adoption. The effect is adjusted by multiplying a parameter of price sensitivity of users *(K_Consumption*) to the relative price of recycled composites (price of recycled composites/price of virgin composites).

Time delays are incorporated in this model as another source of dynamic behavior in the system, along with the previously mentioned loops. In SD theory, delays can either create oscillation and instability, or alternatively filter out noise. Time delays are elements whose output laggardly trails the input, hence, inside every delay there is an embedded stock, in which the difference between the output and the input accumulates. There are 2 types of delays: material delays and information delays. Material delays refer to delays to physical flow of materials, which entails conservation of flow, i.e., elements leaving the delay stock can only do so if they previously entered it. While 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. Equations (6) and (7) respectively show the general formulation of material delay and the first order delay equation. While Eqs. (8) and (9) showcase the formulation for information delay in a generalized form and first order delay equation.

$$\text{Outflow}(t) = \text{Inflow}(t - \text{Average Residence Time}) \tag{6}$$

$$\text{Outflow}(t) = \frac{\text{Accumulated inflow}}{\text{Average residence time}} \tag{7}$$

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

$$\text{Change in perceived value} = \frac{\text{Reported Value} - \text{Perceived Value}}{\text{Adjusted time}} \tag{9}$$

The simulation baseline focuses on the market of carbon fiber reinforced polymers (CFRP), while the recycling technology used for de-manufacturing activities is thermal recycling. Thermal recycling of CFRP is a viable economic solution for industrial scale recycling. At the end of the simulation period (30 years) the market share of rComposites is **5.8%**. Table 3 details the parameters' values for the baseline along with references when applicable.

Following the baseline run, selected parameters are manipulated to infer policy intervention. For each experiment, the parameters are assigned value ranges and step variations in accordance with the CLD and inputs from industry experts within the FiberEUse project. Table 4 illustrates the parameters' setting for different simulation scenarios. In *New Applications*, it can be noted that 2 scenarios are defined under it. The first refers to a scenario where the new applications for rComposites are coupled with an increase of accepted composites. While the second conservatively tackles just the increase in market penetration linked to broadening the use of rComposites in the CFRP sector. In *Technological Development*, the advancement of thermal recycling technologies -meaning more efficient operations- can lower the price of rComposites and increase the quality of rComposites which entails higher market penetration. In *Increase of perception*, awareness activities on the quality of rComposites directly affects the consumer uptake, while incentives to promote recycled components means intentionally lowering the price of rComposites. Whereas in *Trade Barriers*, the price of the virgin composites increases due to tariffs imposed, which also leads to an increase in production lead times. Finally in *Risk Aversion*, increasing the de-manufacturing rate by relieving the inherent risk in production of rComposites is related to an overall increase in rComposites stock.

5 Numerical Results

In this section, each scenario is analyzed and its corresponding effect to the market share of rComposites is reported. The scenarios are ordered in descending fashion relating to effect on the response parameter. Table 5 summarizes the scenarios, effect in increased market share, proxy parameters manipulated, and policy interpterion.

Elaborating on the numerical results, each scenario shall be presented in the following format: (i) tabulated presentation of parameters' step variations with their corresponding market share values at the end of simulation, and (ii) line chart for each setting with a weekly instance. Further, the trend of the results will be analyzed and tied to policy actions.

I. **New Applications Scenarios**

Market penetration represents the extent to which recycled composites can be employed in different applications. The range of increase reported in Table 6 leads to the highest adoption effect, particularly if coupled with allowing more collected composites to enter the circular route. The effect of increasing the accepted input stream to de-manufacturing comes into play when coupled with a high market penetration. The takeaway here is that expanding the range of rComposites applications comes as a priority to unlock positive effects of improved collection rates and recoverable quality.

