Green supply chain design and planning

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***Abstract*—A Mixed Integer Linear Programming model for the design and planning of green supply chains is developed. Strategic and tactical decisions are taken, namely on facility location and capacity installation, supplier selection, technology selection, transportation network definition, supply planning, and product recovery. The aim of this work is to study the use of environmental indicators in these decisions while accounting for profit objectives. Different objective functions concerning environmental aspects are implemented. ReCiPe quantifies the environmental performance of the supply chain and combinations of ReCiPe's midpoint categories allow a deeper analysis of the impact of these categories in strategic and tactical decisions. The goal is to understand if focusing on selected categories affects supply chain decisions and overall supply chain environmental impact. Net Present Value quantifies the economic performance and is used for lexicographic optimization. The model is applied to a case-study and important managerial insights are obtained. From a holistic point of view, it answers the question: how should supply chain environmental impact be assessed? From a case-study perspective, insights are obtained regarding what type of improvements should be implemented to reduce the environmental impact and how this would affect supply chain strategic and tactical decisions, along with economic performance.**

***Keywords*—closed-loop supply chain, optimization, environmental impact assessment, sustainability**

I. INTRODUCTION

Governmental and societal concerns regarding sustainability issues have been pressuring industries to re-evaluate their supply chains. Reducing the environmental impact has become an objective that is now placed at the same level as economic and quality goals. The complexity involved in having two different and in some cases opposing objectives (if considering only the economic and environmental objectives) in addition to the already complex supply chain design and planning problem has defined this as a very current research path. Decisions involving several products, entities, supply chain players, legislation and several other variables have to be taken [1]. If choosing or if having to close the loop to integrate product recovery, the problem becomes even more complex and a well-designed supply chain becomes even more indispensable for a company to prosper [2].

In order to address this complexity, decision support tools need to be developed that can integrate such amount of variables. This is why optimization models such as the one present in this work play an important role. Several works have been published on closed-loop supply chain. Starting with the seminal work of Fleischmann et al. [3], which studies the impact of product recovery on logistics network design. It considers cost minimization as the objective function and studies copier remanufacturing and paper recycling concluding that the influence of product recovery on supply chain decisions is very much context dependent. While in some cases product recovery can be integrated in logistics structures, in others it may require redesigning the network. Salema et al. [4] builds on this model and incorporates capacity limits and uncertainty on demand and return in a multi-product formulation. Cardoso et al. [5] study the integration of reverse logistics activities under demand uncertainty, considering the expected net present value maximization as the objective function and modelling decisions on sizing and location of facilities, installation of processes, forward and reverse flows, as well as inventory levels. Literature is also available on closed-loop supply chain models that integrate environmental objectives, in addition to the economic ones. Paksoy et al. [6] analyze supply planning in a 5 forward plus 5 reverse echelons supply chain considering emissions costs in the economic objective function (total cost minimization) as well as profit from recycled products maximization. Chaabane et al. [7] 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 analyzed include carbon management, namely carbon credits purchase or sale.

Many other interesting works are available in the literature in this line of closed-loop supply chain research. Literature reviews on this subject identified, among others, the following research gaps:

- The need for a more integrated framework that incorporates issues other than location-allocation such as technology decisions, as identified by Ilgin and Gupta [8];
- The need for closed-loop supply chain models that explicitly deal with the environmental impacts, as emphasized by Dekker et al. [9]. The authors state that simply closing the loop does not guaranty a reduction in the supply chain's environmental impact;
- The need for multi-objective decision making that includes appropriate environmental objectives, and for

integration of operational decision variables (such as production planning and inventory decisions) with tactical (such as network flows) and strategic ones (such as facility location and capacity determination), as included in the review by Govindan et al. [10].

