Green supply chain design and planning: the importance of decision integration in optimization models

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Abstract

Sustainability is more than ever a central concern when deciding a company's strategy. Stakeholders are continuously pressuring industries to further reduce their environmental impact. In order to achieve that, it is imperative to look for solutions across all of the company's operations adopting a supply chain view. However, supply chains' complexity makes this a challenging task. Analysing the sustainability of such complex systems requires the use of capable tools as are optimization models. Several of these models can be found in the literature, mostly focusing on specific issues or specific decisions in the supply chain. Therefore, a research gap is found in models capable of handling a wider variety of decisions. With this work a mixed integer linear programming model is used to demonstrate the impact of including more or less options/decisions on design and planning decisions, and on the environmental performance of a supply chain. A case-study based on a Portuguese pulp and paper company is analysed. The results obtained for different scenarios are examined.

Keywords: supply chain, optimization, sustainability, decision integration, Life Cycle Assessment.

1. Introduction

The need for sustainability has been vastly discussed in the literature, as well as the need to assess it across the supply chains (Brandenburg et al., 2014). However, adding sustainability to what is already a complex system often leads

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to intractable problems. Making use of computational tools such as optimization models becomes necessary. Even then the approach to deal with such problems is often to subdivide the problem into smaller ones. Several works have been proposed that follow this type of approach. However, a research gap is found in integrated modelling approaches, as identified in several reviews (Boukherroub et al., 2015; Eskandarpour et al., 2015; Taticchi et al., 2015). By integrated modelling approaches we mean models that include decisions at different levels of the supply chain. For instance, the integration of decision variables allowing for capacity definition, supplier selection, technology selection, and transportation network definition over a time horizon, along with location-allocation decisions. By integrating all of these decisions into one model the array of possible solutions widens, leading to the possibility of finding more sustainable solutions.

In this work we aim to demonstrate the importance of such an integrated approach and how this wider integration of options and decisions is reflected on the environmental performance of a supply chain and consequently on supply chain design and planning decisions. To do so a mixed integer linear programming model is used and applied to a case-study based on a Portuguese pulp and paper producer and distributor. Different scenarios simulating the inclusion of more or less options/decisions are analyzed.

This paper is structured as follows. In section 2 the problem is defined and the developed model characterized. Section 3 presents the case-study. In section 4 results are presented and discussed. Final remarks and future work are provided in section 5.

2. Problem definition

As stated, the goal of this paper is to examine the extent to which a wider or narrower decision integration level in an optimization model can affect supply chain design and planning decisions as well as the sustainability of the supply chain. ToBLoOM (Triple Bottom Line Optimization Modeling), as described in Mota et al. (2017), is used since it is, to the best of our knowledge, the most integrated modelling tool available in the literature. It is a Multi-Objective Mixed Integer Linear Programming (MOMILP) model which includes decisions such as supplier and technology selection, transportation network definition, entity location and capacity definition, and the planning of production, inventory and flow of materials.

The environmental pillar is modelled as an objective function using a Life Cycle Assessment method, ReCiPe 2008 (Goedkoop et al. 2009), on supply chain

operations: production, production at suppliers, carbon credits obtained from purchasing raw materials from certified suppliers, intermodal transportation, and entity installation and/or usage. To assess the economic pillar, the Net Present Value (NPV) is modelled as a second objective function. Included are the revenues from sold final products and CO_2 allowances (under the European Union's emissions trading system), as well as raw material and production costs, transportation (unimodal or intermodal) and hub handling costs, CO_2 allowances costs, and inventory and warehouse renting costs.