Table 3 Simulation baseline parameters values

Parameter	Value	Unit	Reference
Awareness	True	N/A	Assumption that composites sector is aware of recycling option
Change_in_expectations_LT	1	[weeks]	
Collection_LT	0,5	[weeks]	
Commercial_Uptake	60%	N/A	
Controlled_Disposal_LT	0.5	[weeks]	
Demand_Variability	5%	N/A	Low variation assumed based on the study of Vlachos, Georgiadis and Iakovou [13]
Demanufacturing_LT	1	[weeks]	Assumed to be equal to virgin production lead time
Demanufacturing_SR	15%	N/A	Assumed to be equal to virgin manufacturing scrap rate
Initial_Composites_Demand	48,488	[tons/year]	Source: FiberEUse
K_Collection	2.5	N/A	
K_Consumption	2.5	N/A	
K_Technology	10	N/A	
Lifetime_of_Goods	20	[years]	Source: Lefeuvre et al. [14]
Manufacturing_SR	15%	N/A	
Market_Growth_Rate	4%	N/A	
Market_Penetration_of_rComposites	15%	N/A	Source: FiberEUse
Producer_Awareness_on_Composites_Demanufacturing	100%	N/A	Assumption that players are aware of recycling option
Production_LT	1	[weeks]	Source: Vlachos, Georgiadis and Iakovou [13]
Relative_Price_of_Collection	32%	N/A	
Accepted_EoL_Composites	70%	N/A	

(continued)

Table 3 (continued)

Parameter	Value	Unit	Reference
Relative_Price_of_rComposite	60%	N/A	Source: Vo Dong et al. [15] The cost of the recycling process was used as a proxy for the cost of de-manufacturing
Sale_LT	0.5	[weeks]	
Uncontrolled_Disposal_LT	0.2	[weeks]	

Table 4 Parameter's settings for each scenario

Scenario	Parameter	Value range	Step variation
New applications I	Ratio of accepted EoL composite	70–90%	20%
	Ratio of market penetration	15–60%	15%
New applications II	Ratio of market penetration	15–60%	15%
Technological development	Relative price rComposites	60–40%	−10%
	Ratio of market penetration	15–35%	20%
Increase of perception	Commercial uptake	60–100%	20%
	Relative price rComposites	60–40%	−10%
Trade barriers	Production lead time virgin composites	1–5	4
	Relative price rComposites	60–20%	−20%
Risk aversion	De-manufacturing rate	Expected demand + 1 to 1.2 tons	0.1

In Fig. 7, the simulation baseline is represented by the yellow line. Further, the use of rComposites values with low market penetration coincide atop each other represented by the blue line. The effects of increasing market penetration while maintaining the baseline ratio of accepted composites is represented by the gray line. Finally, the double effects of increasing input stream and increasing market penetration is represented by the green line.

Table 5 Rank order of scenarios and policy summary

	Scenario name	Parameter(s)	Policy summary	Market share (%)
1	New applications	– Accepted EoL composites – Market penetration	– EoL regulation – Incentives for cross-sectorial collaboration – Compulsory use of recycled material – Green company policy/PR/image building	17.1
2	New applications	– Market penetration		15.8
3	Technological development	– Relative price of rComposites – Market penetration	– R&D subsidy – EPR regulation – Economic viability	12.8
4	Increase of perception	– Commercial uptake – Relative price of rComposites	– Consumer awareness activities – Sales subsidy	9.9
5	Trade barriers	– Relative price of rComposites – Production LT virgin composites	– Tariffs against import – Shortage in availability	6.9
6	Risk aversion	– De-manufacturing rate	– Production subsidy – Increase in number of agents	6.6
7	Baseline			5.8

Table 6 New applications scenarios results

Market penetration	Accepted composites	Market share rComposites (%)
0.15	0.7	5.9
0.45		14.1
0.6		**15.8**
0.15	0.9	5.9
0.45		14.1
0.6		**17.1**

II. Technological Development Scenario

Investing in the development of recycling technologies can directly affect the price of rComposites, since the recycling operations will be more efficient. Furthermore, new technologies can widen the scope of applications that rComposites can enter, since the quality of rComposites are expected to increase with newer technologies. The range of price decrease, reported in Table 7, can also be attributed to extended producer responsibility regulations. Since sorting activities of collected composites are responsible for a big portion of recycling cost. Thus, having a clean stream of waste would decrease the cost of de-manufacturing and consequently price of rComposites.