This work aims to cover these identified research gaps by developing a Mixed Integer Linear Programming model for the design and planning of green closed-loop supply chains where integrated decisions are taken, namely on supplier selection, facility location and capacity installation, technology selection, transportation network definition, purchase, production, supply and inventory planning, and product recovery. It explicitly incorporates two objective functions covering the pillars of economic and environmental sustainability. The economic pillar is measured through the Net Present Value (NPV).

Regarding the environmental objective, several methods have been proposed in the literature. Some contemplate only part of the overall environmental impact, as the one described by Chaabane et al. [7]. However, contemplating only part of the overall environmental impact of a supply chain, either by not taking into account the entire supply chain or by not taking into account the various environmental impacts contributions, can lead to erroneous results in the design of a green supply chain. Life-Cycle Assessment (LCA) bridges this gap being described as the most scientifically reliable method currently available for studying and evaluating the total environmental impacts of a certain product or process. The European Commission itself reinforces this claim and includes LCA in its Sustainable Development Strategy the goal of developing and standardizing LCA methodologies [11]. Some authors have included Life Cycle Assessment (LCA) methodologies in supply chain design models. Eco-indicator 99 has been by far the LCA methodology mostly used in supply chain optimization models [12], as is the example of the work by Santibañez-Aguilar et al. [13] where planning and site selection for multiproduct sustainable biorefineries are optimized. Bojarski et al. [14] have implemented IMPACT 2002+ for forward supply chain network optimization. However, ReCiPe [15], a follow up of Eco-indicator 99 combined with CML 2002 is according to the European Commission the most developed methodology currently available [16]. To our knowledge it has only been applied to supply chain optimization models by Mota et al. [17; 18].

In the present work, the same environmental impact assessment approach is used. However, different environmental objective functions obtained through combinations of ReCiPe's midpoint categories are explored to allow a deeper analysis of the impact of the environmental indicator on supply chain decisions. The model is applied to an electronic components producer and distributor.

This paper is structured as follows. Section II describes the problem and details the developed model. Section III describes the case-study. In section IV results are presented and discussed. Section V offers conclusions and future work opportunities.

II. PROBLEM DEFINITION AND METHODOLOGY DESCRIPTION

The proposed model aims to serve as a decision support tool for the design and planning of green closed-loop supply chains. The modelled structure is the one presented in Fig. 1.

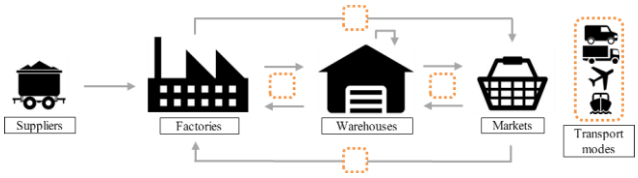

Fig. 1 Modelled closed-loop supply chain structure.

Raw materials are sent from the suppliers to the factories where they are transformed into final products. From there the final products are sent to warehouses or directly to the markets. This transportation can be performed by road, sea or air, or a combination of these (intermodal transportation). From the markets, end-of-life products can be recovered and sent back to the warehouses or directly to the factories where they are remanufactured into final products.

The following decisions are provided by the model:

- facility location and capacity installation;
- supplier selection and purchase planning;
- technology selection;
- production planning;
- transportation network definition, unimodal or intermodal;
- supply planning;
- product recovery; and
- remanufacturing planning.

The model is constrained by:

- Material balance constraints at the factories and warehouses;
- Cross-docking constraints at the airports and seaports;
- Demand and return constraints where a minimum return fraction is imposed;
- Entity capacity constraints, which include supply capacity at the suppliers, flow and physical capacities;
- Transportation constraints, namely physical constraints at the airports and seaports stating that the flow that enters an airport/seaport must leave the airport/seaport; capacity constraints, which take into account the number of trips per time period; contracted capacity constraints with air and sea carriers, necessary number of transportation modes for road transportation; and maximum investment constraints also for road transportation;

- Technology constraints in terms of production and remanufacturing capacities and assuring the installation of at most one production and one remanufacturing technologies in each factory.

