Sustainable supply chains: an integrated modelling approach under uncertainty

Bruna Mota , Maria Isabel Gomes , Ana Carvalho ,
Ana Paula Barbosa-Povoa

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Highlights

- ToBLoOM – Triple Bottom Line Optimization Modelling tool – is presented
- Three pillars of sustainability are modelled: economic, environmental and social
- GDP-based social indicator is proposed and ReCiPe is used as environmental objective
- Interdependent supply chain strategic/tactical decisions are analysed under uncertainty
- Case-study of European based company with markets in Europe and emergent countries

Sustainable supply chains: an integrated modelling approach under uncertainty

Bruna Mota[a] (**Corresponding author**)
e-mail: bruna.mota@tecnico.ulisboa.pt
Phone number: (+351) 927 562 423

Maria Isabel Gomes[b]
e-mail: mirg@fct.unl.pt

Ana Carvalho[a]
e-mail: anacarvalho@tecnico.ulisboa.pt

Ana Paula Barbosa-Povoa[a]
e-mail: apovoa@tecnico.ulisboa.pt

[a]Centro de Estudos de Gestao, IST, de Lisboa, Av. Rovisco Pais, 1049-101 Lisboa, Portugal
[b]Centro de Matematica e Aplicacoes, FCT, Universidade Nova de Lisboa, Monte de Caparica, 2829-516 Caparica, Portugal

Abstract

This work presents ToBLoOM – Triple Bottom Line Optimization Modelling, a decision support tool for the design and planning of sustainable supply chains. It consists of a multi-objective mixed integer linear programming model which integrates several interconnected decisions: facility location and capacity determination; supplier selection and purchase levels definition; technology selection and allocation; transportation network definition including both unimodal and intermodal options; supply planning; product recovery and remanufacturing. The three pillars of sustainability are addressed as objective functions: economic, through Net Present Value; environmental through the Life Cycle Analysis methodology ReCiPe; and social through a developed GDP-based metric. Uncertainty is considered using a stochastic ToBloOM. This applied to a case of a European based company with markets in Europe and South America. This work contributes to the literature by building on several identified research gaps such as the need for an integrated approach that allows simultaneous assessment of different interacting supply chain decisions, the need to explicitly assess the environmental impact in closed-loop supply chains, the need to assess the impact of supply chains on society, and the need for a multi-objective tool that includes all the three pillars of sustainability. Strategies towards a more sustainable supply chain are also derived from this work.

Keywords

Triple bottom line, sustainability, closed-loop supply chain, design and planning, technology selection, intermodal transportation, stochastic optimization

1. Introduction

Sustainable development has been defined by the Brundtland Commission [1] as the "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". Not only economically or environmentally but considering all three pillars of sustainability: economic, environmental and social [2]. In order to achieve such development industries need to be able to design, plan and operate their entire supply chain considering a sustainability path that will not compromise the sustainability of the other players involved [3, 4]. The main problem is the complexity of such system. Supply chain design on itself encompasses complex decisions involving several products, entities, players and several other variables [5, 6]. If choosing or if having to close the loop for end-of-life product recovery these variables involve an even greater degree of complexity and hence a well-designed supply chain becomes an even more important asset [7, 8]. Adding sustainability concerns further increases this complexity. However, it is a path that must be taken considering the current pressures. Governmental legislation has assigned to some industries the responsibility of handling their end-of-life (EOL) products, as is the case with directive 2002/96/EC [9] on waste electrical and electronic equipment (WEEE). ISO 26000:2010 offers guidance on social responsibility encouraging companies to go beyond legal compliance [10]. Additionally, public awareness has been shown to have a significant impact on big industry players which are being held responsible for practices and incidents occurring in their supply chains. A well-known case is the Nike sweatshops scandal in 1991 which has led the company to completely change its corporate social responsibility strategy. Scandals of this dimension continue to be exposed by social media and NGOs across industries: fashion (e.g. H&M), food (e.g. Hershey, Tesco, Walmart), automotive (e.g. Volkswagen), electronics (e.g. Apple). On the other hand sustainability is also being looked at as a business opportunity rather than a constraint through profitable value recovery from EOL products [8].

Production and transportation are critical activities in the sustainable performance of the supply chain given its high environmental impact [11]. Furthermore, these directly influence other decisions, both strategic (3-10 years horizon) and tactical (1-12 months horizon), such as supplier selection, production/remanufacturing technologies selection, product recovery strategies, transportation network definition and facility location. In turn all of these decisions impact the company’s social contribution, not only related to the employment level but also to the influence that the employment will have on the local communities and at society in general. The sustainability lever is significantly larger in network design problems since it involves investment and other strategic decisions which define the boundaries within which subsequent tactical and operational decisions can be taken. Therefore, in order to maximize the degree of optimization freedom, strategic and tactical decisions should be analysed simultaneously.

In this context and in our collaboration with industry where our focus has been sustainability assessment, the need to design a generic optimization tool became clear. This work presents the resulting decision support tool – TOBLOOM - that optimizes the referred decisions. Additionally it shows the application of such tool through the solution of a case-study and analyses the mix of decisions that leads to a more sustainable supply chain concluding on valuable managerial insights to supply chain managers. Thus three research questions are addressed in this paper:

RQ1: Can interconnected strategic and tactical decisions be introduced in a generic and multi-objective modelling approach to address closed-loop supply chain design and planning?

RQ2: How to measure the economic, environmental and social impact of such decisions?

RQ3: What decisions should be taken towards a more sustainable supply chain?

To answer these questions a Multi-objective Mixed Integer Linear Programming (MoMILP) model – TOBLOOM - is developed for the design and planning of closed-loop supply chains. It integrates strategic decisions (such as facility location and capacity determination; supplier selection and technology selection and allocation; transportation network definition, which includes both unimodal and intermodal options) with tactical ones (such as purchase levels definition; supply planning; and product recovery and remanufacturing). The three pillars of sustainability are introduced as objective functions. The economic pillar is measured through Net Present Value (NPV). The environmental impact of production and remanufacturing, transportation and facility installation are measured through ReCiPe, a Life Cycle Analysis (LCA) methodology [12]. The social pillar is measured through a socio-economic indicator applied by the European Union in its Sustainability Development Strategy – Gross Domestic Product (GDP). The model is applied to a representative case of a European based company with markets not only in Europe but also in South America, namely in Brazil.

The paper is structured as follows. In section 2, background literature is presented. Since the paper proposes a generic closed loop supply chain model this literature review will focus on closed loop supply chain research. However, it is worth noting that as depicted in section 4.4 the model is easily generalized to a simply forward or simply reverse supply chain. Also discussed in this literature review are the sustainability indicators that have been included in mathematical models for supply chain design and planning. In section 3 the problem is defined and the developed model is characterized in section 4. Section 5 concerns the case study description, being the results presented and discussed in section 6. Here the importance of an integrated approach is demonstrated, environmental sustainability hotspots are identified, tendencies towards a more socially responsible supply chain are discussed, product recovery policies are questioned and the robustness of the solutions is shown. Lastly, in section 7 final conclusions and future work directions are presented.

2. Literature review

Supply chain design and planning problems involve a set of different strategic-tactical decisions. They will typically include the determination of the number, capacity and location of entities to be installed, transportation link establishment and the flow of products between the installed entities so as to satisfy the clients' needs. However, additional decisions can be integrated in such type of problems, namely supplier selection, product recovery, inventory planning [13]. In terms of origin and destination of product flows it is possible to distinguish three types of supply chains: forward, reverse and closed-loop supply chains. The forward supply chain represents the supply chain in its classical definition where the goal is to satisfy the clients demand [13]. It was mostly due to environmental pressure from clients, NGOs and governmental institutions that the two other types of supply chains emerged [14]. In 1997 Fleischmann *et al.* [15] surveyed the, at that time, recently emerged field of reverse logistics, defining reverse logistics as "the logistics activities all the way from used products no longer required by the user to products again usable in a market". Meanwhile the concept of closed-loop supply chains was proposed by Guide and Van Wassenhove [16] as the supply chains where both flows, forward and reserve, are considered simultaneously. In this paper it was shown that companies that have been most successful with their reverse logistics are those that closely coordinate them with the forward supply chains, managing the so proposed closed-loop supply chain. One decade later closed-loop supply chains continues to increase in importance with environmental regulations and resource depletion being the main drivers of this environmental sustainability path. However, although adding complexity to the problem, effectively managed closed-loop logistics not only improve the company's image towards the environmentally concerned customer but can also result in higher profitability [17].

In this growing research field literature is evolving rapidly. A seminal work on closed-loop supply chain modelling is that of Fleischmann *et al.* [18], which studies the impact of product recovery on logistics network design. In this study it is concluded that the influence of product recovery is very much context dependent. In some cases integration of this activity in existing logistics structures might be viable while other cases may require redesigning the supply chain in an integral way. Since this work several have followed. Salema *et al.* [19] builds on this model incorporating capacity limits and uncertainty on demand and return in a multi-product formulation. Later the same authors integrate strategic and tactical decisions by considering two interconnected time scales: a macroscale that gives the time horizon discretization, where demand and return values must be satisfied, and a micro time that allows for more detailed planning on attaining this satisfaction[14]. Cardoso et al. [7] analyse the integration of reverse logistics activities under demand uncertainty, considering the maximization of the expected net present value as the objective function and modelling decisions such as sizing and location of facilities, installation of processes, forward and reverse flows, as well as inventory levels. This work was later extended, by the authors, to address uncertainty while characterizing resilient closed-loop supply chains [20]. Georgiadis et al. [21] explore flexible long-term capacity planning coupled with uncertainty in demand, sales patterns, quality and timing of end-of-use product returns. Mostly economic or quality-related objective functions have been used in the referred models. However, environmental and social sustainability concerns are beginning to be included as well. Paksoy et al. [22] analyse supply planning considering emissions costs in the economic objective function (total cost minimization) as well as profit from recycled products maximization. Chaabane et al. [23] explicitly include an environmental objective function, which minimizes global warming potential, thus minimizing carbon emissions. Total logistics costs measure the economic performance of the supply chain. Decisions analysed include carbon management, namely carbon credits purchase or sale. Most of the works found in literature only focus on the economic and environmental pillars of sustainability. A few exceptions exist namely the works of Devika et al. [24] and Mota et al. [25] where the three pillars of sustainability are considered as objective functions. In the first work [24] the economic pillar is measured through supply chain cost, the environmental objective function quantifies the environmental impact of the supply chain and the harm caused by the products, and the social objective function quantifies the created job opportunities and workers' safety. In the second referred work [25], a multi-objective mixed integer supply chain design and planning model is presented having the minimization of total supply chain cost as the economic objective function, the minimization of the Life Cycle Assessment (LCA) indicator ReCiPe as the environmental objective function, and having a developed socio-economic indicator that benefits the location of the supply chain activities in less developed regions as the social objective function. The Pareto frontier is obtained allowing the visualization of the trade-offs among the different objective functions. This work presents some limitations such as: not being globally applied, only regionally; returning a limited set of decisions namely the network structure, production, inventory and supply planning; consequently only considering as possible variations in the environmental impact of transportation and facility installation (and not production which was concluded to be the biggest contributor to the environmental impact of the analysed supply chain); and considering the supply chain costs instead of the profit.

Several reviews are available covering a variety of topics and several research gaps have been identified in literature, namely:

- The need for integrated modelling approaches that incorporate issues other than location-allocation such as technology selection (i.e. production/remanufacturing technologies) and intermodal transportation, as identified in several reviews [3, 4, 17, 26-30], additionally to generic modelling features of economic, environmental and social aspects of sustainable supply chains [27]. The authors review the main modelling techniques and topics within closed-loop supply chain research and conclude that the larger the integration the better the results will be across the supply chain since less assumptions among interconnected decisions are made, allowing to search among a larger number of combinations. To our knowledge some integrated modelling approaches exist however with a smaller degree of integration than the one proposed in this paper (e.g. [29, 31-34]).
- The need for closed-loop supply chain models that explicitly deal with the environmental impacts, as emphasized by Dekker et al. [35]. The authors state that simply closing the loop does not guaranty a reduction in the supply chain's environmental impact.
- The need for models that assess the impact of supply chains on people or society, as pointed out by Tang and Zhou [36].
- The need for multi-objective decision making that includes appropriate environmental and social objectives, and for integration of operational decision variables (e.g. production planning and inventory decisions) with tactical (e.g. network flows) and strategic ones (e.g. facility location and capacity determination), as pointed out in the review by Govindan *et al.* [13].

The referred points clearly identify the research gaps in closed-loop supply chain literature that are targeted with the present work.

Overall, research on the different pillars of sustainability has evolved quite differently. While environmental sustainability research has shown a significant growth in recent years, research on social sustainability is still in its infancy.

Research on environmental impact assessment is diverse in terms of applied methodologies. Focusing on optimization-oriented environmental impact assessment, and as reviewed by Eskandarpour *et al.* [28], two options appear in the literature: Life-Cycle Assessment (LCA) based models and partial assessment of environmental factors. Partial assessment of environmental factors focuses on one or more environmental aspects such as GHG emissions, waste and energy use, according to what is more relevant to a given industry or case-study. This approach is used when obtaining environmental data and/or modelling the whole supply chain is too challenging. It also can be viewed as an intermediate step towards full integration in an industrial context. In turn, LCA is the most commonly used technique and has been identified by the European Commission as the best available framework for the assessment of the potential environmental impacts of products and processes [37]. LCA allows the quantification of all emissions and resources consumed as well as the consequent environmental and health impacts and resource depletion issues associated with any products or services. It covers the entire life cycle of the product or service, from extraction of resources, production, use, recycling and disposal [38]. There are several LCA methods available in the literature. Different models are used in the characterization step, as well as different normalization and/or different weighting factors [39]. This has also been reflected in supply chain design literature, as described by Seuring *et al.* [27] and Mota *et al.* [40]. Being the difficulty of selecting a methodology a shortfall in environmental impact assessment, the European Commission has included the objective of developing and standardizing LCA methodologies in its Sustainable Development Strategy. At this point ReCiPe [12], a follow up of Eco-indicator 99 and CML 2002, has been identified as the most developed method currently available [41]. However, to our knowledge, it has only been applied to network design by Mota et al. [25, 42]. The same approach for environmental impact assessment is used in this work with the aim of understanding how environmental assessment influences the supply chain strategic decisions.

The social dimension of sustainability has been defined by the Global Reporting Initiative (GRI) as the dimension that "*concerns the impacts the organization has on the social systems within which it operates*" [43]. As mentioned before, it has been identified in literature as a challenging and significant research gap [3, 4]. Even though social indicators exist and are being developed, as is the case with the Sustainability Reporting Guidelines [43] and several other works reviewed by Jørgensen et al. [44] and Hutchins and Sutherland [45], their measure remains unclear, qualitative and subjective [46]. In addition, most available indicators are either based on passed occurrences or designed to be applied at operational supply chain decisions [47-49]. Hassini et al. [50] further state that none of the measures described in their review were designed for supply chain application. Mota et al. [40] take a step forward into filling this research gap by introducing a social indicator that assesses the impact of social and political concerns on the company's strategy. However, the developed social indicator presented the limitation of only being applicable to regional case-studies. There is still the need for an indicator that can be used on global supply chains, which is addressed in the current research work.

In conclusion there is a need of developing generic supply chain models where real issues faced when designing and planning closed loop supply chains are addressed targeting a sustainable supply chain. This is the aim of the current paper where a generic model is proposed to inform the decision makers managing sustainable supply chains.

3. Problem definition

As mentioned one of the goals of this work is to propose a decision support tool for the design and planning of closed loop sustainable supply chains. This tool focuses on strategic-tactical problems which support the use of aggregated data so as to allow the modelling of the problems detailed below, namely: supply chain design, production/remanufacturing planning, inventory planning, supply planning, purchasing planning, transportation network planning and product recovery planning. Detailed planning obtained at a tactical-operational level can be later obtained for example through vehicle routing and scheduling problems.

The generic representation depicted in Figure 1, constituting a four echelon structure, is then implemented in a MOMILP model. Raw materials flow from suppliers to factories, where they are transformed into final products. Production technology (i.e. process) selection is possible only at the factories and only one production technology can be allocated to each factory. The final products can then flow to warehouses or directly to markets to be sold. Inventory of final products is allowed at factories and warehouses. End-of-life products are recovered at the markets and sent back either to warehouses or directly to factories. Once at the factories, the end-of-life products are remanufactured and transformed again into final products. As before, remanufacturing technology selection is possible only at the factories and only one remanufacturing technology can be allocated to each factory. Transhipment between warehouses is allowed. Transportation between the different entities can be performed by unimodal or intermodal transportation. Intermodal transportation in the presented case-study includes road, air and sea transportation options. Both outsourced and insourced options are modelled: outsourced for air and sea transportation and insourced for road transportation. Rail transportation is not explicitly modelled since it is not included in the presented case-study. However, it can be simply included through adding/changing the model inputs – adding/replacing the corresponding hub terminals locations (e.g. train stations instead of airports and seaports), distances, costs and environmental impacts, number of workers, capacities, etc. Hub terminals are modelled as supply chain entities since they connect and allow for the transfer of material from one transportation mode to the other. The three pillars of sustainability are introduced as objective functions. Boundaries for this analysis are set to only include company-internal costs, environmental and social impacts. The exceptions are the social and environmental impacts of outsourced transportation. The number of jobs created is determined however the labour costs are not directly included in the economic objective function since they are included in the value paid to the transportation company. The environmental impact of outsourced transportation is also included in the analysis since the impact only occurs due to the need to transport the company's products.