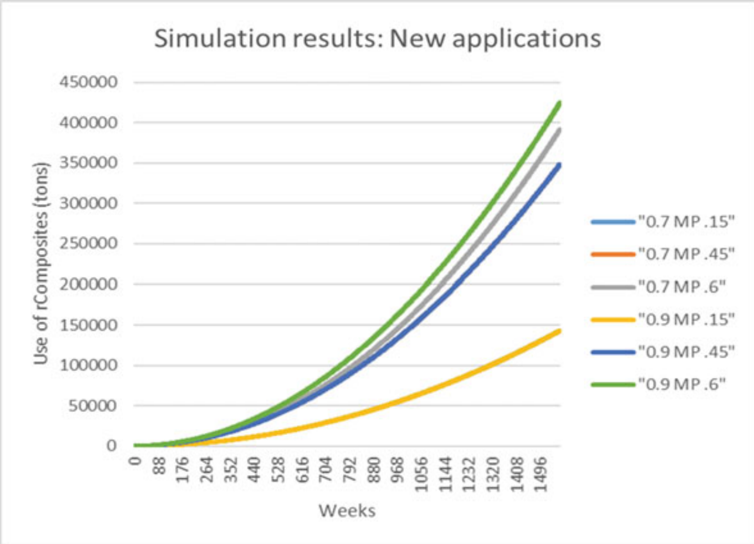

Fig. 7 New applications results trend for different settings

Table 7 Technological development scenario results

Relative price	Market penetration	Market share rComposites (%)
0.6	0.15	5.87
0.5		6.19
0.4		6.47
0.6	0.35	11.76
0.5		12.31
0.4		**12.78**

In Fig. 8, the market penetration changes lead to the creation of two groups. First the increase in market penetration coupled with decrease in rComposites price, represented by the green line. Then the gradual decrease of market share as the effect of price decrease is removed. The second group, represented by blue lines, show the case of just lowering the prices without an increase in market penetration.

III. **Increase in Perception Scenario**

Commercial uptake represents the willingness of FRP market to embrace recycled components in applications that rComposites can be utilized in. Increasing the commercial perception of recycled products has a direct effect on the rate of adoption and consequently the market share of rComposites. Awareness activities can play an important role in relieving the stigma on recycled options as inferior or lacking in quantities. Economic incentives are also essential to

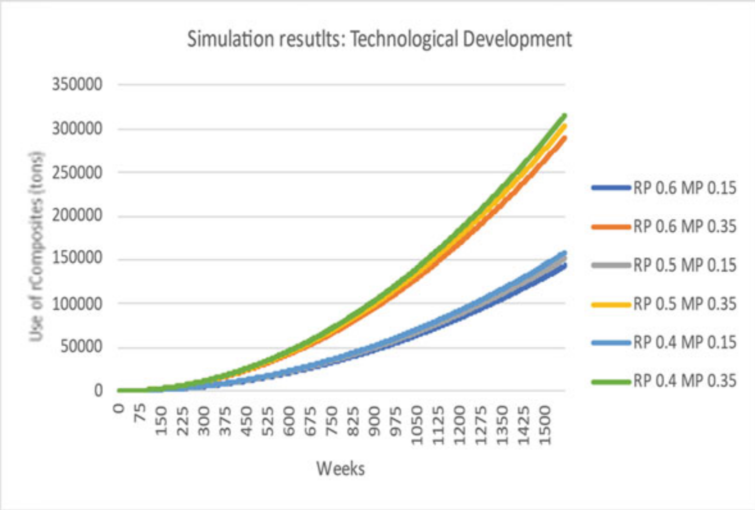

Fig. 8 Technological development results trend for different settings

encourage the sector to adopt recycled components, represented in Table 8 by relative price parameter.