The decision variables are the following:

- 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

Two distinct objective functions are modelled. One quantifies the economic performance of the supply chain through Net Present Value (NPV). The cash flow in each time period is obtained from the difference between net earnings and the fraction of total depreciable capital. For the final time period it is assumed that part of the fixed capital investment may be recovered using a salvage value, as shown in Eq.2. Net earnings are given by the difference between incomes (sales of final products at the markets, as shown in the first term of Eq.3) and total costs, also taking into account the depreciation of the capital invested. Costs include:

- raw material purchase (second term);
- production and remanufacturing operating costs (third and fifth term);
- product recovery costs (fourth term);
- transportation costs (sixth and seventh terms);
- handling costs at hub terminals (eighth term);
- contracted costs with airlines or freighters (ninth term);
- inventory costs (tenth term); and
- labour costs with workers at entities, fixed and variable (eleventh and twelfth terms), at technologies (thirteenth term) and at transportation modes (fourteenth term).

Fixed investment costs in entities (factories and warehouses), technologies installation and fleet purchase are accounted for in Eq.6. For the depreciation of the capital invested the straight-line method is assumed, as described in Eq.4. Through Eq.5 it is assumed that the payment of the fixed capital investment is divided into equal parts for each time period.

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

$$CF_t = \begin{cases} NE_t - FTDC_t & t = 1, \dots, NT-1 \\ NE_t - FTDC_t + sv \times FCI & t = NT \end{cases} \tag{2}$$

$$\begin{aligned}
NE_t = (1-tr) \Bigg[& \sum_{\substack{(m,i,j) \in F_{INCFP} \\ (a,m,i,j) \in NetP}} psu_m\, X_{maijt} \\
& - \Bigg(\sum_{\substack{(m,i,j) \in F_{OUTSUPRM} \\ (a,m,i,j) \in NetP}} rmc_{mi} X_{maij\,t} + \sum_{\substack{(m,g) \in H_{prod} \\ i \in I_f}} opc_g P_{mgit} \\
& + \sum_{\substack{(m,i,j) \in F_{OUTCRP} \\ (a,m,i,j) \in NetP}} rpc_m X_{maijt} + \sum_{\substack{(m,g) \in H_{rem} \\ i \in I_f}} opc_g R_{mgit} \\
& + \sum_{\substack{(a,m,i,j) \in NetP \\ a \in A_{truck}}} \left(\frac{avc_a}{100} . fp + vmc\right) . 2d_{ij} . Q_{aijt} \\
& + \sum_{\substack{(a,m,i,j) \in NetP \\ a \in (A_{plane} \cup A_{boat})}} tc_a . pw_m . d_{ij} . X_{maijt} \\
& + \sum_{\substack{(a,m,i,j) \in NetP \\ (j \in I_{plane} \wedge i \notin I_{plane}) \cup (j \in I_{boat} \wedge i \notin I_{boat})}} hhc_j . X_{maijt} \\
& + \sum_{i \in I_{plane} \cup I_{boat}} cfp_i . Y_i + \sum_{(m,i) \in V} sc_m S_{mit} \\
& + \sum_{i \in I_f \cup I_w} w_i . lc_i . wwh . wpt . Y_i
\end{aligned} \tag{3}$$

$$+ \sum_{i\in I_f \cup I_w} wpsq.\,lc_i\,.\,wwh.\,wpt.\,YC_i$$

$$+ \sum_{\substack{(m,g)\in H\\ i\in I_f}} w_g.\,lc_i.\,wwh.\,wpt.\,Z_{gmi}$$

$$+ \sum_{\substack{(a,i,j)\in Net\\ a\in A_{truck}}} w_a.\,lc_i.\,wwh.\,wpt.\,K_{ai} \Bigg)\Bigg)\Bigg] + tr.\,DP_t$$

$$DP_t = \frac{(1-sv).\,FCI}{NT} \tag{4}$$

$$FTDC_t = \frac{FCI}{NT} \tag{5}$$

$$FCI = \sum_{i\in I_f \cup I_w} sqmc_i.\,YC_i + \sum_{\substack{(m,g)\in H\\ i\in I_f}} tec_g.\,Z_{gmi} + \sum_{\substack{(a,i,j)\in Net\\ a\in A_{truck}}} ftc_a.\,K_{ai} \tag{6}$$