In short, **given:** a) product's demand; b) bills of materials; c) a possible superstructure for the supply chain entities; d) distances between each pair of entities; e) maximum and minimum supplying flow, storage and production capacities, and installation areas; f) area occupied per product unit; g) price per sold product; h) weight of each product unit; i) transportation costs per kilometer and per unit; j) raw material and production costs; k) warehouse renting costs; l) initial stock levels, m) carbon credits from the usage of certified raw materials; and n) the environmental impacts of transportation, production processes, production at suppliers (if applicable), and per square meter of entity opened area, **the goal is to determine** 1) the network structure; 2) the installed production technologies; 3) the production and storage levels at each entity; 4) the transportation network; and 5) the flow between entities, **so as to** minimize the global supply chain environmental impact.
Different scenarios are studied exploring how the simultaneous decisions' integration in the optimization model affects the supply chain design and planning as well as its environmental performance. Each scenario is solved using the lexicographic approach (Mavrotas, 2009) so as to obtain, for each case, the best economic performance for the minimum environmental impact.

3. Case-study

The case-study of a Portuguese company operating in the pulp and paper industry is analysed in this work, specifically focusing on the supply chain of uncoated wood free paper (UWF paper). The pulp and paper industry is one of the most CO_2-intense ones. Strick regulations are imposed and the pressure to continuously reduce the environmental footprint is constant in this sector. It is then important to expand the possible options so as to look for ways to further reduce the environmental impact of the industry's operations.

Figure 1 shows the supply chain structure modelled in ToBLoOM.

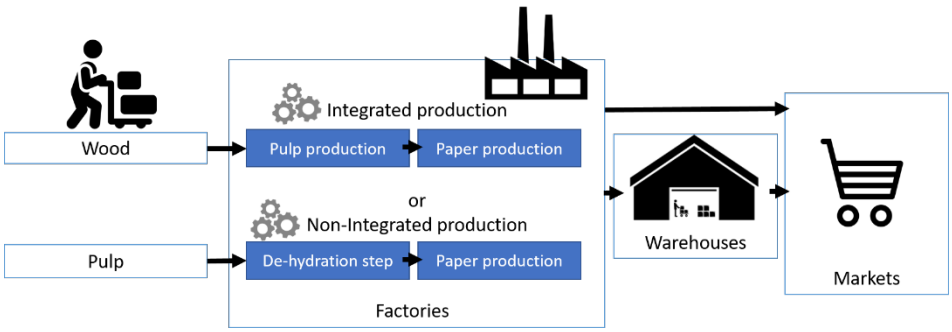


Figure 1. Schematic representation of the UWF paper supply chain.

Paper production at the factories can be either integrated or non-integrated. In the former, both pulp and paper are produced sequentially, in the same facility. In the latter, pulp is received from suppliers, de-hydrated and used for paper production. The same paper production machine is used in both cases. The source of wood is also a decision. Wood can be obtained from certified or non-certified suppliers. We refer to certified suppliers as those who have their forest management practices certified, which ensures that forests are sustainably managed in all three pillars of sustainability: economic, environmental and social.

One of the underlying issues around forest certification is reforestation. Hence, carbon credits (reflecting environmental impact reduction) are attributed per ton purchased from certified suppliers, to account for the sequestrated carbon that can be obtained from replacing the cut trees with new ones. For the presented case study certified pulp suppliers are considered. After production, UWF can either be sent directly to the markets or stored at the warehouses.

The locations of factories and potential locations for the remaining entities are provided in Table 1. Even though not shown it is important to mention that the supply capacities of the Portuguese and Spanish certified wood suppliers are still too short to meet the needs. Thus it becomes necessary to resort to suppliers further away, to source from non-certified suppliers or to opt for non-integrated production to meet the demand.

Four scenarios are studied to assess the impact of a wider or narrower decision integration level on the design and planning of sustainable supply chains. These differ in terms of the decisions the model will take into account and in terms of the objective function:

- Scenario 1 (base scenario): all supply chain activities and options are considered so as to minimize the total environmental impact;
- Scenario 2: base scenario without the option of non-certified wood;

- Scenario 3: base scenario without the option of sea and rail transportation;
- Scenario 4: all supply chain activities and options are considered so as to maximize NPV.