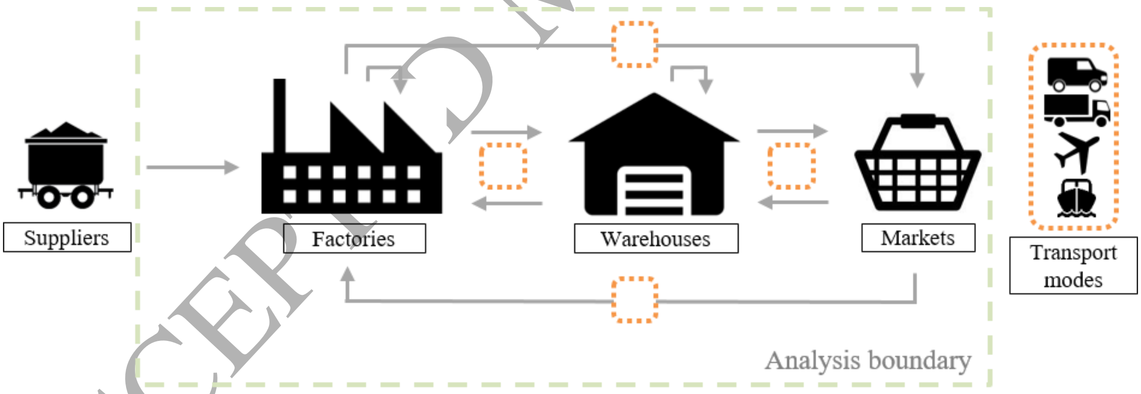

Figure 1. Network representation.

Overall, given:

- A possible superstructure for the location of the supply chain entities, and for each entity/location:
    - Maximum and minimum stock and flow capacities;
    - The maximum installation area;
    - The investment costs;
    - Labour and construction costs;
    - Necessary number of workers;
    - Labour intensity restrictions;
    - Environmental impact characterization factors (per square meter);

  - Social factor based on GDP;
  - Maximum supply capacity (for suppliers only);
- The possible production and remanufacturing technologies, and for each technology:
  - The maximum production/remanufacturing capacities;
  - The investment costs;
  - The operating costs;
  - Necessary number of workers;
  - Environmental impact characterization factors per unit produced/ remanufactured;
- The possible transportation modes between each pair of supply chain entities, and for each transportation mode:
  - Maximum and minimum transportation capacities;
  - Investment/outsourcing costs;
  - Variable transportation costs;
  - Contracted fixed costs (for hub terminals);
  - Handling costs at hub terminals;
  - Necessary number of workers;
  - Environmental impact characterization factors (per kg.km);
- The products within the supply chain, and for each product:
  - The product demand;
  - The products' bill of materials;
  - The raw materials and recovered product costs;
  - The inventory costs;
  - The price per unit sold;
  - The product weight;
  - The necessary area for each product unit;
  - Minimum return fraction of end-of-life products;
- The distance between each pair of entities;
- Financial data such as interest and tax rates.

The goal is to determine:

- the network structure;
- the needed supply and purchase levels;
- the required entities' capacities;
- the transportation network (own fleet, outsourcing or combination of both);
- production and remanufacturing technologies' selection and allocation;
- production, remanufacturing and storage levels;
- supply flow amounts;
- product recovery levels.

So as to:

- Maximize profit, measured through the Net Present Value (NPV);
- Minimize environmental impact, assessed through ReCiPe 2008, a Life Cycle Analysis (LCA) methodology;
- Maximize social benefit, measured through an indicator developed in this work. It relates the number of jobs created by the supply chain with the maximization of job

creation in countries with lower economic development. This is measured through Gross Domestic Product (GDP), as used by the European Commission in funding allocation decisions.

4. Mathematical formulation

4.1. Indices and related sets

i, j	Entities or locations	$I = I_{sup} \cup I_f \cup I_w \cup I_c \cup I_{air} \cup I_{port} = I_{Cont1} \cup I_{Cont2} \cup \ldots$	
		I_{sup}	Suppliers
		I_f	Factories
		I_w	Warehouses
		I_c	Markets
		I_{air}	Airports
		I_{port}	Seaports
		I_{Cont1}, I_{Cont2}	Locations in Continent 1, Continent 2,…
a	Transport modes	$A = A_{truck} \cup A_{plane} \cup A_{boat}$	
		A_{truck}	Truck
		A_{plane}	Plane
		A_{ship}	Ship
g	Technologies (i.e. processes)	$G = G_{prod} \cup G_{rem}$	
		G_{prod}	Production technologies
		G_{rem}	Remanufacturing technologies
m, n	Products	$M = M_{rm} \cup M_{fp} \cup M_{rp}$	
		M_{rm}	Raw materials
		M_{fp}	Manufactured products
		M_{rp}	Recovered products
t	Time periods		
c	Environmental midpoint categories		
γ	Investments (1=entities, 2= technologies, 3=transportation)		

U	Allowed entity-entity connections	$U = \{(i,j): i, j \in I\}$
V	Allowed product-entity relations	$V = \{(m,i): m \in M \wedge i \in I\}$
H	Product-technology pairs	$H = \{(m,g): m \in M \wedge g \in G\}$

H_{prod}: product-technology pairs for production technologies

H_{rem}: product-technology pairs for remanufacturing technologies

F	Allowed flows of materials between entities	$F = \{(m,i,j): (m,i) \in V \wedge (i,j) \in U\}$

For the description of each of these subsets please consider the following examples:

F_{INFFP}: final product (FP) that enters (IN) factories (F) and comes from entity i

F_{OUTFFP}: final product (FP) that leaves (OUT) factories (F) and goes to entity i

F_{OUTW}: allowed flows of products leaving (OUT) warehouses (W)

Net	Allowed transport modes between entities	$Net = \{(a,i,j): a \in A \wedge (i,j) \in U\}$
$NetP$	All allowed network	$NetP = \{(a,m,i,j): (a,i,j) \in Net \wedge (m,i,j) \in F\}$

4.2. Parameters

Parameters are grouped by type (entity, product, technology, transport mode and environment, and others) and then presented by order of appearance in the constraints and objective functions defined in sections 4.4 and 4.5, respectively.

Entity related parameters

sc_{mi}^{max}	Maximum supply capacity for product m by supplier i
sc_{mi}^{min}	Minimum supply quantity of product m at supplier i
ec_{i}^{max}	Maximum flow capacity in entity i
ic_{mi}^{max}	Maximum inventory capacity for product m in entity i
ic_{mi}^{min}	Minimum inventory level for product m in entity i
ins_{mi}	Stock of product m in entity i in time period 1
ea_{i}^{max}	Maximum installation area of entity i
ea_{i}^{min}	Minimum installation area of entity i
hhc_{i}	Handling costs at the hub terminals
w_{i}	Workers needed when opening entity i
lc_{i}	Labour cost at location i
$wpsq_{i}$	Necessary number of workers per square meter for entity i
$sqmc_{i}$	Construction cost of entity i per square meter
μ_{i}^{GDP}	Social factor of location i based on GDP

Product related parameters

dmd_{mit}	Demand of product m by client i in time period t
$retF_{m}$	Minimum return fraction of end-of-life products
BOM_{mn}^{f}	Bill of materials at the factory for non-transformed products
BOM_{mng}^{prod}	Production bill of materials
BOM_{mn}^{rem}	Remanufacturing bill of materials
BOM_{mn}	Bill of materials at warehouses, airports and seaports
BOM_{mn}^{recov}	Bill of materials at clients for recovered products
apu_{m}	Necessary area per unit of product m
$apur_{m}$	Necessary area per unit of product m assuming product rotation
psu_{m}	Price per sold unit of product m
rmc_{mi}	Cost of raw material m supplied by supplier i
rpc_{m}	Cost of recovered product m
pw_{m}	Weight of product m
sc_{m}	Inventory cost of product m

Technology related parameters

pc_{g}^{max}	Maximum production capacity of technology g
pc_{g}^{min}	Minimum production level of technology g
opc_{g}	Operational costs of technology g
w_{g}	Fixed workers per technology g
tec_{g}	Installation cost of technology g

Transport mode related parameters

ct_{a}^{max}	Maximum capacity of transportation mode a

ct_a^{min}	Minimum cargo to be transported by transportation mode a
cca_a^{max}	Contracted capacity with airline/freighter
avs	Average speed (km/h)
mhw	Maximum driving hours per week
ftc_a	Fixed transportation cost for transport mode a
$invt$	Maximum investment in trucks
avc_a	Average vehicle consumption (l per 100km)
fp	Fuel price (€/l)
vmc	Vehicle maintenance costs (€/km)
tc_a	Variable transportation cost of transportation mode a per kg.km
cfp_i	Contracted payment to the airline or freighter for allocated capacity per time period and/or for hub terminal use
w_a	Workers per transport mode a for the case of road transportation. For the case of air and sea transportation, it represents the average number of jobs created in airlines and freighters per kg.km.

Environment related parameters

ei_{mgc}	Environmental impact characterization factor of producing product m with technology g, at midpoint category c (per product unit)
ei_{ac}	Environmental impact characterization factor of transport mode a, at midpoint category c (per kg.km)
ei_{ic}	Environmental impact characterization factor of installing entity i, at midpoint category c (per square meter)
η_c	Normalization factor for midpoint category c

Others

d_{ij}	Distance between entities i and j (km)
$BigM$	Large number
yth	Number of periods in time horizon (e.g. years)
wpt	Number of weeks per time period
ir	Interest rate
sv_γ	Percentage salvage value of investment γ
tr	Tax rate
wwh	Weekly working hours

4.3. Decision variables

Continuous variables

S_{mit}	Amount of inventory of product m in entity i in time period t
P_{mgit}	Amount of product m produced with technology g at entity i in time period t
R_{mgit}	Amount of product m remanufactured with technology g at entity i in time period t
X_{maijt}	Amount of product m transported by transport mode a from entity i to entity j in time period t
YC_i	Capacity of entity i
YCT_{it}	Used capacity in entity i in time period t
K_{ait}	Upper bound for the number of transportation modes a leaving entity i in time period t

Integer variables

K_{ai}	Number of transportation modes a in entity i

Q_{aijt}	Number of trips with transportation mode a between entities i and j in time period t

Binary variables

Y_i	=1 if entity i is installed
Z_{gmi}	=1 if technology g that produces product m is installed in entity i

Auxiliary variables at objective functions

NPV	Net Present Value
CF_t	Cash flow in time period t
NE_t	Net earnings in time period t
$FTDC_t$	Fraction of the total depreciation capital in time period t
FCI_γ	Fixed capital investment of investment γ
DP_t	Depreciation of the capital at time period t
$EnvImpact$	Environmental impact indicator
$GDPInd$	Social indicator based on GDP

4.4. Constraints

The model constraints are grouped into four categories, namely: material balances; entity capacity; transportation; and technology constraints, which are below defined and characterized.

Material balances

Material balance at the factories:

$$S_{mi(t-1)} + \sum_{g:(m,g)\in H_{prod}} P_{mgit} + \sum_{g:(m,g)\in H_{rem}} R_{mgit} = S_{mit} + \sum_{\substack{n,j:(n,i,j)\in F_{OUTFFP}\\ a:(a,n,i,j)\in NetP}} BOM^{f}_{mn} X_{naijt}\,,$$
$$t\in T \wedge m\in M_{fp} \wedge i\in I_f \tag{1}$$

$$\sum_{\substack{j\in I_{sup}\\ a:(a,m,j,i)\in NetP}} X_{majit} = \sum_{(n,g)\in H_{prod}} BOM^{prod}_{mng} P_{ngit}\,, m\in M_{rm} \wedge i\in I_f \wedge t\in T \tag{2}$$

$$\sum_{\substack{j:(m,j,i)\in F_{INFRP}\\ a:(a,m,j,i)\in NetP}} X_{maijt} = \sum_{(n,g)\in H_{rem}} BOM^{rem}_{mn} R_{ngit}\,, m\in M_{rp} \wedge i\in I_f \wedge t\in T \tag{3}$$

Material balance at the warehouses:

$$S_{mi(t-1)} + \sum_{\substack{n,j:(n,j,i)\in F_{INW}\\ a:(a,n,j,i)\in NetP}} BOM_{mn} X_{najit} = S_{mit} + \sum_{\substack{n,j:(n,i,j)\in F_{OUTW}\\ a:(a,n,i,j)\in NetP}} BOM_{mn}\, X_{naijt}\,,$$
$$t\in T \wedge m\in (M_{fp}\cup M_{rp}) \wedge i\in I_w \tag{4}$$

Cross-docking at the airports:

$$\sum_{\substack{n,j:(n,j,i)\in F_{INAIR}\\ a:(a,n,j,i)\in NetP}} BOM_{mn} X_{najit} = \sum_{\substack{n,j:(n,i,j)\in F_{OUTAIR}\\ a:(a,n,i,j)\in NetP}} BOM_{mn} X_{naijt}\,,$$
$$m\in \left(M_{fp}\cup M_{rp}\right) \wedge i\in I_{air} \wedge t\in T \tag{5}$$

Cross-docking at the seaports:

$$\sum_{\substack{n,j:(n,j,i)\in F_{INPORT}\\ a:(a,n,j,i)\in NetP}} BOM_{mn}X_{najit} = \sum_{\substack{n,j:(n,i,j)\in F_{OUTPORT}\\ a:(a,n,i,j)\in NetP}} BOM_{mn}X_{naijt},$$
$$m \in (M_{fp} \cup M_{rp}) \wedge i \in I_{port} \wedge t \in T \qquad \textbf{(6)}$$

Demand and return at the markets:

$$\sum_{\substack{j:(m,j,i)\in F_{INCFP}\\ a:(a,m,j,i)\in NetP}} X_{majit} = dmd_{mit}, i \in I_c, t \in T \qquad \textbf{(7)}$$

$$\sum_{\substack{j:(m,i,j)\in F_{OUTCRP}\\ a:(a,m,i,j)\in NetP}} X_{maijt} \geq RetF_m \sum_{\substack{n,j:(n,j,i)\in F_{INCFP}\\ a:(a,n,j,i)\in NetP}} BOM_{mn}^{recov} X_{naji(t-1)},$$
$$t > 1 \wedge m \in M_{rp} \wedge i \in I_c \qquad \textbf{(8)}$$

$$\sum_{\substack{j:(m,i,j)\in F_{OUTCRP}\\ a:(a,m,i,j)\in NetP}} X_{maijt} \leq \sum_{\substack{n,j:(n,j,i)\in F_{INCFP}\\ a:(a,n,j,i)\in NetP}} BOM_{mn}^{recov} X_{naji(t-1)}, \qquad t > 1 \wedge m \in M_{rp} \wedge i \in I_c \qquad \textbf{(9)}$$

Constraint (1) models material balance constraints at each time unit at factories. It assures that the existing stock of final products (first term) plus the new and remanufactured products (second and third terms) must equal the amount kept in stock plus the outgoing product flow. Notice that for easier reading, the constraint for the first time period was not included. When $t = 1$, the variable $S_{mi(t-1)}$ should be replaced by parameter ins_{mi}, the initial stock of product m in entity i. Production and remanufacturing operations are taken into account by constraints (2) and (3), respectively. The former one sets the necessary amount of raw-materials to be sent by suppliers. The latter relates to all ingoing flows of recovered products to the factory.

The warehouse balance constraint is assured by equation (4) where products kept in stock at the previous time unit plus the inbound flow must equal the current stock volume plus the outbound flows. As for the material balance constraint at factories, at $t = 1$, the variable $S_{mi(t-1)}$ should be replaced by parameter ins_{mi}.

The airports and seaports operate in a cross-docking mode. This is to mean that stock amounts are not made available at these sites. Equations (5) and (6) assure that for each product and time unit, the inbound flow at each location equals the outbound flow.

Demand at markets has to be totally satisfied as stated through constraint (7). This model assumes that products have a usage period of a time unit, therefore no returns are available at time $t = 1$. This is reflected in constraint (8) where the return amount is at least a fraction of the volume supplied in the previous time unit, and at most the quantity delivered to the markets as shown in constraint (9).