In Fig. 9, the effect of increasing the commercial uptake parameter while decreasing the price of rComposites leads to higher adoption rate. It can be also noted that while decoupling the price parameter (green, dark blue and yellow lines) leads to comparatively lower market share, yet the effect of increasing uptake remains more significant.

IV. **Trade Barriers Scenario**

Trade barriers scenario tackles the volatility of raw material imports coming to the EU, these imports are crucial for the production of virgin composites. Imposing tariffs would lead to an increase of the price of virgin composites, represented in the parameter relative price. It can be noted that the range of decrease in this scenario is bigger to convey the price gap between virgin and recycled composites. Additionally, delays in shipment and other import hurdles

Table 8 Increase in perception scenario results

Commercial uptake	Relative price	Market share rComposites (%)
0.6	0.6	5.9
0.8		7.5
1		9.0
0.6	0.4	6.5
0.8		8.3
1		**9.9**

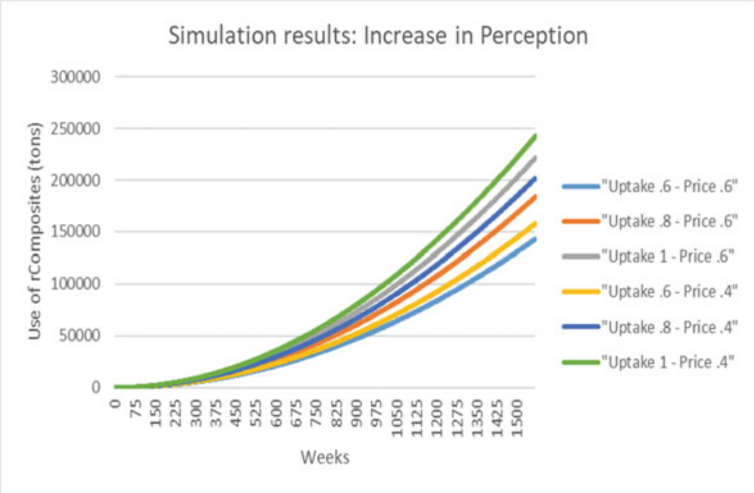

Fig. 9 Increase in perception results trend for different settings

would cause an increase in the production lead time for virgin composites manufacturing. Table 9 highlights the consequent increase in rComposites market share.

In Fig. 10, the effects of increased lead time and lower relative price are depicted. It is worth noting that on its own, the increase of production lead time did not yield significant change to the baseline; the parameter is mentioned for logical consistency. In order to reach significant increase in rComposites adoption, lead time increase should have been much higher which would not have conveyed a realistic market behavior. The effects of trade barriers are thus shown to be short-term, hence its low rank.

V. **Risk Aversion for De-manufacturers Scenario**

The production rate of de-manufacturing is responsible for the availability of rComposites in market, and consequently their adoption rate. This scenario envisions the effect of increasing the recycled composites inventory, as a sector, as a factor of de-manufacturers risk aversion. Table 10 shows how with small changes in production policies -stemming from higher risk tolerance -leads to high increase in market share of rComposites. From a regulatory perspective,

Table 9 Trade barriers scenario results

Production LT virgin composites	Relative price	Market share rComposites (%)
5	0.6	5.88
	0.4	6.49
	0.2	**6.91**