The other objective function quantifies the environmental performance of the supply chain through the Life Cycle Assessment (LCA) methodology ReCiPe. As shown in Eq. 7, the environmental impact of:

- production and remanufacturing (per kg of product produced or remanufactured), first and second terms;
- transportation (per kg transported and km travelled), third term; and
- entity installation (per m^2 installed), fourth term

are determined. Also used as objective functions are the normalized environmental impacts for each of the midpoint categories of ReCiPe (17 midpoint categories), as well as combinations of these based on their contribution to the total environmental impact.

$$min\, EnvImpact =$$

$$\sum_c \eta_c \left(\sum_{\substack{t\in T, i\in I_f\\ (m,g)\in H}} ei_{mgc} pw_m \left(P_{mgit} + R_{mgit}\right) + \sum_{\substack{t\in T\\ (a,m,i,j)\in NetP}} ei_{ac} pw_m d_{ij} X_{maijt} \right. \tag{7}$$

$$\left. + \sum_{i\in I_f \cup I_w} ei_{ic} YC_i \right)$$

III. CASE-STUDY

The case-study presented in this work analyses the supply chain of an electronic components producer and distributor. It currently owns a factory and a warehouse in Italy, having established markets in Italy (IT), Spain (ES) and Germany (DE). A potential expansion to other European markets as well as to South American markets motivated this work. The following information is given as input to the model:

- Entities: possible suppliers' locations are set in Verona, Hannover and Leeds. Additional possible factories' locations are Hannover (DE) and Leeds (UK). Regarding warehouses Hannover (DE), Leeds (UK), Zaragoza (ES), Lisbon (PT), São Paulo (BR-SP), Recife (BR-RE), Budapest (HU) and Sofia (BG) are additional possible locations. An expansion to markets in the United Kingdom (UK), Portugal (PT), São Paulo (BR-SP) and Recife (BR-RE) is studied.
- Products: in this supply chain products were aggregated into types but are differentiated as raw materials (rm1, rm2, rm3 and rm4), final products (fp1, fp2) and recovered products (rp1, rp2). All four raw materials types are necessary to produce both final products, in different quantities.
- Technologies: two alternative production technologies are available for each final product (gp1 and gp1alt for fp1, gp2 and gp2alt for fp2). One remanufacturing technology is available for each final product (gr1 and gr2). The recovered products are transformed back into final products at a ratio of 4 to 1 for fp1 and 5 to 1 for fp2, through these remanufacturing technologies, respectively. Remanufacturing technology gr1 is considered to have an environmental impact 25% lower than that of gr1 while gr2 is considered to have an environmental impact 20% lower than that of gr2. All technologies are characterized by different costs, capacities, environmental impacts and number of workers. Technologies gp1, gp2, gr1 and gr2 are installed at the existent factory in Verona and cannot be removed.
- Transportation: three types of transportation modes are implemented - road, air and sea. Road transportation is assumed to be owned by the company with two types of trucks being available for purchase (Truck1 and Truck2). Sea and air transportation is outsourced. All modes are characterized by different costs, capacities, environmental impact and number of workers. Available airports are those of Zaragoza (ES), Paris-Charles de Gaulle (FR), Kortrij-Wevelgem (BE) and São Paulo (BR-SP). Considered seaports are those of Hamburg (DE) and Santos (BR-SA). In case a hub terminal is installed, it is also characterized by different costs, according to location.

The superstructure considered for this case-study is depicted in Fig. 2.