Table 1. Potential location for the entities.

Wood suppliers		**Pulp suppliers**	**Factories**
Certified	**Non-certified**		
Portugal	Portugal	Spain	Figueira da Foz (Portugal)
Brazil	Spain	France	Setubal (Portugal)
Spain		Austria	
Sweden			

Warehouses and markets			**Rail stations**	**Seaports**	
Portugal	Belgium	Sweden	Portugal	Portugal	Germany
Spain	Netherlands	Poland	Spain – Algeciras	Spain	Italy
France	Germany	Greece	Spain – Valladolid	United Kingdom	Greece
United Kingdom	Italy		France	Belgium	Brazil
			Germany	Netherlands	

Figure 2 depicts the decisions considered in each of the four scenarios. In grey are the decisions that will not be taken into account in scenarios 2 and 3.

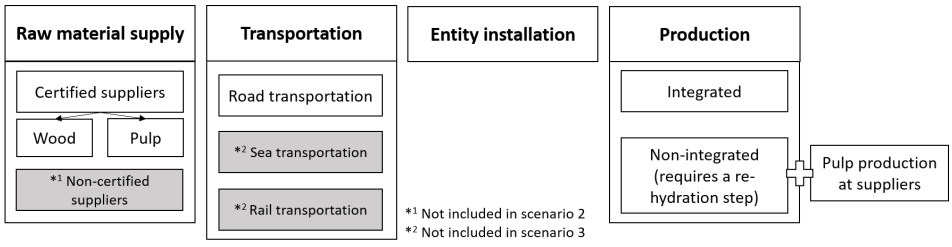


Figure 2. Decisions considered (with environmental impact) in each of the four scenarios.

4. Results

Results obtained for the total environmental impact (solid line) and for the NPV (dotted line) across the different scenarios are presented in Figure 3.