Entity capacity constraints

Supply capacity:

$$\sum_{\substack{a,j:(a,m,i,j)\in NetP\\ (m,i,j)\in F_{OUTSUP}}} X_{maijt} \leq sc_{mi}^{max} Y_i, \qquad i \in I_{sup} \wedge m \in M_{fp} \wedge t \in T \qquad \textbf{(10)}$$

$$\sum_{\substack{a,j:(a,m,i,j)\in NetP\\ (m,i,j)\in F_{OUTSUP}}} X_{maijt} \geq sc_{mi}^{min} Y_i, \qquad i \in I_{sup} \wedge m \in M_{fp} \wedge t \in T \qquad \textbf{(11)}$$

Flow capacity:

$$\sum_{a,m,j:(a,m,i,j)\in NetP} X_{maijt} \leq ec_i^{max} Y_i, \qquad i \in I \wedge t \in T \tag{12}$$

$$\sum_{a,m,i:(a,m,i,j)\in NetP} X_{maijt} \leq ec_j^{max} Y_j\,, \qquad j \in I \wedge t \in T \tag{13}$$

Stock capacity:

$$S_{mit} \leq ic_{mi}^{max} Y_i, \qquad m \in M_{fp} \wedge i \in (I_f \cup I_w) \wedge t \in T \tag{14}$$

$$S_{mit} \geq ic_{mi}^{min} Y_i, \qquad m \in M_{fp} \wedge i \in (I_f \cup I_w) \wedge t \in T \tag{15}$$

Entity capacity:

$$YCT_{it} = \sum_{maj:(m,a,j)\in NetP} apur_m\, X_{majit} + \sum_{m:(m,i)\in V} apu_m S_{mit}\,, i \in I_f \cup I_w \wedge t \in T \tag{16}$$

$$YC_i \geq YCT_{it}, i \in I_f \cup I_w \tag{17}$$

$$YC_i \leq ea_i^{max} Y_i, i \in I_f \cup I_w \tag{18}$$

$$YC_i \geq ea_i^{min} Y_i, i \in I_f \cup I_w \tag{19}$$

Entity existence constraints:

$$\sum_{a,m,i,t:(a,m,i,j)\in NetP} X_{maijt} \geq Y_j\,, j \in I \wedge t \in T \tag{20}$$

$$\sum_{a,m,j,t:(a,m,i,j)\in NetP} X_{maijt} \geq Y_i\,, i \in \ I \ \wedge t \in T \tag{21}$$

Constraints (10) to (19) set capacity limits: maximum and minimum supply of raw-materials – constraints (10) and (11), flow amounts between each pair of entities in the network – constraints (12) and (13), minimum and maximum stock capacity at factories and warehouses – constraints (14) and (15). Notice that these constraints also assure that the related variables can only differ from zero if the facilities integrate the supply chain (when $Y_i = 1$).

While the above entities capacities are pre-established, the installation area of warehouses and factories is modelled differently. For these two facilities, capacities are matter of decision. With equation (16) the capacity required at each time unit at each facility is determined by making sure that it is sufficient to accommodate the incoming flow and the current stock levels. Constraint (17) sets the maximum capacity that is needed over the time horizon. Observe that we followed the minmax approach since variable YC_i is minimized at the economic objective function (addressed below). Equations (18) and (19) limit the installation area at each location, maximum and minimum, respectively. Constraints (20) and (21) guaranty that entities are only installed if there is material flow going through them. These constraints can also be viewed as minimum flow constraints. For such an extension, one should define the minimum flow parameter which should be multiplied to variable Y_i (similarly to constraint (13)).

Transportation constraints:

Physical constraints:

$$\sum_{\substack{a,j:(a,m,j,i)\in NetP \\ j\in I\setminus(I_{air}\cup I_{sup})}} X_{majit} = \sum_{\substack{a,j:(a,m,i,j)\in NetP \\ j\in I_{air}}} X_{maijt}\,, m \in (M_{fp} \cup M_{rp}) \wedge i \in I_{air} \wedge\ t \in T \qquad \textbf{(22)}$$

$$\sum_{\substack{a,j:(a,m,j,i)\in NetP \\ j\in I\setminus(I_{port}\cup I_{sup})}} X_{majit} = \sum_{\substack{a,j:(a,m,i,j)\in NetP \\ j\in I_{port}}} X_{maijt}\,, m \in (M_{fp} \cup M_{rp}) \wedge i \in I_{port} \wedge t \in T \qquad \textbf{(23)}$$

Necessary number of trips:

$$\sum_{m:(a,m,i,j)\in NetP} X_{maijt} \leq ct_a^{max} Q_{aijt}, \qquad (a,i,j) \in Net \wedge\ t \in T \qquad \textbf{(24)}$$

$$\sum_{m:(a,m,i,j)\in NetP} X_{maijt} \geq\ ct_a^{min} Q_{aijt}, \qquad (a,i,j) \in Net \wedge\ t \in T \qquad \textbf{(25)}$$

$$Q_{aijt} \leq BigM.Y_i, \qquad (a,i,j) \in Net \wedge\ t \in T \qquad \textbf{(26)}$$

$$Q_{aijt} \leq BigM.Y_j, \qquad (a,i,j) \in Net \wedge\ t \in T \qquad \textbf{(27)}$$

Contracted capacity with air and sea carrier:

$$\sum_{m:(a,m,i,j)\in NetP} X_{maijt} \leq cca_a^{max}, (a,i,j) \in Net \wedge a \in A_{plane} \cup A_{ship} \wedge\ t \in T \qquad \textbf{(28)}$$

Necessary number of transportation modes:

$$KT_{ait} = \frac{\sum_j 2.\, d_{ij} Q_{aijt}}{avs.\, mhw.\, wpt}, (a,i,j) \in Net \wedge a \in A_{truck} \wedge\ t \in T \qquad \textbf{(29)}$$

$$K_{ai} \geq KT_{ait}, \qquad a \in A_{truck} \wedge\ i \in I \wedge\ t \in T \qquad \textbf{(30)}$$

$$\sum_{\substack{a:\, a\in A_{truck} \\ i:i\in I}} ftc_a K_{ai} \leq invt \qquad \textbf{(31)}$$

$$K_{ai} \leq BigM.Y_i, \qquad a \in A_{truck} \wedge\ i \in I \qquad \textbf{(32)}$$

$$K_{ai} \leq BigM. \sum_{\substack{m,j:(a,m,i,j)\in NetP \\ t\in T}} X_{maijt}\,, \qquad a \in A_{truck} \wedge\ i \in I \qquad \textbf{(33)}$$

Constraint (22) states that material flow entering an airport must be transported by plane to another airport. A similar constraint is imposed for sea transportation constraint (23). Furthermore, the network superstructure (established when defining the above sets) assures that intercontinental trips can only use sea or air transportation.

Through constraint (24) it is assured that the number of trips between the entities times the capacity of the corresponding transportation mode is larger than the flow between entities. Equation (25) imposes minimum cargo in each transport mode.

Constraints (26) and (27) assure that variable Q_{aijt} is only activated if the entities of origin and destination are installed, respectively.

Equation (28) establishes that the transportation performed by air or sea in each time period is limited by a contracted capacity with the airline or the freighter.

Constraint (29) defines an upper bound for the number of trucks in each entity of origin in each time period, KT_{ait}. In the model, each truck is assumed to be assigned to one truck driver. Hence trucks must be enough to obey the European Union Rules on Driving Hours, which state that an average maximum of 45 hours per week (mhw) is allowed. The denominator of the equation reflects then an average of the maximum number of kilometres a truck is allowed to travel in each time period. The numerator reflects the number of kilometres that are actually travelled per time period having as starting point entity i and considering that trucks must return to the entity of origin. Similarly to the definition of the capacities of the entities, equation (30) defines the number of trucks necessary in each entity over the time horizon. As in entities capacity, we also followed the minmax approach to model the number of workers allocated to transportation activities. Constraint (31) imposes a maximum investment in road transportation, defined by the company decision makers. Constraint (32) assures trucks are only purchased if the entity of origin is installed. Constraint (33) guaranties trucks are only purchased if there is flow to be transported with those same trucks.

Technology constraints

Technology capacity:

$$P_{mgit} \leq pc_g^{max} Z_{gmi}, i \in I_f \wedge (m,g) \in H_{prod} \wedge \ t \in T \tag{34}$$

$$R_{mgit} \leq pc_g^{max} Z_{gmi}, i \in I_f \wedge (m,g) \in H_{rem} \wedge \ t \in T \tag{35}$$

$$P_{mgit} \geq pc_g^{min} Z_{gmi}, i \in I_f \wedge (m,g) \in H_{prod} \wedge \ t \in T \tag{36}$$

$$R_{mgit} \geq pc_g^{min} Z_{gmi}, i \in I_f \wedge (m,g) \in H_{rem} \wedge \ t \in T \tag{37}$$

Technology installation:

$$\sum_{g:(m,g)\in H_{prod}} Z_{gmi} \leq Y_i\,, \qquad m \in M_{fp} \wedge i \in I_f \tag{38}$$

$$\sum_{g:(m,g)\in H_{rem}} Z_{gmi} \leq Y_i\,, \qquad m \in M_{fp} \wedge i \in I_f \tag{39}$$

$$\begin{aligned} &P_{mgit}, R_{mgit}, X_{maijt}, S_{mit}, YC_i, YCT_{it,} KT_{ait} \geq 0 \\ &K_{ai}, Q_{aijt} \geq 0 \text{ and integer} \\ &Y_i, Z_{gmi} \in \{0,1\} \end{aligned} \tag{40}$$

Constraints (34) to (39) are the technology constraints. In particular, constraints (34) and (35) model production and remanufacturing maximum capacity, respectively, while constraints (36) and (37) impose minimum production levels in each time period. They also assure that if the technology is not established ($Z_{gmi} = 0$), the corresponding manufacturing and remanufacturing volumes are set to zero. In turn, at most one technology can only be allocated to open facilities (when $Y_i = 1$), for both production and remanufacturing technologies, as evidenced in equations (38) and (39). Different technologies, i.e. production/remanufacturing processes, can differ in the number of necessary workers to operate them, production/remanufacturing capacity, environmental impact and involved costs.

Lastly, the decision variables domains are given at constraint (40).

4.5. Objective functions

Two options exist when dealing with multi-objective problems: modelling the objective functions separately or combining them in the same objective function. Including the three pillars of sustainability in the same objective function requires the utilization of weighting factors. It is our belief that doing so has three negative consequences:

1) Subjectivity: Defining weighting factors is subjective since the decision maker is attributing different degrees of importance to the three pillars according to his/her own beliefs;
2) Uncertainty: It adds another layer of uncertainty (on the weighting factors) to what is already a complex problem;
3) Lack of clarity: Trade-offs between the objectives are not easily comprehensible.

Therefore we opted to model the three pillars of sustainability: economic, environmental and social, as three different objective functions, with three different units.

4.5.1. Economic objective function

The economic objective function is obtained from the maximization of the NPV. It extends the work of Cardoso *et al.* [7] by also modelling recovered product costs, unimodal and intermodal transportation options, transhipment costs at hub terminals, fixed payments to airlines/freighters and labour costs, as well as by detailing investment in road transportation.

$$max\,NPV = \sum_{t \in T} \frac{CF_t}{(1+ir)^t} - \sum_{\gamma} FCI_\gamma \tag{41}$$

$$CF_t = \begin{cases} NE_t & t = 1, \dots, NT-1 \\ NE_t + \sum_{\gamma} (sv_\gamma FCI_\gamma) & t = NT \end{cases} \tag{42}$$

$$
\begin{aligned}
NE_t = (1-tr)\Bigg[& \sum_{\substack{(m,i,j)\in F_{INCFP}\\(a,m,i,j)\in NetP}} psu_m\, X_{maijt} \\
& -\Bigg(\sum_{\substack{(m,i,j)\in F_{OUTSUPRM}\\(a,m,i,j)\in NetP}} rmc_{mi} X_{maijt} + \sum_{\substack{(m,g)\in H_{prod}\\ i\in I_f}} opc_g P_{mgit} \\
& + \sum_{\substack{(m,i,j)\in F_{OUTCRP}\\(a,m,i,j)\in NetP}} rpc_m X_{maijt} + \sum_{\substack{(m,g)\in H_{rem}\\ i\in I_f}} opc_g R_{mgit} \\
& + \sum_{\substack{(a,m,i,j)\in NetP\\ a\in A_{truck}}} \left(\frac{avc_a}{100}.fp + vmc\right).2d_{ij}.Q_{aijt} \\
& + \sum_{\substack{(a,m,i,j)\in NetP\\ a\in (A_{plane}\cup A_{boat})}} tc_a.pw_m.d_{ij}.X_{maijt} \\
& + \sum_{\substack{(a,m,i,j)\in NetP\\ (j\in I_{plane}\wedge i\notin I_{plane})\cup(j\in I_{boat}\wedge i\notin I_{boat})}} hhc_j.X_{maijt} \\
& + \sum_{i\in I_{plane}\cup I_{boat}} cfp_i.Y_i + \sum_{(m,i)\in V} sc_m S_{mit} + \sum_{i\in I_f\cup I_w} w_i.lc_i\,.wwh.wpt.Y_i \\
& + \sum_{i\in I_f\cup I_w} wpsq.lc_i\,.wwh.wpt.YC_i + \sum_{\substack{(m,g)\in H\\ i\in I_f}} w_g.lc_i.wwh.wpt.Z_{gmi} \\
& + \sum_{\substack{i\in I\\ a\in A_{truck}}} w_a.lc_i.wwh.wpt.K_{ai} \Bigg)\Bigg] + tr.DP_t
\end{aligned}
\tag{43}
$$

$$
DP_t = \sum_{\gamma} DP_{\gamma t} FCI_{\gamma} \tag{44}
$$

$$
FCI_{\gamma} = \begin{cases} \displaystyle\sum_{i\in I_f\cup I_w} sqmc_i.YC_i, & \gamma = 1 \\ \displaystyle\sum_{\substack{(m,g)\in H\\ i\in I_f}} tec_g.Z_{gmi}\,, & \gamma = 2 \\ \displaystyle\sum_{\substack{(a,i,j)\in Net\\ a\in A_{truck}}} ftc_a.K_{ai}\,, & \gamma = 3 \end{cases} \tag{45}
$$

In equation (41) NPV is obtained through the sum of the discounted cash flows of each time period, at interest rate ir. Equation (42) gives the cash flow in each time period, obtained from the net earnings (NE_t). For the last time period the recovery of salvage value (sv_{γ}) of each type of investment (FCI_{γ}) is also assumed. Equation (43) depicts the net earnings in each time period, which are given by the difference between the incomes, defined by the amount of products sold times the price per unit (psu_m), and the costs. The costs include:

- raw material costs (first term), given by the amount of products purchased from the suppliers times the unit raw material cost (rmc_m),
- production operating costs (second term), given by the amount of final products produced (P_{mgit}) times the unitary operating costs of each production technology (opc_g),
- product recovery costs (third term), given by the amount of end-of-life products recovered from the clients times the unit recovered product cost (rpc_m),
- remanufacturing operating costs (fourth term), given by the amount of final products obtained through remanufacturing (R_{mgit}) times the unitary operating costs of each remanufacturing technology (opc_g),
- transportation costs for road transportation (fifth term), given by the number of trips between entities (Q_{aijt}) times twice the distance travelled ($2d_{ij}$) (since it is assumed that the truck must return to the entity of origin) times the transportation cost per km which is given by the vehicle average fuel consumption (avc_a), the fuel price (fp) and the vehicle maintenance costs (vmc),
- transportation costs for air and sea transportation (sixth term), given by the flow of products transported through transportation mode a (X_{maijt}) times the transportation cost per kg.km (tc_a) times the weight of each unit of product transported (pw_m) times the distance travelled (d_{ij}),
- handling costs at the hub terminal (seventh term), given by the flow of products through the hub terminals at the airports or seaports times the unit handling costs at these terminals (hhc),
- contracted costs with the airline or freighter (cfp_i) for the allocated transportation capacity and/or for hub terminal use per time period (eighth term), where it is assumed that a contract is established with companies operating at hub terminals,
- inventory costs (ninth term) given by the amount of products in stock (S_{mit}) times the unitary stock cost (sc_m),
- labour costs at entities (tenth and eleventh terms), labour costs for production and remanufacturing technologies (twelfth term) and labour costs for owned transportation modes, in these case the road transportation (thirteenth term). These costs vary with the fixed (w_i) and the variable ($wpsq$) number of workers at each entity, the number of workers needed for each technology (w_g) and the number of workers per transportation mode (w_a), respectively. Also a factor is the labour cost at each location (lc_i), the weekly working hours (wwh) and the number of weeks per time period (wpt).

The last term describes the depreciation of the capital invested (DP_t) with tr being the tax rate. The depreciation is determined for each type of investment, γ, as described in equation (44). The fixed capital investment (FCI) is defined in equation (45) and is given by:

- the investment in facilities (first term) given by the necessary installation area (YC_i) times the construction costs which vary according to the location of the facilities ($sqmc_i$),
- investment in technologies (second term) given by the number of installed technologies times the installation cost of each technology (tec_g), and

- investment in transportation links (third term) given by the fixed investment in road transportation (ftc_a), where it is assumed that the company purchases the fleet.