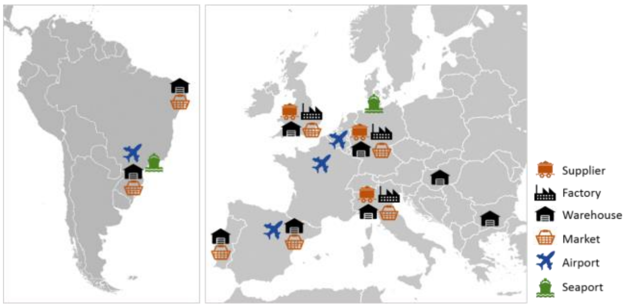

Fig. 2 Superstructure considered for the case-study.

IV. RESULTS AND DISCUSSION

The study started with the model optimization using the minimum environmental impact objective function followed by lexicographic optimization (to assure the maximum NPV for the minimum total environmental impact). The goal was to determine the contribution of each supply chain activity and of each midpoint environmental impact category to the total supply chain environmental impact, so as to understand if focusing on selected categories affects supply chain decisions and overall supply chain environmental impact.

First, let us characterize the solution obtained for minimum environmental impact:

- Supplier selection and purchase allocation: all three suppliers are selected; each supplier completely supplies the nearest factory's needs;
- Raw material purchase levels: the supplier at Verona is the least used (0.86%), followed by Hannover (42.45%) and then by Leeds (56.69%);
- Facility installation and capacity: both optional factories are installed with maximum capacity; two warehouses, one in São Paulo and the other in Recife are built, in addition to the existent warehouse in Verona;
- Technology selection and allocation: in addition to the technologies gp1, gp2, gr1 and gr2 already existent in the factory at Verona, gp1alt, gp2alt, gr1 and gr2 are installed in the new factories in Hannover and Leeds; production levels are kept to a minimum at Verona although the highest percentage of the total remanufacturing activities takes place at this factory;
- Product recovery and remanufacturing: 53.7% of product fp1 and 15% (the minimum imposed) of product fp2 are recovered and remanufactured;
- Road fleet selection and purchase: 39 trucks of type Truck2
- Average truck occupation (based on maximum capacity): 27.1%
- Airport and seaport selection: Paris-Charles de Gaulle, Kortrijk-Wevelgem and São Paulo airports, Hamburg and Santos seaports
- Transport modes utilization: intermodal transportation is only used for intercontinental distribution; most of the transportation is performed by sea;
- Cost distribution: variable transportation costs account for 95.61% of the total variable costs, followed by labour with 2.92%, production with 0.81%, recovered product with 0.19%, raw material with 0.18%, hub handling costs with 0.15%, contracted hub terminals with 0.10%, remanufacturing with 0.04% and finally stock with 0.004%; regarding investments, entity installation accounts for 92.5%, followed by transportation (namely, truck purchase) with 4.5% and technology installation with 3%
- Environmental distribution: production activities represent 99.93% of the total environmental impact, followed by transportation activities with 0.04% and facility installation with 0.02%

Regarding the contribution of each midpoint environmental impact category, using a Pareto principal based approach it was concluded that 5 categories are responsible for 94.4% of the total environmental impact, as shown in Fig. 3: Freshwater Eutrophication (FE), Marine Ecotoxicity (MET), Freshwater Ecotoxicity (FET), Metal Depletion (MRD) and Human Toxicity (HT).

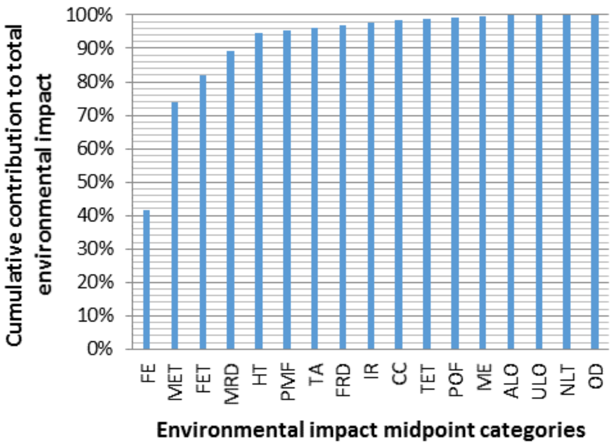

Fig. 3 Pareto principle based analysis of environmental impact midpoint categories contribution to total environmental impact.