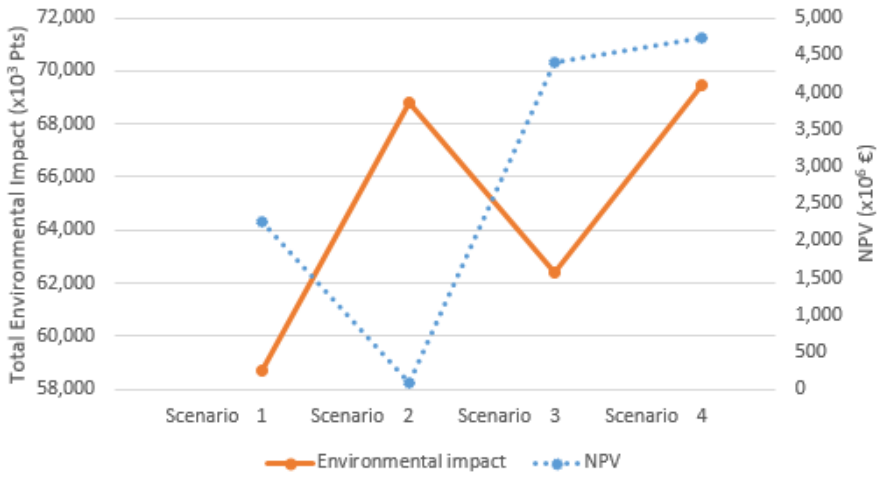


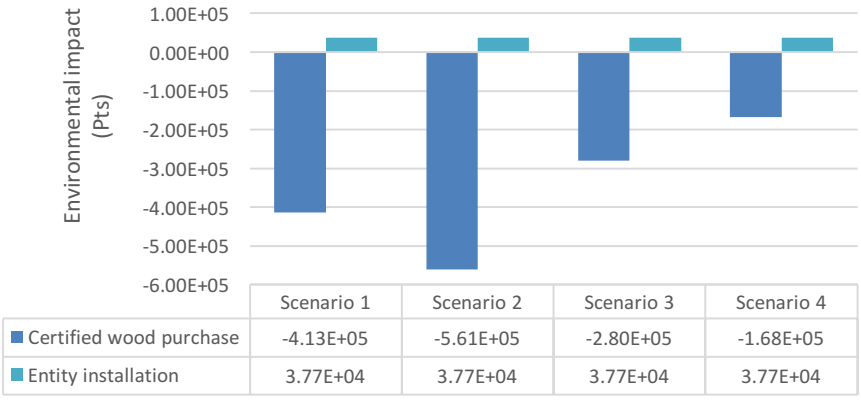
Figure 3. Results obtained across the four scenarios for the economic and environmental indicators.

The minimum environmental impact (58,680x10^3Pts) is obtained when considering all decisions simultaneously (scenario 1). Interestingly, this supply chain does not correspond to the worst economic performance. However, the NPV is 52.7% (2,246 x10^6€ versus 4,743x10^6€) lower than the optimal NPV value (scenario 4). Also, very interesting is the fact that optimizing the economical objective function (scenario 4) leads to the worst environmental supply chain structure (18.4% higher than in scenario 1). The reasoning for these results is presented further ahead.

Scenario 2, the one considering only certified suppliers, performs worse in both objectives than scenario 1 (17.3% worse for the environmental performance and 96% worse for the economic performance). Having 100% certified suppliers, a measure that is often presented as environmentally positive in sustainability reports and sustainability policies, may not be so positive after all if considering the collateral damage it may have on the supply chain. In this case, opting for 100% certified suppliers actually increases the environmental impact of transportation and of production. However, one should not forget that it all depends on the availability of certified suppliers, which is still not enough to meet the demand of the pulp and paper industry.

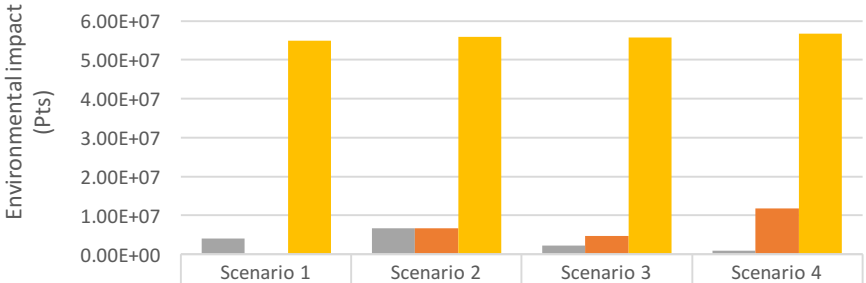
Scenario 3, the one with no intermodal transportation option, performs significantly better economically (96.2%) but worse environmentally (6.4%) compared to scenario 1. This shows that for this case-study, intermodal transportation is better environmentally but not economically as explained further ahead.

Figure 4 and Figure 5 depict the environmental impact of each activity across the four scenarios, while Table 2 presents a summary of selected decisions across the different scenarios. Combined they shed light into the results obtained in Figure 3.



	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Certified wood purchase	-4.13E+05	-5.61E+05	-2.80E+05	-1.68E+05
Entity installation	3.77E+04	3.77E+04	3.77E+04	3.77E+04

Figure 4. Environmental impact distribution per supply chain activity across the four scenarios: certified wood purchase and entity installation.



	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Transportation	4.09E+06	6.75E+06	2.32E+06	1.03E+06
Pulp Production		6.66E+06	4.68E+06	1.19E+07
Production	5.50E+07	5.60E+07	5.57E+07	5.67E+07

Figure 5. Environmental impact distribution per supply chain activity across the four scenarios: transportation, pulp production at suppliers and paper production.