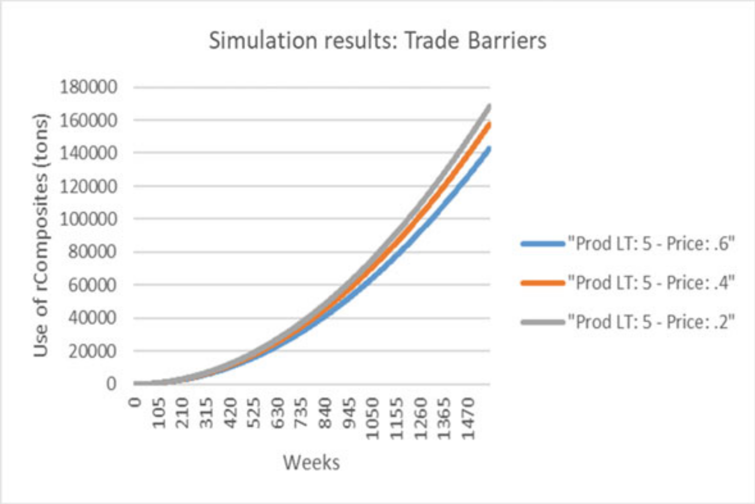

Fig. 10 Trade barriers results trend for different settings

Table 10 Risk aversion scenario results

De-manufacturers risk	Market share rComposites (%)
Base line	5.87
Expected demand + 1.1t	6.35
Expected demand + 1.2t	**6.58**

subsidizing recycling activities would encourage de-manufacturers to increase production leading to a boom in the rComposites sector. Another interpretation of aggressive production when compared to expected demand would be an increase in total number of players or de-manufacturers (Fig. 11).

6 Conclusion

In this Chapter, the impact of different policy actions on the deployment of the circular value-chain for composites has been evaluated through a mathematical approach. In particular, a model based on System Dynamics have been developed. The first step has been the creation of the Causal Loop Diagram to identify the interrelations among different actors in the composite sector. In the second step the dynamics of the system have been depicted through the use of Stock and Flow map. Finally, this methodology has been applied to different selected scenarios to identify the prioritization order of policies affected those specific scenarios. Table 11 summarizes policy actions against the level of impact on rComposites market share.

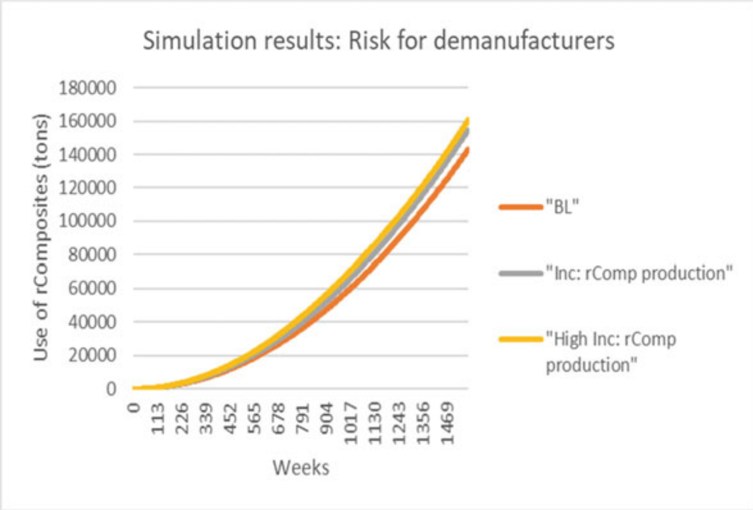

Fig. 11 Risk for de-manufacturers results trend for different settings

Table 11 Summary of policy actions

Policy actions	Level of impact
Creation of a unified legislation at EU level	High
Incentives for cross-sectorial collaboration	High
Force the reuse/recycling of composite materials (as in automotive sector)	High
Green trademarks and incentives for virtuous companies	High
R&D subsides and incentives	Medium
EPR regulation	Medium
Economic viability	Medium
Consumers' awareness activities	Medium
Sales subsidy for products embedding recycled materials	Medium
Tariffs against import of virgin materials	Low
Face shortage in availability	Low
Production subsidies	Low
Favor the increase in number of recyclers	Low
Tighten regulation on landfilling (till to prohibition)	Low
Facilitate cross-boundary transportation	Low

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