Considering these results it would be reasonable to assume that one could select only these environmental impact categories in the objective function, reducing the complexity of the problem, and still obtain the same results. We then went to confirm if this assumption would be correct for this case-study as it is a justification that is very frequently used when choosing to focus only on a given environmental impact aspect (e.g. focusing only on CO_2 emissions). A new objective function was then designed to account only for these 5 environmental impact categories. From the optimization of this objective function it resulted that the supply chain decisions are different from the previous solution, leading to a significantly different economic performance (83.2% decrease), but also the total environmental impact slightly increased by 0.0001%. This difference although very small is still below the error associated with the algorithm stopping criteria (GAP of 0.000001%). Further analysis would be important to perform and understand the sensitivity of these results. However it is safe to say that considering only the 5 mentioned environmental impact categories, whose main culprit is production, leaves out the contribution of other environmental impact categories such as Climate Change (CC), Agricultural Land Occupation (ALO) and Fossil Depletion (FRD), which are important contributors to the environmental impact of transportation and entity installation. In this way, when optimization only considers the top contributors to the environmental impact of this supply chain we are also excluding the environmental impact of the two other activities: transportation and entity installation (input data not shown). Even if the overall increase in environmental impact is not significant at this point, it can be in the long term. For example, if improvements occur in the production processes in order to reduce the environmental impact, which is the tendency either through governmental pressures or company strategy (taking advantage of carbon management), the company might have to redesign its supply chain to achieve further environmental impact reduction targets, which will likely result in significant investments. So in conclusion it can be said that when aiming to design and plan a green supply chain it is imperative to consider an environmental impact indicator as complete as possible. Data collection might be and still is at this point difficult to collect, but efforts should be made so as to achieve an overall greener supply chain.

Another question that arises from the initial optimization, considering the complete environmental impact indicator (with all environmental impact categories), is precisely regarding production's contribution to the total environmental impact. Given the significant contribution of production to the total environmental impact, we investigated how improvements in the environmental impact of production technologies would affect the supply chain structure as well as its economic performance. A sensitivity analysis was then performed decreasing the environmental impact of the alternative production technologies (gp1alt that produces final product fp1 and gp2alt that produces final product fp2). Each point was obtained through a lexicographic optimization approach with the minimization of the environmental impact followed by the maximization of the NPV objective function to avoid weak-efficient solutions. Results are shown in Fig. 4.

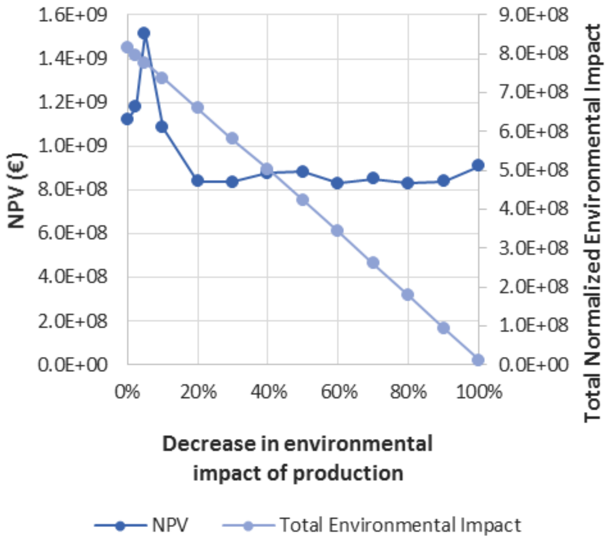

Fig. 4 Sensitivity analysis on the environmental impact of production technologies.