4.5.2. Environmental objective function

The environmental objective function is modelled using the ReCiPe methodology and follows the approach described in Mota *et al.* (2014), tailored to the problem presented in this work. This translates in an extension of the mentioned approach to include different production and remanufacturing technologies and different transportation modes. Mota et al. [40] includes a very detailed explanation of the application of ReCiPe to network design models. The functional unit is the supply chain. This means that the obtained results, in its aggregated form, should be used to compare different supply chain designs and decisions and not as a tool to accurately determine the environmental impact of the supply chain.

As shown in equation (46), the environmental impact of four supply chain activities is determined for each midpoint category c:

- the environmental impact of production and remanufacturing (first term), given by the environmental impact per kg produced or remanufactured with technology g (ei_{mgc}) times the weight of product m times the amount of final products produced (P_{mgit}) or remanufactured (R_{mgit}),
- the environmental impact of transportation (second term), given by the environmental impact per kg.km transported with transportation mode a (ei_{ac}) times the weight of each unit of product transported (pw_m) times the distance travelled (d_{ij}) times the product flow (X_{maijt}), and
- the environmental impact of entity installation (third term), given by the environmental impact per square meter of entity i installed (ei_{ic}) times the installed area (YC_i).

The environmental indicator is given by the sum of these normalized impacts, with normalization factor η_c. This normalization factor is used to reduce the results of each of the impact categories to the same units and is part of the ReCiPe methodology.

$$min\, EnvImpact = \sum_c \eta_c \left(\sum_{\substack{t\in T, i\in I_f \\ (m,g)\in H}} ei_{mgc} pw_m (P_{mgit} + R_{mgit}) + \sum_{\substack{t\in T \\ (a,m,i,j)\in NetP}} ei_{ac} pw_m d_{ij} X_{maijt} + \sum_{i\in I_f \cup I_w} ei_{ic} YC_i \right) \tag{46}$$

4.5.3. Social objective function

The social objective is measured through the social indicator defined in equation (47). It gives preference to the supply chain entities and activities to be located in regions with lower GDP. Parameter μ_i^{GDP} represents a regional factor based on GDP statistics. The contribution of the following activities is considered in this social objective:

- Entity installation, which takes into account the number of jobs created in each location, with w_i in the first term and $wpsq$ in the second term. The former reflects the minimum number of workers needed when opening a facility (e.g. administrative staff). The latter models the workers that operate facilities of different sizes (measured through capacity).

- Technology installation, which takes into account the number of jobs created through each technology, with w_g in the third term;
- Transportation, taking into account the number of workers per transportation mode (w_a) in the company's fleet (fourth term) but also estimating the number of jobs created per kg.km transported through air or sea transportation (fifth term), averaged through the number of years in the time horizon considered (yth). Notice that the economic equivalent of this last term is not explicitly presented in the economic objective function since this service is outsourced and so this value is diluted in the variable and fixed costs paid to the airlines or freighters.

$$max\ GDPInd = \sum_{i \in I_f \cup I_w} \mu_i^{GDP} w_i Y_i + \sum_{i \in I_f \cup I_w} \mu_i^{GDP} wpsq_i YC_i + \sum_{\substack{(m,g) \in H \\ i \in I_f}} \mu_i^{GDP} w_g Z_{gmi} + \sum_{\substack{(a,i,j) \in Net \\ a \in A_{truck}}} \mu_i^{GDP} w_a K_{ai} + \sum_{\substack{(a,m,i,j) \in NetP \\ a \in A_{plane} \cup A_{ship} \\ t \in T}} \mu_i^{GDP} \frac{w_a}{yth} . pw_m . d_{ij} . X_{maijt} \qquad \textbf{(47)}$$

It should be noted that the utilization of this indicator needs to be conducted wisely. Since it does not account for the negative social impact of layoffs, it should only be used in cases that do not require layoffs but do require (or may require) hiring. Examples of these situations are the introduction of a new product, expansion to new markets, among others. This indicator is to be used to compare the social impact of different supply chain alternatives that accommodate the described situations. Furthermore, when selecting which locations/players to include as options in the model, a preliminary analysis needs to be performed to insure that these locations/players guaranty good working conditions and fair salaries for their workers.

5. Case-study

In the case-study presented in this work, the developed model is applied to an electronic components' producer based in Verona, Italy. Currently the company owns a factory and a warehouse in Verona, which have sufficient capacity to meet the demand of their existing clients. These clients are clustered according to their locations into three main markets: Italy, Germany and Spain. These markets account for 41.8%, 37% and 21.2% of the company's sales, respectively. Company's suppliers are also located in Verona.

Four potential clients instilled company's decision makers to study different possibilities of expansion since the current capacities will not be capable of meeting the expected demand increase. The company's decision makers are interested in understanding the range of possibilities for the design of the new supply chain, which take into account the different sustainability objectives. This is in line with the European Commission's objective of promoting socially and/or environmentally beneficial projects.

The largest new client is located in the United Kingdom. Its potentially significant contribution to the company's sales (projected 26.4%) suggested the possibility of installing a factory in Leeds. Another possibility to a new factory location would be Hannover, since Germany represents a well-established and stable client. This would represent a relatively low risk option, compared to the previous one. In both locations contacts with possible suppliers have already been established.

The three other new clients are located in Portugal and in the Brazilian states of São Paulo and Recife. This business opportunity arose from contacts established in Portugal. Collectively these three markets are expected to account for 73.8% of total sales. However, fulfilling these markets means going outside European borders, which constitutes a significant change in the company's strategy and therefore at the supply chain structure. This change brings several challenges to the company, in particularly the existence of different modes of transportation, such as moving from a unimodal transportation system to an intermodal one. Currently the company is outsourcing road transportation but wishes to gain more control in the distribution and product recovery activities. Therefore the company is planning to acquire a fleet. Company's decision makers have selected four airports and two seaports to include as possible connections for intermodal transportation: the airports of Zaragoza (Spain), Paris-Charles de Gaulle (France), Kortrijk-Wevelgem (Belgium) and São Paulo (Brazil), and the seaports of Hamburg (Germany) and Santos (São Paulo).

Regarding possible warehouse locations, those close to the referred markets are included, namely Hannover, Leeds, Zaragoza, Lisbon, São Paulo and Recife. Additionally two other possible locations are considered: Budapest and Sofia, given some attractive features both in terms of economic (low labour and construction costs) and social performances (low GDP), in light of the European commission target. All of the possible locations included in the case-study were previously analysed to assure adequate working conditions and productivity levels.

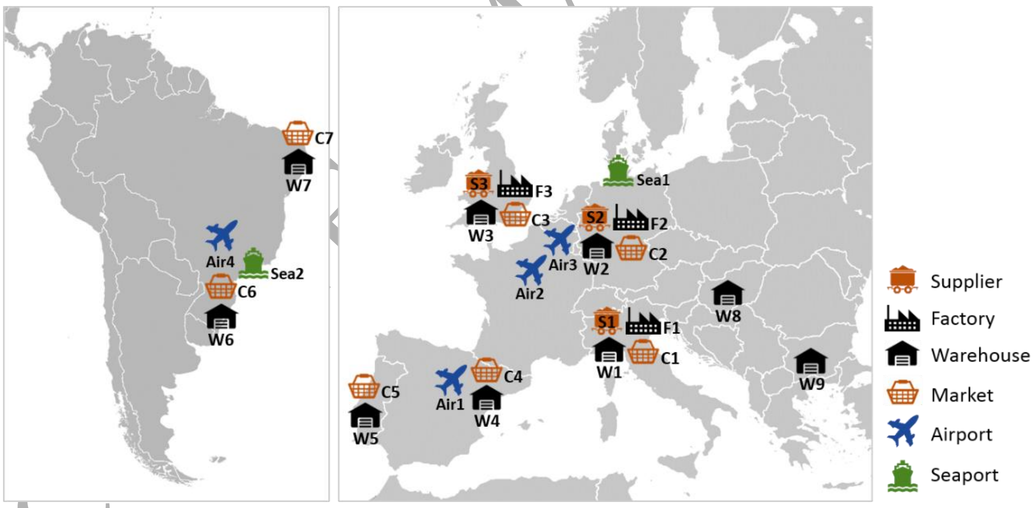

Figure 2. Case-study superstructure.

The superstructure representing this case-study is presented in Figure 2 and a code is attributed to each entity in Table 1. The time horizon considered is ten years with yearly increments for planning decisions.

In the following subsections the reader will find a detailed description of the case-study parameters and assumptions. These are grouped by category: entity, product, technology and transportation mode-related parameters, environmental parameters, financial parameters, projected demand and distances between entities.

Table 1. Codification of each entity in the case-study superstructure.

Suppliers		Factories		Warehouses		Markets		Airports		Seaports	
Verona	S1	Verona	F1	Verona	W1	Italy	C1	Zaragoza	Air1	Hamburg	Sea1
Hannover	S2	Hannover	F2	Hannover	W2	Germany	C2	Paris-Charles de Gaulle	Air2	Santos	Sea2
Leeds	S3	Leeds	F3	Leeds	W3	United Kingdom	C3	Kortrijk-Wevelgem	Air3		
				Zaragoza	W4	Spain	C4	São Paulo	Air4		
				Lisbon	W5	Portugal	C5				
				São Paulo	W6	São Paulo	C6				
				Recife	W7	Recife	C7				
				Budapest	W8						
				Sofia	W9						

For simplicity each of the objective functions are identified as follows: Obj1, the economic objective, Obj2, the environmental objective, Obj3, the social objective.

5.1. Product and technology characterization

The company sells two main types of products referred to as fp1 and fp2. Please keep in mind that given the short life cycles of products in the electronics' industry the products mentioned in this case study should not be viewed as specific products but as a representation of a family of products that is being frequently updated.

Currently these products are being produced at the factory in Verona (F1) through technologies gp1 and gp2, respectively. However, two new technologies, gp1alt and gp2alt, are available in the market for the production of these products. The company's decision makers proposed the introduction of these technologies as options if new factories need to be installed.

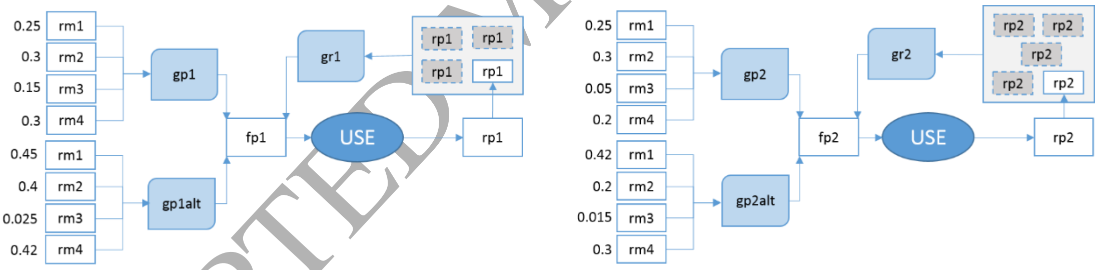

Figure 3. Product-technology relation (fp1 on the left and fp2 on the right).

As seen on Figure 3, final product fp1 can be obtained either through technology gp1 or technology gp1alt, each requiring different amounts of raw materials rm1 through rm4. The same takes place for final product fp2 with technologies gp2 and gp2alt. These final products can then be recovered at the end of their life. At that point they are referred to as recovered products rp1 and rp2, respectively. These can then be remanufactured back into final products to again be sold at the markets. This can be done through remanufacturing technology gr1, which on average requires 4 recovered products rp1 to obtain 1 final product fp1, and through remanufacturing technology gr2, which on average requires 5 recovered products rp2. Table 2 depicts the bill of materials for both products, relating raw materials with final products, depending on the different technologies options. It also provides similar information for remanufacturing operations. A minimum return fraction, $RetF_m$, of 15% of the products sold is imposed.

Table 2. Production, BOM_{mng}^{prod}, and remanufacturing bill of materials, BOM_{mn}^{rem}.

Production	**fp1**		**fp2**		**Remanufacturing**	**fp1**	**fp2**
Raw materials/technologies	**gp1**	**gp1alt**	**gp2**	**gp2alt**	**Recovered products/technologies**	**gr1**	**gr2**
rm1	0.25	0.45	0.25	0.42	**rp1**	4	-
rm2	0.3	0.4	0.3	0.2			
rm3	0.15	0.025	0.05	0.015	**rp2**	-	5
rm4	0.3	0.42	0.2	0.3			

Table 3 presents product characterization in terms of recovery cost (rpc_m), inventory cost (sc_m), price of sold products (psu_m), product weight (pw_m) and necessary storage area per unit of product (apu_m). $apur_m$ is obtained assuming a product rotation of 4.5 times per year. The raw material cost varies with the supplier (shown in section 5.2.1.). Inventory is only kept at warehouses and only of final products fp1 and fp2, as depicted in section 5.3.

Table 3. Product characterization.

Product	**Recovered product cost, rpc_m (€)**	**Inventory cost per unit, sc_m (€)**	**Price per unit sold, psu_m (€)**	**Product weight, pw_m (kg)**	**Necessary area per unit of product, apu_m (m^2)**
rm1	-	-	-	0.118	0.002
rm2	-	-	-	0.184	0.001
rm3	-	-	-	0.365	0.004
rm4	-	-	-	0.913	0.003
fp1	-	0.01	23	0.4	0.007
fp2	-	0.01	37	0.5	0.009
rp1	0.15	-	-	0.4	0.007
rp2	0.15	-	-	0.5	0.009

Production and remanufacturing technologies are characterized in Table 4 in terms of production capacity, maximum (pc_g^{max}) and minimum (pc_g^{min}), installation costs (tec_g), operating costs (opc_g) and necessary workers (w_g).

Table 4. Technology characterization.

		Production capacity		**Installation costs, tec_g**	**Operating costs per unit produced, opc_g**	**Fixed necessary workers, w_g**
		Maximum, pc_g^{max}	**Minimum, pc_g^{min}**			
Production technologies	**gp1**	5,800,000	30,000	150,000	0.212	2
	gp1alt	6,000,000	30,000	175,000	0.196	1
	gp2	4,600,000	30,000	167,000	0.324	4
	gp2alt	5,200,000	30,000	186,000	0.267	3
Remanufacturing technologies	**gr1**	2,900,000	0	50,000	0.116	1
	gr2	2,300,000	0	45,000	0.134	1

5.2. Entity characterization

Within the model six types of entities are considered: suppliers, factories, warehouses, airports, seaports and markets. Since airports and seaports are related to transportation their characterization is only performed in section 5.4. Projected demand and distances between entities are provided as supplementary material.

5.2.1. Suppliers

When selecting suppliers or possible locations for new factories, the company decision makers want to guaranty that both entities are located in the surroundings of each other. The three groups of suppliers identified in Table 5 already meet this constraint, being located in the surroundings of each of the possible factory locations: Verona (already operating), Hannover and Leeds, respectively S1, S2 and S3. Each of the selected suppliers is considered to supply products with the same quality level. They are characterized in Table 5 according to their maximum supply capacity per time period (sc_{mi}^{max}), minimum order quantity per time period (sc_{mi}^{min}), and cost per unit (rmc_{mi}), for each of the required raw materials.

Table 5. Maximum supply capacity, sc_{mi}^{max} , minimum order quantity, sc_{mi}^{min}, and raw material cost, rmc_{mi} .

Supplier, i	**S1**			**S2**			**S3**		
Raw material, m	**Maximum supply capacity (units)**	**Minimum order quantity (units)**	**Cost, rmc_{mi} (€/unit)**	**Maximum supply capacity (units)**	**Minimum order quantity (units)**	**Cost, rmc_{mi} (€/unit)**	**Maximum supply capacity (units)**	**Minimum order quantity (units)**	**Cost, rmc_{mi} (€/unit)**
rm1	3,600,000	1,000	0.01	3,800,000	1,000	0.035	3,800,000	1,000	0.03
rm2	3,600,000	1,000	0.025	3,800,000	1,000	0.0875	3,800,000	1,000	0.075
rm3	1,000,000	200	0.03	1,200,000	200	0.105	1,200,000	200	0.09
rm4	4,000,000	1,000	0.09	5,000,000	1,000	0.315	5,000,000	1,000	0.27

5.2.2. Factories and warehouses

Table 6 depicts the characterization of factories and warehouses according to maximum (ea_i^{max}) and minimum (ea_i^{min}) installation area. Note that F1 and W1 are facilities already in operation, thus the areas have been established.

Table 6. Maximum, ea_i^{max}, and minimum, ea_i^{min}, installation areas for factories and warehouses.