Analysing Fig. 4 one can see that the total environmental impact of the supply chain varies linearly with the environmental impact of production, due to its significant contribution. The effect of these changes on NPV reveals interesting results, particularly the peak at 5%, see later on, which can potentiate managers' interest on investing in greener production technologies. Also interesting is the plateau from 20% environmental impact of production reduction forward. A deeper analysis of each of the solutions obtained also revealed other interesting conclusions on the way the supply chain reacts and adjusts to changes in the environmental impact of production. Overall, across solutions, the following is maintained comparatively to the minimum environmental impact solution described before:

- Supplier selection: all three suppliers are selected
- Facility installation and capacity: the two optional factories are installed but not always with the same capacity
- Technology selection and allocation: gp1 and gp2 are used only at the Verona factory at minimum production levels; Verona is the main remanufacturing facility; gp1alt and gp2alt are installed in both new factories
- Road fleet selection: only Truck2 is purchased
- Airport and seaport selection: the airports of Paris-Charles de Gaulle and São Paulo, and the seaports of Hamburg and Santos are always selected
- Transport modes utilization: intermodal transportation is only used for intercontinental distribution; most of the transportation is performed by sea, with the remaining being transported by plane. This amount is always the same. The number of kilometres travelled is

what differs which is connected to the location of selected airports and/or the existence of warehouses in Brazil (where stocks would be possible).

Selected points which represent significant alterations in either the supply chain structure or the planning are further detailed, namely 5%, 20%, 40%, 60% and 100% decrease in environmental impact of production.

By decreasing the environmental impact of production by 5%, NPV increases over 35%, getting closer to the NPV of the maximum NPV solution which has a value of over $1{,}6\text{x}10^9$€ (over a 5-year time horizon). The following decisions differ from the solution obtained with the original environmental impact minimization:

- Raw material purchase levels: purchase from the supplier at Verona increases to 5.83% and decreases for the remaining two suppliers, which translates in a decrease in the raw material costs since the supplier at Verona practices lower prices;
- Road fleet selection and purchase: one less truck is purchased;
- Average truck occupation: increases to 28.57%;
- Airport and seaport selection: the airport of Zaragoza is chosen instead of Kortrijk-Wevelgem, which translates in lower contract costs with the carrier, lower handling costs at hub terminals and lower labour costs;
- Transport modes utilization: kilometres travelled by plane (approximately) decrease and by road increase, leading to a variable transportation costs overall decrease;
- Stock costs: increase by 14%, representing the solution with the highest stock costs.

Other than purchasing one less truck and establishing a contract with the Zaragoza airport instead of the Kortrijk-Wevelgem airport, it is mostly planning alterations that are responsible for the significant increase in NPV. In this way it seems that these results are likely to instil the will of investing in greener production technologies.

At 20% reduction of the environmental impact of production, NPV decreases by 25.2% when compared to the original minimum environmental impact solution. What makes this solution interesting is that from this point on, the warehouses in São Paulo and in Recife are not opened, which reduces the investment costs in entities and the environmental impact of entity installation. Moreover:

- Product recovery and remanufacturing: slightly decreases for product fp1 to 53.5%;
- Road fleet selection and purchase: two less trucks are purchased, which translates in a reduction in investment;
- Transport modes utilization: kilometres travelled by plane increase, in this case because the products are more distributed among the two air routes used (Paris-Charles de Gaulle – São Paulo and Kortrijk-Wevelgem - São Paulo) and along the time horizon period. Given the inexistence of warehouses in Brazil, the products need to be delivered directly to the client, without the possibility of creating stock. In fact, stock costs decrease to 21.8% of those in the original solution.