Locations/entities		**F1**	**F2**	**F3**	**W1**	**W2**	**W3**	**W4**	**W5**	**W6**	**W7**	**W8**	**W9**
Installation area	**Maximum, ea_i^{max}**	20,000	25,000	25,000	5,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000
	Minimum, ea_i^{min}		2,000	2,000		500	500	500	500	500	500	500	500

Table 7 shows the necessary number of workers estimated per entity type. Some are capacity dependent (variable number of workers) and others are fixed regardless of the installed capacity. The fixed number of workers, w_i, includes administrative and management positions. The variable number of workers, $wpsq$, includes picking and shipping positions. Factory workers in charge of production and remanufacturing are not included in these numbers.

Table 7. Necessary number of workers per type of entity, fixed and per square meter of installed capacity.

	Fixed workers per entity, w_i	**Workers per sqm, $wpsq$**
Factories	11	0.01
Warehouses	9	0.01

5.2.3. Country characterization

Table 8 depicts location variable costs, namely average labour (lc_i) and construction costs ($sqmc_i$). Construction costs are only applicable to factories and warehouses. For simplicity it is assumed that truck drivers are hired at the entity from which the truck departs since the truck needs to return back to that same entity. Therefore, average labour costs are applicable to all entities. Also shown is the GDP per capita, which corresponds to the inverse of the regional factor, μ_i^{GDP}, in the previously presented social objective function (47). Consequently, according to this social criteria, the preferred locations by decreasing order are those in Brazil, Bulgaria, Hungary, Portugal, Spain, Italy, United Kingdom, France, Belgium and Germany.

Table 8. Characterization of each country with entities included in this case-study according to location variable costs and GDP.

Countries	Entities	Location variable costs		GDP per capita in PPP (EU28=1), $\frac{1}{\mu_i^{GDP}}$
		Average labour cost, lc_i	Construction cost, $sqmc_i$	
Brazil	W6, W7, C6, C7, Air4, Sea2	8.98	538	0.355
Bulgaria	W9	3.7	270	0.47
Hungary	W8	7.5	282	0.67
Portugal	W5, C5	12.2	318	0.75
Spain	W4, C4, Air1	21	373	0.95
Italy	S1, F1, W1, C1	28.1	-*	0.98
United Kingdom	S3, F3, W3, C3	15.3	601	1.06
France	Air2	32.4	-	1.08
Belgium	Air3	37.2	-	1.19
Germany	S2, F2, W2, C2, Sea1	30.4	661	1.24

*** No construction cost is considered since both factory and warehouse are already operating in this location.**

5.3. Inventory policy

It is company policy not to keep stock of raw materials or of recovered products. As soon as raw materials or recovered products arrive to the factories, they are transformed into final products and shipped to warehouses or to the markets. Stock of final products is only allowed at warehouses. Table 9 details the maximum, ic_{mi}^{max}, and minimum, ic_{mi}^{min}, inventory levels of each of the final products as well as the initial stock, ins_{mi}, existent at the Verona warehouse (W1).

Table 9. Inventory levels of each product at the warehouses.

Product	Inventory levels		
	Maximum, ic_{mi}^{max}	Minimum, ic_{mi}^{min}	Initial at W1, ins_{mi}
fp1	1,200,000	12,000	196,000
fp2	1,000,000	10,000	84,000

5.4. Transportation

Two transportation options are available, as depicted in Figure 4. Unimodal transportation is performed only by road. Intermodal transportation can occur through different combinations. It always starts with road transportation, which takes the products from the entity of origin to an airport or a seaport. Here transhipment is performed to the airplane or to the ship. Loads coming from different places can be consolidated at the airport or seaport. After the trip the products are again transhipped to a truck, or to several trucks, and transported to their destination.

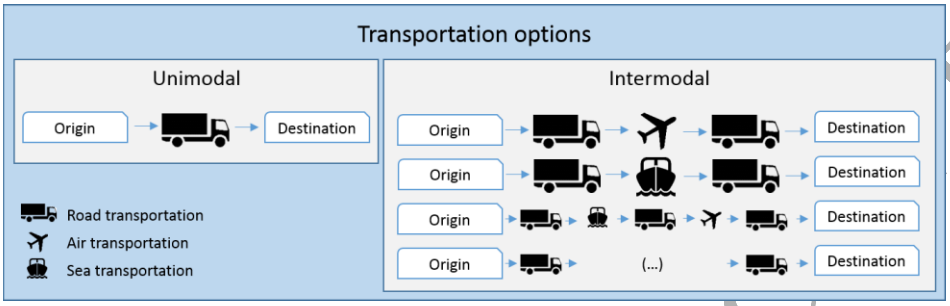

Figure 4. Illustration of the transportation options modelled in the case-study.

Each kind of truck is characterized in terms of capacity, investment costs, depreciation rate, variable costs, necessary number of workers and average vehicle consumption. Variable transportation costs for road transportation take into account the average vehicle consumption (l/100km), avc_a, the fuel price, fp, and the vehicle maintenance costs (€/km), vmc, as modelled in equation (48). These and other transportation related parameters are given as supplementary material.

$$tc_a = \frac{avc_a}{100} . fp + vmc \tag{48}$$

Parameters characterizing air and sea transportation are also supplied as supplementary material. Maximum and minimum capacity per trip, as well as, maximum capacity per time period are contractualized with the airline or freighter. Fixed payment to the airline or freighter ensures that this capacity is available whenever needed. Handling costs at hub terminals account for the products transhipment from one transportation mode to the other. Also given are variable transportation costs per kg.km and necessary workers per kg.km. The labour costs at air and sea transportation are already included in the described costs. However, the number of jobs created is estimated separately to be included in the social objective function.

5.5. Environmental characterization

Each of the activities in the supply chain is characterized in terms of environmental impact using SimaPro Ecoinvent database version 8.01. Through this database the data characterizing two different production technologies, four different transportation modes and the installation of entities are identified. Alternative technologies gp1alt and gp2alt are considered to contribute with a 30% and 20% reduction in the environmental impact, respectively, when compared to the original production technologies. Remanufacturing technologies gr1 and gr2 are assumed to have an environmental impact 25% and 20% lower to the environmental impact of gp1 and gp2, respectively. The characterization factors as well as the normalization factors applied are provided as supplementary material.

Within LCA two distinct methodological choices exist. Attributional LCA refers to retrospective analysis while consequential LCA refers to prospective analysis. The latter is aimed for the study of environmental consequences of possible changes between alternative systems, being typically applied in public policy making [51]. Hence, consequential LCA has been selected for this study.

5.6. Other parameters

Additional economic parameters were considered in line with the company's objectives: an interest rate, ir, of 10%, and a tax rate, tr, of 30%.

6. Results and discussion

This section is structured as follows. In section 6.1 the cases under analysis are presented and the results discussed focusing on the three pillars of sustainability. In section 6.2 the importance of using an integrated approach is demonstrated based on a more detailed analysis of the results. In section 6.3 the environmental impact of the supply chain is analysed and environmental hotspots are identified. In section 6.4 tendencies towards a more socially responsible supply chain are shown. Section 6.5 presents the results obtained through a sensitivity analysis to different product recovery rates to understand if the current company policy is the most sustainable one. Finally in section 6.6 demand uncertainty is analysed using a scenario approach.

The model was implemented in GAMS 23.6 and the case study solved using CPLEX 12.0, in a two Intel Xeon X5680, 3.33 GHz computer in 12 GB RAM.

6.1. Cases under analysis

Aiming to understand how each of the sustainability pillars, measured through the described objective functions, influence the presented closed-loop supply chain design and planning problem, five cases are studied:

- Case A: corresponds to the solution with the optimum economic performance;
- Case B: corresponds to the solution with the optimum environmental performance;
- Cases C and D: provide the best social performance with a maximum of a 5% and 15% reduction in the NPV determined in Case A, respectively. These result from the maximization of the social objective function, having an additional constraint that states that the NPV must be at least 95%, for case C, and 85%, for case D, of the profit obtained in Case A (ε-constraint method for two objectives);
- Case E: corresponds to the solution with the optimum social performance.

The last three cases, C, D and E, are considered so as to envisage tendencies towards a more socially sustainable supply chain. Also they allow the exploring of potential economic incentives from entities such as the European Commission that aim to support projects that contribute to improve societal issues.

The superstructure obtained for each one of the cases is depicted in Figure 5. Table 10 shows the corresponding indicator values obtained for a 10 year time horizon. A higher value in the environmental indicator means a higher negative environmental impact. A higher value in the social indicator means more benefit for society (more job opportunities and/or the selection of locations in countries with lower GDP). Table 11 summarizes the corresponding decisions' results for each of the cases.

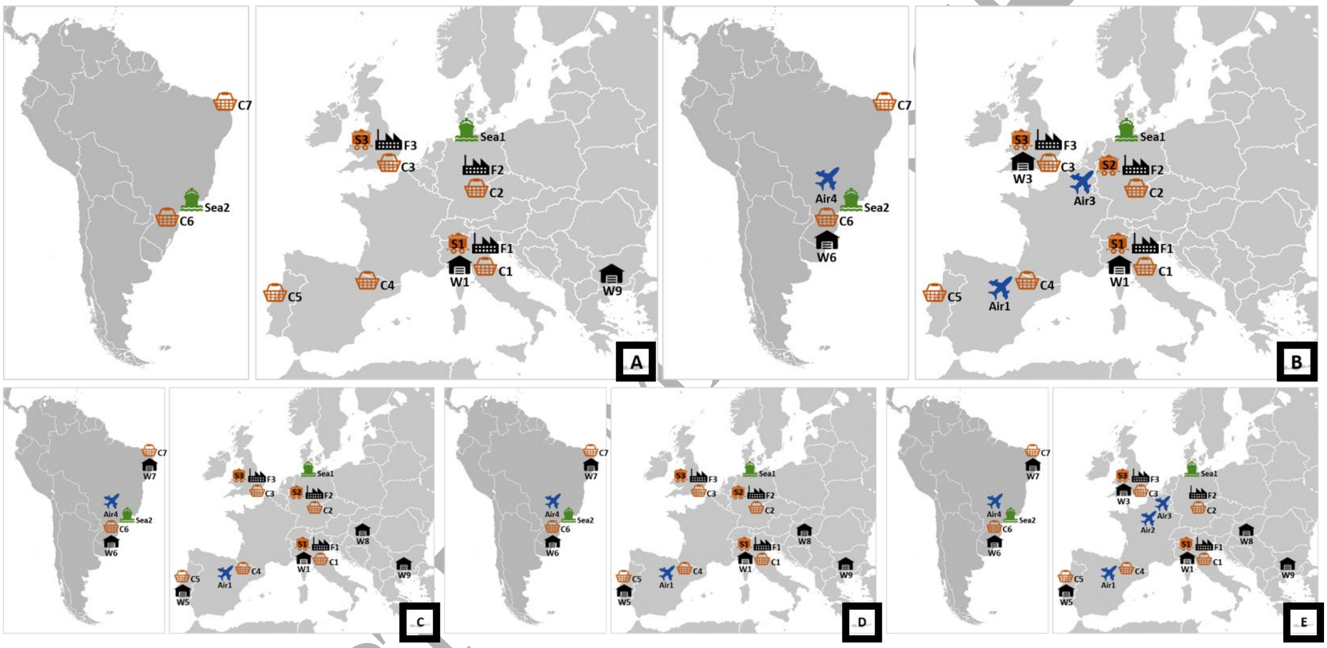

Figure 5. Superstructures obtained for each of the cases analysed: A – NPV maximization, B – environmental impact minimization, C and D – social benefit maximization within a 5% and 15% maximum reduction on NPV, respectively; E – social benefit maximization.

Table 10. Obtained indicator results for each of the described cases for a 10 year time horizon.

		Cases				
Indicator	**Units**	**A**	**B**	**C**	**D**	**E**
Economic	€	1,280,985,986	866,479,118	1,216,936,687	1,088,838,088	0
Environmental	-	996,589,688	905,849,526	996,522,581	995,990,099	988,465,182
Social	-	534	1,148	1,608	2,537	8,671

Normalization of these results, through rescaling to the range [0,1], allowed the radar chart representation depicted in Figure 6. Normalization means the best score of each indicator was set to 1 and the worst score was set to 0.

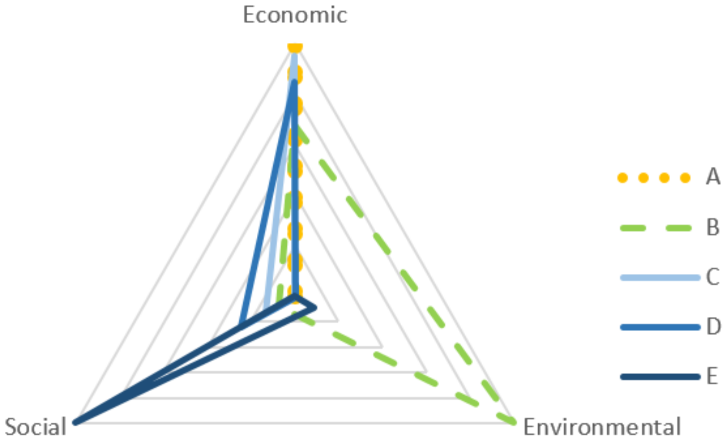

Figure 6. Radar chart of the normalized optimization results.

One can see that the most profitable solution (Case A) has both the worst environmental and social performances. The greener solution (Case B), with a 9% reduction in the total environmental impact, is achieved at the cost of a 32% reduction in the NPV over a 10-year time horizon. However, the social performance also increases by 115%, which translates in 589 more job opportunities. This job creation can stimulate local economy which in turn can create even more job opportunities. The socially more beneficially solution (Case E) is obtained considering at most a non-negative NPV value. This solution improves by 1524% the social performance when compared to the first one (the economical one), which translates into 3,182 more job opportunities. Cases C and D are explored in section 6.4.

Also visible from Table 10 is the small variation of environmental impact across the five solutions. This is justified by the significant contribution of production to the total environmental impact. Notice that since all demand must be met this impact can only be reduced up to a certain point (through alterations in technology selection and remanufacturing levels).

Table 11. Decisions' results summary.

	Cases				
	A	**B**	**C**	**D**	**E**
Factories	Factory in Verona is installed with maximum capacity. Factories in Hannover and Leeds are installed with 8% and 19% of maximum capacity, respectively.	Factory in Verona is installed with maximum capacity. Factories in Hannover and Leeds are installed with 43% and 39% of maximum capacity, respectively.	Factory in Verona installed with maximum capacity. Factory in Hannover installed with minimum capacity. Factory in Leeds installed with 15.95% of maximum capacity.	Factory in Verona installed with maximum capacity. Factory in Hannover installed with minimum capacity. Factory in Leeds installed with 16.16% of maximum capacity.	All installed with maximum capacity.
Warehouses	Verona Sofia	Verona Leeds São Paulo	All but Hannover, Leeds and Zaragoza installed with maximum capacity.		All but Hannover and Zaragoza installed with maximum capacity.
Suppliers	82% supplied from Verona 18% from Leeds	64% supplied from Verona 12% from Hannover 24% from Leeds	71% supplied from Verona 10% from Hannover 19% from Leeds	64% supplied from Verona 18% from Hannover 18% from Leeds	84% supplied from Verona 16% from Leeds
Supplier's allocation	Supplier in Verona supplies almost entirely factories in Verona and Hannover. Factory in Leeds supplied by both Leeds (75%) and Verona (25%).	Factories are supplied in totality by closest supplier.	Most of the supply (70-100%) is performed by closest supplier. Mostly Verona supplies the remaining amount. .		Supplier in Verona supplies almost entirely factories in Verona and Hannover. Factory in Leeds supplied by both Leeds (76%) and Verona (24%).
Production	Alternative production technologies are preferred.				
	Most production of *fp1* is in Verona (46-54%).				
	Most production of *fp2* is divided between Hannover (46-56%) and Leeds (30-48%).				
Remanufacturing	Most remanufacturing of rp1 is performed in Leeds (89%). Most remanufacturing of rp2 is performed in Hannover (48%).	Divided between Hannover and Leeds.	Mostly performed in Leeds (52%/56%). The remaining is divided between Verona and Hannover.		Mostly performed in Leeds (72%/86%). The remaining is divided between Verona and Hannover.
Product recovery	Minimum possible (15%)	81% for fp1	Minimum possible.	15% for fp1	21% for fp1
		Minimum possible for fp2		16% for fp2	25% for fp2
Inventory	More inventory of fp1 is kept than of fp2				
	Divided between Verona and Sofia.	Most inventory of fp1 is kept at São Paulo (44%) and fp2 at Verona (46%).	Most inventory of fp1 is kept at Lisbon (47%) and fp2 at Budapest (73%).	Most inventory of fp1 is kept at Lisbon (43%) and fp2 at Verona (37%).	Inventory is distributed among the seven warehouses.
Transportation	Mostly trucks of bigger capacity are purchased (15 versus 8).	Mostly trucks of bigger capacity are purchased (36 versus 3).	Mostly trucks of smaller capacity are purchased.		
	Air transportation is not used.	Air transportation is used for some intercontinental (Spain-São Paulo and Belgium-São Paulo) and intracontinental transportation (connecting Belgium-Spain).	Air transportation is only used for intercontinental transportation (Spain-São Paulo).		All links are established.
	Sea transportation is used in all cases.				