This solution actually results in lower total costs (0.32% for variable costs and 20.1% for investment costs). In fact different planning decisions across the time horizon allow lower investments. However, and consequently, a lower salvage value is available for recovery at the end of the time horizon, which explains the significant decrease in the Net Present Value. This is a clear example of the importance of properly selecting the economic objective function. If total costs would have been considered as the economic objective function, as is the case with most of the works referred in section I, investment analysis would not be possible and results would be significantly different.

At 40% decrease in the environmental impact of production there seems to be no significant changes in the supply chain structure relatively to the one at 20% and 30% other than:

- Road fleet selection and purchase: reduced to 36, which increases average truck occupation to 28.11%;
- Airport and seaport selection: the airport of Zaragoza is chosen instead of Kortrijk-Wevelgem, which translates in lower contract costs with the carrier, lower handling costs at hub terminals and lower labour costs;
- Transport modes utilization: kilometres travelled by plane decrease, as a consequence of the selection of the Zaragoza airport;

Again, total costs are lower than those of the original solution (0.77% and 20.2% for variable and investment costs respectively) even though the NPV decreases by 22%.

From 60% decrease in the environmental impact of production onwards, the Zaragoza airport is again replaced by Kortrijk-Wevelgem. The plot twist is in product recovery where now product fp1 is being remanufactured at the minimum imposed (15%). In fact, at this point the environmental impact of the production of fp1 through technology gp1alt is quite close to that of remanufacturing. The recovery and remanufacturing of product fp2, on the other hand, increases to 49.9%. Accordingly, purchase of raw material from the supplier at Hannover increases to account for the overall decrease in remanufacturing, leading to an increase in raw material and production costs and to a decrease in the recovered products and remanufacturing costs. Stock costs also suffer a significant decrease to 9% of the original costs.

Only with no environmental impact of production, the model proposes to minimize remanufacturing for both products fp1 and fp2. To account for this, raw material purchase increases by 30% at Hannover and by 5% in Leeds. Also, changing a component that was kept the same across all solutions except this one, capacities in the factories in Hannover and Leeds are reduced to 10.281m2 and 11.983m2, respectively. To compensate, 37 trucks are purchased having an average occupation of 32.1%, and kilometres travelled by plane also increase. Total costs significantly decrease by 1.11% and 60.65% for variable and investment costs, respectively. However, again NPV decreases by 19%.

Overall the results show the importance of selecting appropriate economic and environmental impact indicators as well as the importance of optimization models with integrated strategic, tactical and operational decisions. It was shown that both have significant impacts on supply chain outcomes and that what seem to be small alterations can actually significantly affect both economic and environmental performances.

V. CONCLUSIONS

This work addressed, through a Multi-Objective Mixed Integer Linear Programming model, the design and planning of green closed-loop supply chains. The objective was to analyse the impact of the environmental impact indicator and of different approaches in its application in supply chain decisions, namely considering the total environmental impact indicator or just selected categories according to their contribution to overall supply chain environmental impact. The model was applied to an electronic components producer and distributor and the obtained results allowed drawing important conclusions. The main one is that, overall, what would seem to be slight alteration in the application of the environmental indicator actually it is translated in a very intricate combination of results that can significantly alter the supply chain decisions and affect its economic performance. Particularly, it is important to be careful in the selection of environmental impact categories that are used in the decision making process. One might be focusing only in certain company's activities and neglecting others, increasing overall environmental impact and potentiating future unnecessary investments to achieve higher environmental impact reduction targets. Another major conclusion was on the importance of adequately selecting the economic indicator since planning has shown to have a significant influence on NPV as it allows to explore different solutions in terms of investment that compensate significant cost increase. Furthermore it was seen that competitive advantage creation and investment opportunities can surface when doing such kind of analysis. In fact, the presented intricate results justify the importance of such type of integrated optimization models.

Future work should include further sensitivity analysis on other supply chain activities, namely on the environmental impact of remanufacturing activities. Carbon management decisions should also be included in the model and their impact analysed. Uncertainty analysis on both internal and external parameters would add additional interesting insights to the problem.

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