6.2. The importance of an integrated approach

Given the amount of information offered through the developed model, a detailed discussion of the results is not possible to be presented in this paper. Instead the more interesting results are discussed, highlighting the core contributions of this work.

Overall we see that changes in the optimization objectives return significantly different strategic and tactical decisions. Looking closer we also see that within each case studied, the decisions are so interconnected with each other that in order to accommodate a given decision, other levels and activities of the supply chain also have to adapt. This allows for a better performance across the supply chain. If decisions (other than location-allocation) were not modelled simultaneously in an integrated approach, the results would be, from the start, conditioned by the assumptions regarding the state of these non-considered supply chain decisions. The results discussed below evidence the importance of having an integrated approach that integrates decisions at the various levels of the supply chain (as reviewed by Ilgin and Gupta [17] and Govindan et al. [13].

A brief discussion of the most interesting results is made below (for more detailed data, refer to Table A. 1 and Table A. 2 in appendix):

- Facilities and installed capacity: Across the different cases studied in addition to the already installed factory in Verona (F1) also both other factories in Hannover (F2) and Leeds (F3) are installed. A preference is given to Leeds (across the cases factory F3 is installed with a bigger capacity) except in case B where the opposite occurs and an overall bigger factory area is installed. This decision is closely related with remanufacturing activities. In order to accommodate more remanufacturing, additional handling capacity is needed. Simultaneously there is also an increase on the warehouse capacity (from 10 thousand to about 18 thousand square meters). Looking at the cases more socially beneficial, we see as expected that as profit constraints become more relaxed (allowing for less profitable structures), installed capacity increases at factories and warehouses as this allows for the creation of more job opportunities.
- Supply: Across the different cases the supplier in Verona (S1) is preferred. Around 80 million units are being sourced from this supplier compared to around 20 million units being sourced from each of the other suppliers. This may occur for different reasons however the main one would be the lower raw material costs of the supplier in Verona. In fact this supplier supplies 100% of the needs of Verona factory, 100% of the needs of the factory located in Hannover and 25% of the needs of the one in Leeds (in case A). These results are most certainly the result of a balance between the raw material costs and the transportation costs (function of the distance between these entities). In case B, given that the cost factor is not considered, 100% of the needs of each factory are met by the closest supplier, so has to reduce the environmental impact of transportation. A more mixed sourcing plan, in cases C, D and E, allows for more job creation since more distance needs to be travelled and hence more trucks are required.
- Production and remanufacturing: Production activities are balanced across the three factories and across the analysed cases with a total of 56 to 68 million units being produced at each factory. Remanufacturing is more differentiated with the factory in

Verona (F1) being the less used for these activities. Reducing transportation costs from clients/warehouses back to the factories is likely the main reason behind this decision. Overall, a greener supply chain is obtained by increasing remanufacturing activities (from 6 million units in case A to more than 22 million in case B). To make this possible, as mentioned before, factory capacity increased from about 27 to more than 40 thousand square meters. Increased remanufacturing is also socially more beneficial since more jobs are created to recover the end-of-life products.

- Product recovery: As discussed by Dekker et al. [35], simply closing the loop does not guarantee a greener solution. This is corroborated by our results. In fact, closing the loop and increasing product recovery above the minimum required is only environmentally beneficial for one of the products (fp1) and to a certain extent (81%, see case B under product recovery). An association of factors favours this behaviour. To begin with, remanufacturing fp2 requires on average 5 units of end-of-life product rp2 while for fp1 only 4 units of rp1 are necessary. In addition, rp1 weights less than rp2. Both factors directly influence the transportation of these products to the recovering facility and, consequently, have an effect on the environmental performance. It is likely that the environmental impact benefit of remanufacturing fp2 does not trade-off the environmental impact increase due to transporting more end-of-life products (rp2 products).
- Inventory: The amount of inventory varies with each of the sustainability goals. For instance, in case A the final products inventory is greater than in case B (7 million *vs*. 6 million units). The reason concerns both transportation cost and environmental impact. In case A keeping more inventory allows for full truck loads so as to reduce the need to purchase more trucks or resort to other more expensive transportation modes. In case B the air transportation option is activated, likely because it allows a shorter distance to be travelled and hence reduces the transportation environmental impact. The average truck occupation changes from 30% in case A to 15% in case B. From the social point of view, more inventory allows for the already referred increase in warehouse capacity and hence the increase in job opportunities created.
- Transportation: Transportation directly influences most of the analysed supply chain decisions. Considering both intermodal and unimodal options offers a new range of options that, has seen before, influence the supply chain performance across the three sustainability pillars. In terms of road transportation, the truck with more capacity (Truck2) is preferred both in case A (15 trucks of type Truck2 compared to 8 of type Truck1) and case B (36 trucks of type Truck2 versus 3 of type Truck1). These options allow reducing both costs (with purchasing new trucks) and environmental impact (since Truck2 has a lower environmental impact than Truck1). Looking at the social impact of this decision the opposite takes place since selecting the truck with less capacity opens the need for more trucks and hence more truck drivers. In terms of intermodal transportation, the sea option (road + sea + road) is preferred across all cases. The air option is introduced in case B for the intercontinental connections Spain-São Paulo and Belgium-São Paulo as well as for the connection Belgium-Spain. From Spain, the Portuguese and Spanish markets are then supplied by road. In case E the plane option expands to include the airport in France (Air2).

The result obtained for case B comes across as strange however it can be explained from the fact that we are using a life cycle analysis methodology and not just focusing on a specific stage of the life cycle of these transportation modes. As one can see in Table 12, the total normalized environmental impact of using a plane is smaller (1.93E-6 Pt) than that of using Truck1 (1.05E-5 Pt), which has a lower transportation capacity, and is in the same order of magnitude of Truck2 (1.72E-6 Pt), which has a higher transportation capacity. This seems counterintuitive, however, looking in detail to the normalized values of each environmental impact midpoint category we see that there are 6 categories in which the plane performs better that Truck 2. These are FE (Freshwater Eutrophication), TET (Terrestrial Ecotoxicity), MET (Marine Ecotoxicity), IR (Ionizing Radiation), ULO (Urban Land Occupation) and MRD (Metal Depletion).

Table 12. Comparison of the environmental impact of the transportation modes: truck1, truck2 and plane. Red indicates highest, green indicates lowest and yellow indicates intermediate environmental impact for each midpoint category.

	Transportation mode, per kg.km			
Midpoint category	**Truck1**	**Truck2**	**Plane**	**Units**
CC	1.80E-03	4.34E-04	1.03E-03	kg CO_2 eq
OD	1.28E-10	3.31E-11	7.70E-11	kg CFC-11 eq
TA	8.29E-06	1.26E-06	3.35E-06	kg SO_2 eq
FE	5.04E-07	4.00E-08	-1.07E-08	kg P eq
ME	4.43E-07	7.07E-08	1.89E-07	kg N eq
HT	3.14E-03	4.19E-04	6.54E-04	kg 1,4-DB eq
POF	1.25E-05	2.18E-06	5.93E-06	kg NMVOC
PMF	3.87E-06	7.02E-07	1.08E-06	kg PM10 eq
TET	3.18E-06	9.77E-07	3.01E-07	kg 1,4-DB eq
FET	5.80E-07	1.81E-07	2.02E-07	kg 1,4-DB eq
MET	2.22E-03	3.98E-04	3.56E-04	kg 1,4-DB eq
IR	1.61E-04	2.53E-05	6.39E-05	kg U235 eq
ALO	3.68E-04	1.09E-04	2.00E-04	m^{2}a
ULO	7.43E-05	2.85E-05	8.67E-06	m^{2}a
NLT	5.12E-07	1.39E-07	3.02E-07	m^2
MRD	3.71E-04	5.25E-05	5.85E-06	kg Fe eq
FRD	6.64E-04	1.68E-04	3.79E-04	kg oil eq
Total normalized	**1.05E-05**	**1.72E-06**	**1.93E-06**	

These values are retrieved from existent databases resulting from extensive data gathering which includes several aggregations and allocations along the life cycle of each of the means of transport. The corresponding documentation in SimaPro indicates which of the life cycle stages of the product/service are included in the collected data. For the plane these include the operation of the aircraft, the production of aircraft, the construction of airport and the energy use and combustion emissions. It is also indicated that the fuel considered for air transportation is kerosene. The combustion of kerosene in aircraft engines is directly coupled with the production of carbon dioxide and water. The fact that water is released in the combustion process is accounted for as a credit in the Ecoinvent database, meaning that it is seen as a beneficial environmental impact (and hence the negative value). For trucks included activities are the operation of vehicle, production and maintenance of vehicles, construction of road, energy use and combustion emissions which include fuel consumption. In this case no credits are attributed. This analysis coupled with the total distance travelled, which is lower if travelled by plain, explains the results obtained.

6.3. Identifying environmental sustainability hotspots and defining strategies

Table 13 summarizes the main environmental results, namely the contribution of each of the supply chain activities to the total environmental impact in each of the cases analysed. Data detailing the contribution of each case/activity to each of the midpoint environmental impact categories is also available upon request.

Table 13. Environmental impact (x10^5) of the different supply chain activities for the five cases analysed.

	A	B	C	D	E
Production/remanufacturing	9,960	9,053	9,958	9,951	9,869
Transportation	5.2	4.6	5.8	7.5	13.4
Facility installation	0.7	1.2	1.5	1.5	2.0
TOTAL	9,974	9,484	9,964	9,953	9,876

The analysis of these results allows the identification of environmental sustainability hotspots while also providing the opportunity to define specific strategies to improve the supply chain sustainability. Three of them are presented:

- Production/remanufacturing activities are the greatest contributors to these supply chain environmental impacts. This takes place across all considered cases. It is also clear that remanufacturing activities allow improving the environmental performance of this supply chain (9,960x10^5 in case A to 9,053 x10^5 in case B). However this decision affects not only remanufacturing and production activities but also raw material purchasing, product recovery, transportation and necessary installed area. Exploring research opportunities on ways to further reduce the costs and the environmental impact of remanufacturing technologies would be an important step to take. Another interesting conclusion of this analysis is that as solutions improve in their social sustainability (see cases C, D and E), the environmental performance also improves since the remanufacturing volume increases. Therefore, investing in remanufacturing technologies and related R&D would be beneficial for all the three pillars of sustainability.
- Transportation is the second highest contributor to the total environmental impact and, in relative terms, is the one that varies the most across the different cases. In this case study, intermodal solutions seem to be environmentally beneficial in some cases (as explained previously for the case of air transportation) but again come with the increased cost of air transportation. Pursuing better contracts with both airlines and freighters, testing different hub locations or even exploring rail options (not accounted for in this work) would be strategies worth following.
- Investing in other activities of the value chain, namely technology development concerning the reduction of product weight would also be an important step towards a more sustainable supply chain both in terms of environmental and economic impact, specifically in the case of product fp2, (see discussion in section 6.2).

6.4. Tendencies towards a more socially responsible supply chain

In order to study the possibility of achieving more social benefit by aligning the goals of the company with those of organizations such as the European Commission in terms of sustainable development strategies, cases C and D were designed. Both cases offer solutions of compromise where the NPV obtained in Case A is reduced by 5% and 15%, respectively. Notice that by compromising NPV both the environmental and the social performances are improved. In particular, for case C, this means an improvement of 0.01% in terms of environmental impact and 201% in terms of social impact, accounting for 475 more job opportunities at a cost of 64M€ over a 10-year time horizon. For case D it corresponds to 0.06% and 375% improvement, respectively, which translates into 810 more job opportunities at a cost of 192M€ over a 10-year time horizon. If these costs are accounted per worker per year, we see a unit value of 13,500€, for case C, and 24,000€, for case D, which are reasonable amounts in light of possible economic incentives from the governments, European Union or similar organizations. Potentially these additional job opportunities will stimulate the economy of the regions where they are implemented, and therefore these organizations are likely to see a return on their investment and further use it to subsidize companies what can result in a virtuous circle.

Figure 7 depicts the number of workers across countries and across the different cases analysed. Detailed information regarding the distribution of the workers through the supply chain activities as well as the countries can be found in supplementary material.

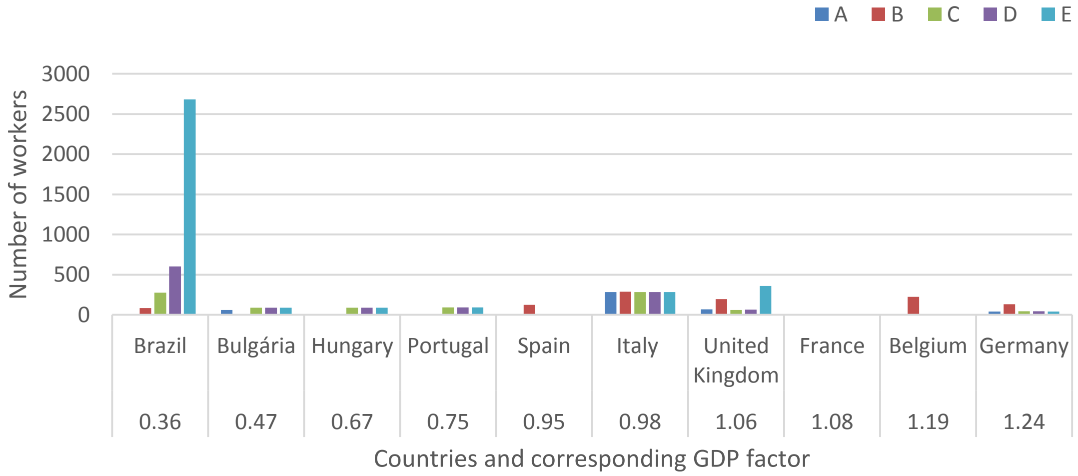

Figure 7. Number of workers per country for each of the five cases analysed.

The results show a tendency towards Brazil, given that not only is it the country with the lowest GDP among the available options but it is also a country with averagely low labour costs. Belgium stands out in case B due to the increased usage of air transportation, specifically of the airport in Belgium (Air3). In fact the solution obtained with case B is an interesting one, since it actually provides more job creation than solution C. However its social indicator is significantly different from cases D and E given the large GDP per capita of Belgium with respect to the other countries.

6.5. Questioning product recovery policies

One of the most interesting results obtained (as discussed in section 6.2) was that product recovery rates differed for the two products (fp1 and fp2) when minimizing environmental impact (case B). In fact, 81% of product fp1 is recovered in case B when compared to 15% (minimum required by company policy) of fp2. This seems to indicate that product recovery policy should be adjusted to product characteristics (e.g. product weight or volume which has a direct impact on the environmental impact of transportation). Following these results three new scenarios were created and optimized towards minimum environmental impact:

- Case B1: no minimum recovery fraction is imposed for any of the products;
- Case B2: a minimum recovery fraction of 5% is imposed for both products;
- Case B3: a minimum recovery fraction of 10% is imposed for both products.

Figure 8 shows the percentage of recovered units in each of the described cases, also including Case A and Case B for comparison. Figure 9 details the environmental impact obtained in each of the supply chain activities: transportation, entity installation and production.

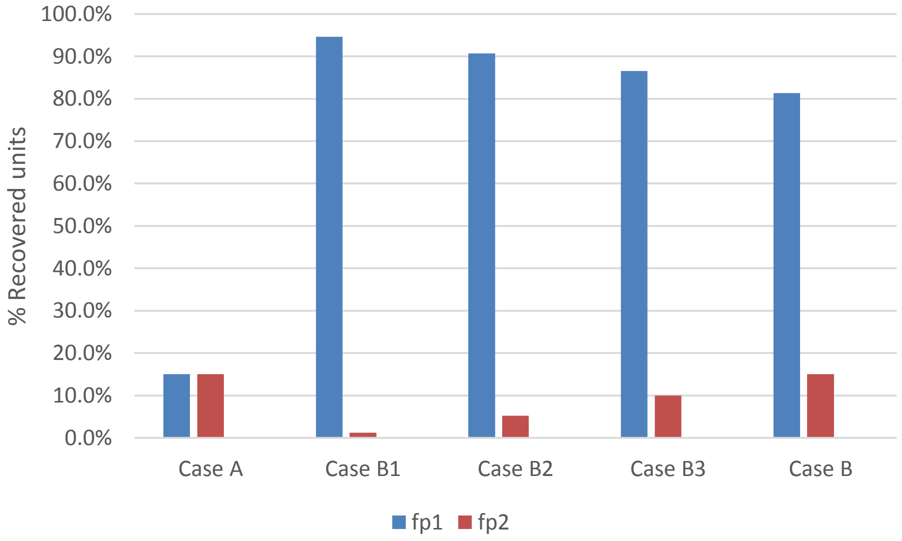

Figure 8. Percentage of recovered units of products fp1 and fp2 in each of the considered cases.

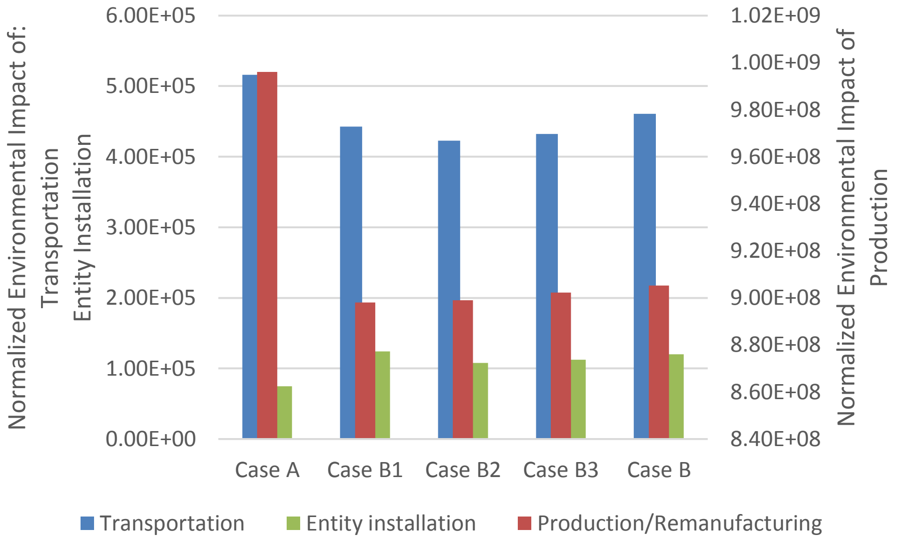

Figure 9. Normalized Environmental Impact of transportation, entity installation and production for the described cases.

Results show that product recovery is clearly environmentally more beneficial for product fp1 than for product fp2, allowing to reduce the environmental impact not only of transportation but also of entity installation and production/remanufacturing. These results again show the importance of an integrated framework in such type of analysis.

6.6. Demand uncertainty analysis

The deterministic solution was defined by the company as being the worst case scenario in terms of economic performance where a higher penetration level in both the new European and Brazilian markets is assumed. Even though entering the Brazilian market is not profitable under the presented conditions the company does not consider the hypothesis of not entering this market. The goal is then to understand how the profit margin and the supply chain network would be affected in face of a decline in the expected demand, that is, a decline in the expected level of market penetration.

With the described goal a stochastic approach was developed. A scenario analysis was performed and therefore a subscript s (for scenarios) was added to the following decision variables: X_{maijt}, S_{mit}, YCT_{it}, P_{mgit}, R_{mgit}, Q_{aijt} and K_{ait}. Constraints were adjusted accordingly. The stochastic objectives functions now replace equations (41), (42) and (43) in the economic objective function, equation (46) in the environmental objective function, and equation (47) in the social objective function.

The new equations in the economic objective function are given by equations (49), (50) and (51).

$$max\,ENPV = \sum_{s} prob_s \left(\sum_{t \in T} \frac{CF_{st}}{(1+ir)^t} - \sum_{\gamma} FCI_\gamma \right) \quad \textbf{(49)}$$

$$CF_{st} = \begin{cases} NE_{st} & t = 1, \dots, NT-1, s \in S \\ NE_{st} + \sum_{\gamma} (sv_\gamma FCI_\gamma) & t = NT, s \in S \end{cases} \quad \textbf{(50)}$$

$$
\begin{aligned}
NE_{st} = (1-tr)\Bigg[& \sum_{\substack{(m,i,j)\in F_{INCFP}\\(a,m,i,j)\in NetP}} psu_m\, X_{maijts} \\
& - \Bigg(\sum_{\substack{(m,i,j)\in F_{OUTSUPRM}\\(a,m,i,j)\in NetP}} rmc_{mi}X_{maijts} + \sum_{\substack{(m,g)\in H_{prod}\\ i\in I_f}} opc_g P_{mgits} \\
& + \sum_{\substack{(m,i,j)\in F_{OUTCRP}\\(a,m,i,j)\in NetP}} rpc_m X_{maijts} + \sum_{\substack{(m,g)\in H_{rem}\\ i\in I_f}} opc_g R_{mgits} \\
& + \sum_{\substack{(a,m,i,j)\in NetP\\ a\in A_{truck}}} \left(\frac{avc_a}{100}.fp + vmc\right).2d_{ij}.Q_{aijts} \\
& + \sum_{\substack{(a,m,i,j)\in NetP\\ a\in (A_{plane}\cup A_{boat})}} tc_a.pw_m.d_{ij}.X_{maijts} \\
& + \sum_{\substack{(a,m,i,j)\in NetP\\ (j\in I_{plane}\wedge i\notin I_{plane})\cup(j\in I_{boat}\wedge i\notin I_{boat})}} hhc_j.X_{maijts} \\
& + \sum_{i\in I_{plane}\cup I_{boat}} cfp_i.Y_i + \sum_{(m,i)\in V} sc_m S_{mits} + \sum_{i\in I_f\cup I_w} w_i.lc_i.wwh.wpt.Y_i \\
& + \sum_{i\in I_f\cup I_w} wpsq.lc_i.wwh.wpt.YC_i + \sum_{\substack{(m,g)\in H\\ i\in I_f}} w_g.lc_i.wwh.wpt.Z_{gmi} \\
& + \sum_{\substack{i\in I\\ a\in A_{truck}}} w_a.lc_i.wwh.wpt.K_{ai} \Bigg)\Bigg] + tr.DP_t
\end{aligned} \tag{51}
$$

The environmental objective function is now given by equation (52).

$$
\begin{aligned}
& \min EEnvImpact \\
& = \sum_s prob_s \left(\sum_c \eta_c \left(\sum_{\substack{t\in T, i\in I_f\\(m,g)\in H}} ei_{mgc} pw_m (P_{mgits} + R_{mgits}) \right.\right. \\
& \left.\left. + \sum_{\substack{t\in T\\(a,m,i,j)\in NetP}} ei_{ac} pw_m d_{ij} X_{maijts} + \sum_{i\in I_f\cup I_w} ei_{ic} YC_i \right)\right)
\end{aligned} \tag{52}
$$

The social objective function is now given by equation (53).

$$max\,EGDPInd = \sum_{s} prob_s \left(\sum_{i \in I_f \cup I_w} \mu_i^{GDP} w_i Y_i + \sum_{i \in I_f \cup I_w} \mu_i^{GDP} wpsq_i YC_i + \sum_{\substack{(m,g) \in H \\ i \in I_f}} \mu_i^{GDP} w_g Z_{gmi} + \sum_{\substack{(a,i,j) \in Net \\ a \in A_{truck}}} \mu_i^{GDP} w_a K_{ai} + \sum_{\substack{(a,m,i,j) \in NetP \\ a \in A_{plane} \cup A_{ship} \\ t \in T}} \mu_i^{GDP} \frac{w_a}{yth}.pw_m.d_{ij}.X_{maijts} \right) \quad \textbf{(53)}$$

Five scenarios are considered in the stochastic case (Case A1):

- The base scenario, with the original expected demand;
- Scenarios e1, and e3, which represent scenarios where expected demand in European clients was reduced by 1% and 3%, respectively;
- Scenarios b5, and b10, which represent scenarios where expected demand in clients in Brazil was reduced by 5% and 10%, respectively.

The following probabilities were assigned: 45% to the base scenario, 15% to scenario e1, 5% to scenario e3, 25% to scenario b5 and 10% to scenario b10.

The model was optimized towards profit maximization.

The computational and operational results obtained are presented in Table 14 for the deterministic (Case A) and stochastic (Case A1) cases.

Table 14. Computational results for case A (deterministic) and case A1 (stochastic).

		Case A	**Case A1**
Computational results	# Total variables	28,611	142,555
	# Binary variables	27,096	135,078
	# Restrictions	33,454	166,442
	GAP (%)	0.23	0.34
	CPU (s)	32,752	313,414
Operational results	Raw material purchasing (x10^6 €)	4.9	5.5
	Recovered product costs (x10^6 €)	4.1	4.1
	Production costs (x10^7 €)	4.6	4.6
	Remanufacturing costs (x10^5 €)	7.7	7.6
	Transportation (includes hub costs) (x10^9 €)	2.7	2.6
	Inventory costs (x10^4 €)	6.8	5.7
	Labor costs (x10^8 €)	2.2	2.2
	Sales (x10^9 €)	6.0	5.9
	NPV (x10^9 €)	1.3	1.3
	Environmental impact (x10^8 Pts)	10	9.9
	Social benefit	534	540
	Investment in facilities (x10^6 €)	5.5	5.5
	Investment in technologies (x10^6 €)	1.3	1.3
	Investment in trucks (x10^5 €)	9.9	11.2

The inclusion of uncertainty did not result in any significant changes in the supply chain design and planning decisions as the obtained results for cases A and A1 are very similar. Even though the weighted sales decrease, the net present value is maintained. Additionally, a small positive variation is observed in the environmental impact and in the social benefit. All in all one can conclude that the deterministic solution obtained is able to be profitable while supporting a higher level of market penetration. In case the expected demand is not verified the supply chain is still able to respond positively with no major adjustments and can even internally improve its environmental and social performances.

Overall the developed and presented tool provides support for decisions to be taken both internal and external to the company and at several levels of the supply chain. Specifically it allows to:

- Understand the connections between the different supply chain activities and because of that obtain a better combined performance across the supply chain. This would not be possible if we were only considering the commonly published location-allocation supply chain decisions.
- Understand the impact of these decisions on the three pillars of sustainability and from there derive potential strategies that can reduce the trade-offs between these pillars.
- Identify environmental sustainability hotspots and prioritize actions to reduce the environmental impact of the supply chain activities.
- Explore socially responsible alternatives without compromising either the economic performance of the company or the potential funding bodies.
- Derive potential improvement strategies and study its impact across supply chain activities as well as on the three pillars of sustainability.
- Design and plan a supply chain capable of accommodating parameters’ uncertainty (e.g. market penetration) through a stochastic approach.

7. Conclusions and future work

This work builds on several research gaps identified in literature. It does so: 1) by providing an integrated supply chain design and planning optimization model that incorporates several different interconnected supply chain decisions such as supplier selection, raw material purchase planning, facility location and capacity installation, technology selection, production and remanufacturing planning, product recovery strategies, transportation network definition (with both unimodal and intermodal options), and inventory planning; 2) by presenting a closed-loop supply chain model that explicitly evaluates the environmental impact of all the supply chain activities, corroborating the conclusion that by simply closing the loop one does not guarantee a better environmental performance, as stated by Dekker et al. [35]; 3) by assessing the impact of supply chains on society, specifically on socio-economic indicators used by the European Commission in its Sustainable Development Strategy; and 4) by providing a multi-objective decision making tool that addresses the three pillars of sustainability allowing the study of their interactions and deriving strategies towards a more socially responsible and environmentally friendly supply chain.

Overall this work presents a decision support tool – TOBLOOM - to be used when designing and planning supply chains, where an integrated perspective approach is developed that accounts for the simultaneous solution of a set of main sustainable supply chain decisions. It should again be referred that even though TOBLOOM is generic the application of the social indicator presented in this work should be limited to the modelling of situations that do not require layoffs but do require hiring, such as the introduction of a new product, expansion to new markets, material or product design selection, among others. Demand uncertainty is also analysed in this work through a stochastic approach. Different levels of market penetration are investigated.

Although an important step was taken on the definition of sustainable supply chains future work should still be done, which can evolve in three ways. At the model level, the dynamic nature of the supply chain needs to be explored as well as the uncertainty involved in other additional internal and external parameters. Also at the sustainability analysis level, the impact of different environmental and social indicators should be analysed. Finally, within our research work in collaboration with companies we have been pursuing the validation of the presented tool, and several problems have been studied. The present paper is a result of such work, however we believe that new applications may improve the present tool and therefore this work is to be pursued.

Acknowledgements

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APPENDIX A. Decisions' results summary - detailed

Table A. 1 and Table A. 2 depict the summary of the results obtained for each decision and each case-study analysed in this work, as described in section 6.2. These are grouped by supply chain activity: facilities, supply, production and remanufacturing (Table A. 1), inventory, and transportation (Table A. 2).

Table A. 1. Summary of decisions to be taken considering the five different cases: facilities, supply, production and remanufacturing.

				Cases				
				A	B	C	D	E
			Entities					
Facilities	Facilities and installed capacity (m^2)	Factories	F1	20,000	20,000	20,000	20,000	20,000
			F2	2,000	10,704	2,000	2,000	2,000
			F3	4,749	9,712	3,989	4,041	25,000
			TOTAL	26,749	40,416	25,989	26,041	47,000
		Warehouses	W1	5,000	5,000	5,000	5,000	5,000
			W2					
			W3		6,341			8,000
			W4					
			W5			8,000	8,000	8,000
			W6		6,832	8,000	8,000	8,000
			W7			8,000	8,000	8,000
			W8			8,000	8,000	8,000
			W9	4,893		8,000	8,000	8,000
			TOTAL	9,893	18,172	45,000	45,000	53,000
Supply			Suppliers					
	Raw materials purchase levels ($x10^6$ units)		S1	87	70	75	67	87
			S2		13	10	19	
			S3	19	27	20	19	17
			TOTAL	106	110	105	104	104
		Factories	Suppliers					
	Suppliers' allocation (%)	F1	S1	100.00	100.00	99.97	100.00	99.92
			S2			0.03		
			S3					0.08
		F2	S1	99.64		28.19	13.86	92.73
			S2		100.00	71.32	86.14	
			S3	0.36		0.49		7.27
		F3	S1	25.12		24.97	2.82	23.90
			S2				0.01	
			S3	74.88	100.00	75.03	97.17	76.10
Production and remanufacturing		Factories	Technologies					
	Production levels ($x10^4$ units)	F1	gp1	5,797	4,197	5,796	5,789	5,785
			gp2	553	2,155	464	432	544
		F2	gp1	0	0	0	0	0
			gp2	0	0	0	0	0
			gp1 alt	1,909	1,656	1,786	2,686	2,356
			gp2 alt	4,973	4,044	5,050	4,177	4,550
		F3	gp1	0	0	0	0	0
			gp2	0	0	0	0	0
			gp1 alt	3,182	3,364	3,311	2,419	2,593
			gp2 alt	3,316	2,644	3,332	4,220	3,585
			TOTAL	19,730	18,059	19,739	19,722	19,414
	Remanufacturing levels ($x10^4$ units)	F1	gr1	42	3	64	71	74
			gr2	41	0	70	74	29
		F2	gr1	0	1,172	117	92	0
			gr2	117	129	48	42	88
		F3	gr1	336	877	198	216	465
			gr2	87	116	127	146	294
			TOTAL	623	2,296	623	639	949
			Product					
	Product recovery (%)		fp1	15	81	15	15	21
			fp2	15	15	15	16	25

Table A. 2. Summary of decisions to be taken considering the five different cases: inventory and transportation.

				Cases			
				A	B	C	D	E
Inventory	Average inventory (over the 10 year period) of each final product at each warehouse (x10^4 units)	fp1	**Warehouses**					
			W1	237	145	166	301	138
			W2	0	0	0	0	0
			W3	0	99	0	0	211
			W4	0	0	0	0	0
			W5	0	0	392	451	337
			W6	0	0	12	12	112
			W7	0	194	12	12	155
			W8	0	0	206	251	43
			W9	316	0	51	23	12
			TOTAL	553	439	840	1,050	1,007
		fp2	W1	64	92	28	33	73
			W2	0	0	0	0	0
			W3	0	55	0	0	86
			W4	0	0	0	0	0
			W5	0	0	30	13	60
			W6	0	0	10	10	10
			W7	0	54	10	10	10
			W8	0	0	235	13	45
			W9	61	0	10	10	16
			TOTAL	125	202	322	90	300
Transportation	Number of trucks to purchase		**Trucks**					
			Truck1	8	3	36	40	43
			Truck2	15	36	18	16	14
	Established air and sea connections ('X' if they are established, '-' if not)	Air	**Airports**					
			Air1		x	x	x	x
			Air2					x
			Air3		x			x
			Air4		x	x	x	x
		Sea	**Seaports**					
			Sea1	x	x	x	x	x
			Sea2	x	x	x	x	x

APPENDIX B. Environmental impact results

Table B. 1. Abbreviations and units of each midpoint environmental impact categories of ReCiPe.

Abbrev.	Midpoint impact categories	Units	Abbrev.	Midpoint impact categories	Units
CC	Climate Change	Kg CO_2 eq	**FET**	Freshwater Ecotoxicity	Kg 1,4-DB eq
OD	Ozone Depletion	Kg CFC-11 eq	**MET**	Marine Ecotoxicity	Kg 1,4-DB eq
TA	Terrestrial Acidification	Kg SO_2 eq	**IR**	Ionising Radiation	Kg U235 eq
FE	Freshwater Eutrophication	Kg P eq	**ALO**	Agricultural Land Occupation	m^2a
ME	Marine Eutrophication	Kg N eq	**ULO**	Urban Land Occupation	m^2a
HT	Human Toxicity	Kg 1,4-DB eq	**NLT**	Natural Land Transformation	m^2
POF	Photochemical Oxidant Formation	Kg NMVOC	**MRD**	Metal Depletion	Kg Fe eq
PMF	Particulate Matter Formation	Kg PM10 eq	**FRD**	Fossil Depletion	Kg oil eq
TET	Terrestrial Ecotoxicity	Kg 1,4-DB eq			

APPENDIX B.1. Transportation environmental impact results

Table B.1. 1. Environmental impact results for transportation for each midpoint impact category.

	Cases											
Imp. Cat.	A				B				C			
	Truck1	Truck2	Ship	Plane	Truck1	Truck2	Ship	Plane	Truck1	Truck2	Ship	Plane
CC	3.26E+03	1.81E+04	5.25E+02		5.89E+02	1.82E+04	5.89E+02	2.52E+03	5.39E+03	1.77E+04	5.20E+02	4.69E+02
OD	3.41E+01	2.03E+02	5.18E+00		6.16E+00	2.05E+02	5.82E+00	2.78E+01	5.64E+01	1.98E+02	5.13E+00	5.18E+00
TA	1.97E+03	6.90E+03	1.48E+03		3.56E+02	6.95E+03	1.67E+03	1.08E+03	3.26E+03	6.73E+03	1.47E+03	2.01E+02
FE	1.74E+04	3.19E+04	1.33E+03		3.14E+03	3.21E+04	1.50E+03	-4.99E+02	2.88E+04	3.11E+04	1.32E+03	-9.29E+01
ME	6.05E+02	2.22E+03	2.23E+02		1.09E+02	2.24E+03	2.50E+02	3.49E+02	1.00E+03	2.17E+03	2.21E+02	6.51E+01
HT	2.16E+04	6.66E+04	1.92E+03		3.91E+03	6.71E+04	2.15E+03	6.12E+03	3.58E+04	6.50E+04	1.90E+03	1.14E+03
POF	2.20E+03	8.90E+03	8.15E+02		3.98E+02	8.96E+03	9.15E+02	1.42E+03	3.64E+03	8.68E+03	8.06E+02	2.64E+02
PMF	2.75E+03	1.15E+04	1.31E+03		4.97E+02	1.16E+04	1.47E+03	1.04E+03	4.56E+03	1.13E+04	1.29E+03	1.93E+02
TET	3.90E+03	2.77E+04	1.31E+02		7.05E+02	2.79E+04	1.47E+02	5.01E+02	6.46E+03	2.70E+04	1.29E+02	9.33E+01
FET	1.27E+03	9.17E+03	1.25E+02		2.30E+02	9.24E+03	1.40E+02	6.01E+02	2.11E+03	8.95E+03	1.23E+02	1.12E+02
MET	3.28E+04	1.36E+05	4.77E+03		5.94E+03	1.37E+05	5.36E+03	7.15E+03	5.44E+04	1.33E+05	4.72E+03	1.33E+03
IR	1.22E+03	4.43E+03	2.53E+02		2.21E+02	4.47E+03	2.84E+02	6.58E+02	2.03E+03	4.33E+03	2.51E+02	1.23E+02
ALO	6.80E+02	4.63E+03	6.26E+01		1.23E+02	4.66E+03	7.03E+01	5.01E+02	1.13E+03	4.51E+03	6.20E+01	9.33E+01
ULO	9.60E+02	8.50E+03	3.55E+01		1.73E+02	8.56E+03	3.98E+01	1.52E+02	1.59E+03	8.29E+03	3.51E+01	2.83E+01
NLT	4.26E+02	2.66E+03	6.36E+01		7.71E+01	2.68E+03	7.14E+01	3.41E+02	7.06E+02	2.60E+03	6.29E+01	6.36E+01
MRD	8.33E+03	2.72E+04	2.93E+02		1.51E+03	2.74E+04	3.29E+02	1.79E+02	1.38E+04	2.66E+04	2.90E+02	3.33E+01
FRD	5.15E+03	3.02E+04	7.74E+02		9.31E+02	3.04E+04	8.69E+02	3.99E+03	8.53E+03	2.94E+04	7.66E+02	7.44E+02
Norm. total	3.26E+03	1.81E+04	5.25E+02		1.89E+04	4.00E+05	1.59E+04	2.61E+04	1.73E+05	3.87E+05	1.40E+04	4.87E+03
Total	5.16E+05				4.61E+05				5.80E+05			

(cont.)

	Cases							
Imp. Cat.	D				E			
	Truck1	Truck2	Ship	Plane	Truck1	Truck2	Ship	Plane
CC	1.22E+04	1.43E+04	4.98E+02	2.90E+03	2.51E+04	1.53E+04	5.01E+02	1.81E+04
OD	1.28E+02	1.61E+02	4.91E+00	3.20E+01	2.63E+02	1.71E+02	4.94E+00	2.00E+02
TA	7.40E+03	5.46E+03	1.41E+03	1.24E+03	1.52E+04	5.82E+03	1.42E+03	7.75E+03
FE	6.54E+04	2.52E+04	1.26E+03	-5.75E+02	1.34E+05	2.69E+04	1.27E+03	-3.59E+03
ME	2.27E+03	1.76E+03	2.11E+02	4.02E+02	4.67E+03	1.88E+03	2.13E+02	2.51E+03
HT	8.14E+04	5.27E+04	1.81E+03	7.05E+03	1.67E+05	5.62E+04	1.83E+03	4.40E+04
POF	8.27E+03	7.03E+03	7.72E+02	1.63E+03	1.70E+04	7.50E+03	7.77E+02	1.02E+04
PMF	1.03E+04	9.12E+03	1.24E+03	1.20E+03	2.12E+04	9.72E+03	1.25E+03	7.47E+03
TET	1.47E+04	2.19E+04	1.24E+02	5.77E+02	3.01E+04	2.33E+04	1.25E+02	3.60E+03
FET	4.79E+03	7.25E+03	1.18E+02	6.92E+02	9.83E+03	7.73E+03	1.19E+02	4.32E+03
MET	1.23E+05	1.08E+05	4.52E+03	8.24E+03	2.53E+05	1.15E+05	4.55E+03	5.14E+04
IR	4.61E+03	3.50E+03	2.40E+02	7.58E+02	9.45E+03	3.74E+03	2.42E+02	4.73E+03
ALO	2.56E+03	3.66E+03	5.93E+01	5.77E+02	5.24E+03	3.90E+03	5.97E+01	3.60E+03
ULO	3.61E+03	6.72E+03	3.36E+01	1.75E+02	7.41E+03	7.17E+03	3.38E+01	1.09E+03
NLT	1.60E+03	2.10E+03	6.02E+01	3.93E+02	3.29E+03	2.24E+03	6.06E+01	2.45E+03
MRD	3.13E+04	2.15E+04	2.77E+02	2.06E+02	6.43E+04	2.30E+04	2.79E+02	1.28E+03
FRD	1.94E+04	2.39E+04	7.33E+02	4.60E+03	3.97E+04	2.54E+04	7.38E+02	2.87E+04
Norm. total	3.93E+05	3.14E+05	1.34E+04	3.01E+04	8.07E+05	3.35E+05	1.35E+04	1.88E+05
Total	7.51E+05				1.34E+06			

APPENDIX B.2. Production environmental impact results

Table B.2. 1. Environmental impact results for production and remanufacturing for each midpoint impact category.

	Cases							
	A				B			
Imp. Cat.	**Production**		**Remanufacturing**		**Production**		**Remanufacturing**	
	fp1	**fp2**	**fp1**	**fp2**	**fp1**	**fp2**	**fp1**	**fp2**
CC	3.63E+06	3.34E+06	3.67E+04	2.27E+04	2.99E+06	3.49E+06	1.99E+05	2.27E+04
OD	1.95E+04	1.58E+04	1.97E+02	8.63E+01	1.61E+04	1.66E+04	1.07E+03	8.63E+01
TA	4.38E+06	3.37E+06	4.43E+04	1.84E+04	3.61E+06	3.52E+06	2.40E+05	1.84E+04
FE	3.24E+08	8.86E+07	3.28E+06	4.82E+05	2.67E+08	9.26E+07	1.78E+07	4.83E+05
ME	1.75E+06	8.40E+05	1.77E+04	4.57E+03	1.44E+06	8.77E+05	9.60E+04	4.57E+03
HT	2.84E+07	2.16E+07	2.87E+05	1.17E+05	2.34E+07	2.25E+07	1.55E+06	1.17E+05
POF	2.13E+06	1.24E+06	2.15E+04	6.76E+03	1.76E+06	1.30E+06	1.17E+05	6.77E+03
PMF	4.93E+06	4.00E+06	4.99E+04	2.18E+04	4.06E+06	4.18E+06	2.70E+05	2.18E+04
TET	2.31E+06	1.76E+06	2.33E+04	9.57E+03	1.90E+06	1.84E+06	1.26E+05	9.58E+03
FET	7.00E+07	1.07E+07	7.08E+05	5.85E+04	5.77E+07	1.12E+07	3.84E+06	5.85E+04
MET	2.53E+08	6.61E+07	2.56E+06	3.60E+05	2.08E+08	6.91E+07	1.39E+07	3.60E+05
IR	3.23E+06	3.70E+06	3.26E+04	2.01E+04	2.66E+06	3.87E+06	1.77E+05	2.01E+04
ALO	1.03E+06	9.60E+05	1.04E+04	5.22E+03	8.46E+05	1.00E+06	5.63E+04	5.23E+03
ULO	7.97E+05	4.91E+05	8.06E+03	2.67E+03	6.57E+05	5.13E+05	4.37E+04	2.68E+03
NLT	3.58E+05	2.26E+05	3.62E+03	1.23E+03	2.95E+05	2.36E+05	1.96E+04	1.23E+03
MRD	6.03E+07	1.19E+07	6.10E+05	6.46E+04	4.97E+07	1.24E+07	3.31E+06	6.46E+04
FRD	4.00E+06	3.46E+06	4.04E+04	1.88E+04	3.29E+06	3.62E+06	2.19E+05	1.88E+04
Norm. Total	7.65E+08	2.22E+08	7.73E+06	1.21E+06	6.30E+08	2.32E+08	4.19E+07	1.22E+06
Total	9.96E+08				9.05E+08			

(cont.)

	Cases											
	C				D				E			
Imp. Cat.	**Production**		**Remanufacturing**		**Production**		**Remanufacturing**		**Production**		**Remanufacturing**	
	fp1	**fp2**	**fp1**	**fp2**	**fp1**	**fp2**	**fp1**	**fp2**	**fp1**	**fp2**	**fp1**	**fp2**
CC	3.63E+06	3.33E+06	3.67E+04	2.27E+04	3.63E+06	3.32E+06	3.67E+04	2.42E+04	3.59E+06	3.28E+06	5.22E+04	3.82E+04
OD	1.95E+04	1.58E+04	1.97E+02	8.63E+01	1.95E+04	1.58E+04	1.97E+02	9.21E+01	1.93E+04	1.56E+04	2.81E+02	1.45E+02
TA	4.38E+06	3.37E+06	4.43E+04	1.84E+04	4.38E+06	3.36E+06	4.43E+04	1.96E+04	4.33E+06	3.31E+06	6.31E+04	3.08E+04
FE	3.25E+08	8.84E+07	3.28E+06	4.82E+05	3.24E+08	8.82E+07	3.28E+06	5.15E+05	3.21E+08	8.70E+07	4.67E+06	8.10E+05
ME	1.75E+06	8.38E+05	1.77E+04	4.57E+03	1.75E+06	8.36E+05	1.77E+04	4.88E+03	1.73E+06	8.24E+05	2.52E+04	7.68E+03
HT	2.84E+07	2.15E+07	2.87E+05	1.17E+05	2.84E+07	2.14E+07	2.87E+05	1.25E+05	2.80E+07	2.12E+07	4.08E+05	1.97E+05
POF	2.13E+06	1.24E+06	2.15E+04	6.76E+03	2.13E+06	1.24E+06	2.15E+04	7.22E+03	2.11E+06	1.22E+06	3.07E+04	1.14E+04
PMF	4.93E+06	4.00E+06	4.99E+04	2.18E+04	4.93E+06	3.99E+06	4.99E+04	2.33E+04	4.87E+06	3.93E+06	7.10E+04	3.66E+04
TET	2.31E+06	1.75E+06	2.33E+04	9.57E+03	2.31E+06	1.75E+06	2.33E+04	1.02E+04	2.28E+06	1.73E+06	3.32E+04	1.61E+04
FET	7.00E+07	1.07E+07	7.08E+05	5.85E+04	7.00E+07	1.07E+07	7.08E+05	6.24E+04	6.92E+07	1.05E+07	1.01E+06	9.82E+04
MET	2.53E+08	6.60E+07	2.56E+06	3.60E+05	2.53E+08	6.58E+07	2.56E+06	3.84E+05	2.50E+08	6.49E+07	3.64E+06	6.05E+05
IR	3.23E+06	3.69E+06	3.26E+04	2.01E+04	3.23E+06	3.68E+06	3.26E+04	2.15E+04	3.19E+06	3.63E+06	4.65E+04	3.38E+04
ALO	1.03E+06	9.58E+05	1.04E+04	5.22E+03	1.03E+06	9.55E+05	1.04E+04	5.58E+03	1.01E+06	9.42E+05	1.48E+04	8.78E+03
ULO	7.98E+05	4.90E+05	8.06E+03	2.67E+03	7.97E+05	4.89E+05	8.06E+03	2.85E+03	7.88E+05	4.82E+05	1.15E+04	4.49E+03
NLT	3.58E+05	2.26E+05	3.62E+03	1.23E+03	3.58E+05	2.25E+05	3.62E+03	1.31E+03	3.54E+05	2.22E+05	5.15E+03	2.07E+03
MRD	6.03E+07	1.18E+07	6.10E+05	6.46E+04	6.03E+07	1.18E+07	6.10E+05	6.89E+04	5.96E+07	1.16E+07	8.68E+05	1.08E+05
FRD	4.00E+06	3.45E+06	4.04E+04	1.88E+04	4.00E+06	3.44E+06	4.04E+04	2.01E+04	3.95E+06	3.40E+06	5.76E+04	3.16E+04
Norm. Total	7.65E+08	2.22E+08	7.73E+06	1.21E+06	7.65E+08	2.21E+08	7.73E+06	1.30E+06	7.56E+08	2.18E+08	1.10E+07	2.04E+06
Total	9.96E+08				9.95E+08				9.87E+08			

APPENDIX B.3. Entity installation environmental impact results

Table B.3. 1. Environmental impact results for entity installation for each midpoint impact category.

	Cases				
Imp. Cat.	**A**	**B**	**C**	**D**	**E**
CC	2.50E+03	4.00E+03	4.85E+03	4.85E+03	6.83E+03
OD	2.17E+01	3.47E+01	4.21E+01	4.21E+01	5.93E+01
TA	3.49E+03	5.58E+03	6.76E+03	6.77E+03	9.53E+03
FE	1.56E+04	2.50E+04	3.03E+04	3.03E+04	4.26E+04
ME	8.27E+02	1.32E+03	1.60E+03	1.60E+03	2.26E+03
HT	2.10E+04	3.36E+04	4.07E+04	4.07E+04	5.73E+04
POF	1.41E+03	2.25E+03	2.72E+03	2.72E+03	3.84E+03
PMF	3.61E+03	5.77E+03	6.99E+03	6.99E+03	9.84E+03
TET	2.10E+03	3.35E+03	4.06E+03	4.06E+03	5.72E+03
FET	9.73E+03	1.56E+04	1.89E+04	1.89E+04	2.66E+04
MET	-9.96E+02	-1.59E+03	-1.93E+03	-1.93E+03	-2.72E+03
IR	2.13E+02	3.41E+02	4.13E+02	4.13E+02	5.82E+02
ALO	1.50E+03	2.40E+03	2.91E+03	2.91E+03	4.10E+03
ULO	1.60E+02	2.56E+02	3.10E+02	3.10E+02	4.37E+02
NLT	9.76E+01	1.56E+02	1.89E+02	1.89E+02	2.66E+02
MRD	1.08E+04	1.73E+04	2.09E+04	2.09E+04	2.95E+04
FRD	2.90E+03	4.63E+03	5.61E+03	5.62E+03	7.91E+03
Norm. Total	7.50E+04	1.20E+05	1.45E+05	1.45E+05	2.05E+05