Table 2. Summary of selected supply chain decisions obtained across the different scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Certified wood (%)	55.1	100	45.5	40.7
Non-certified wood (%)	44.9	0	54.5	59.3
Integrated production (%)	100	74.8	82.3	55.2
Non-integrated production (%)	0	25.2	17.7	44.8
Warehouse locations	Portugal; Spain; France	Portugal; Spain; France	Portugal; Spain; France	Portugal; Spain; United Kingdom
Transportation network				
Rail stations	Portugal Spain-Algeciras Spain-Valladolid France	Portugal Spain-Algeciras Spain-Valladolid France		Portugal Spain-Valladolid France
Seaports	Spain Germany Brazil	Spain Germany		Portugal United Kingdom Germany Brazil

Each scenario is analysed based on the presented results. Note that all comparisons below are made in relation to the base scenario (scenario 1):

- Results show that purchasing pulp, and therefore having a non-integrated production, is avoided when minimizing the environmental impact (scenario 1, Table 2). Given the scarcity of certified wood in the proximity of the company's installations (as mentioned above), the purchasing of non-certified wood is preferable to the purchasing of certified pulp and, consequently, an integrated production option is proposed. The minimum amount of certified wood necessary to meet the demand with the non-integrated production technology is totally purchased in Brazil (results not shown).
- When imposing 100% certified raw materials (scenario 2), the best strategy is to purchase, as much as possible, certified wood and to resort to pulp supply to fulfil the demand. That is why only 25% of the production is non-integrated (Table 2). The environmental impact of transportation increases by 65% and the combined impact of pulp purchasing and paper production increases by 14%. Since raw-materials are all certificated, carbon credits increase by 36% (Figure 4).

- When removing the intermodal transportation option (scenario 3), Brazilian suppliers are not chosen (results not shown) and the certified wood supplied decreases to 45.5% (Table 2). Both certified and non-certified wood is bought mostly from Portuguese and Spanish suppliers (to their maximum capacity). The remaining needs are met through non-integrated production. The nearness of the suppliers leads to a significant reduction of the environmental impact concerning transportation activities (by 43%, as shown in Figure 5).
- Finally, when maximizing the economic performance of the supply chain (scenario 4) non-integrated production increases by 44.8%, which corresponds to the maximum allowed under the imposed constraints (Table 2). The solution is then to source certified wood only if the distance compensates the extra cost of certified wood (which only happens if the certified wood is bought locally) and then meet the remaining needs using non-certified wood (59.3%). Even though the combined impact of pulp production at suppliers and paper production increases by 25%, the environmental impact of transportation reduces by 75% (Figure 5). Carbon credits, which are not included in the economic objective function, also decrease in consequence of the reduction of certified wood supply. Overall scenario 4 solution leads to an increase of 111% increase in net present value and 18.4% in the total environmental impact (Figure 3).

All in all, results show that by widening the options available through increasing decision integration in this type of models one may uncover solutions that result in an overall lower environmental impact, without imposing such a burden on the economic performance of the company. Also, from a different perspective, it may also be that only focusing on the environmental impact of a specific part of the complex system, that is a supply chain, may actually result in both higher costs and environmental impact.

5. Conclusions

In this work an analysis of the potential impact of a wider or narrower decision integration level in the design and planning decisions of green supply chains was performed. More precisely, the impact that including more or less decisions (for example, including supplier selection) as well as options within those decisions (for instance, including intermodal transportation options versus simply including

road transportation) has on the environmental and economic performances of the system. Different options in terms of the number of integrated decisions were investigated with ToBLoOM, a mixed integer linear programming model for the design and planning of sustainable supply chains.

The results of a case-study based on the UWF paper company corroborated that the impact of the level of decision integration is significant both on the design and planning decisions and on the environmental and economic performance of supply chains. This particularly sheds light on the implications that certain measures traditionally considered environmentally friendly in sustainability reports and sustainability policies can actually have.

This work shows how important it is to carefully design the studies that support supply chain design and planning decision making as well as sustainability policy making in order to reduce environmental collateral damages that can take place on other supply chain activities.

Future work should further look into the trade-offs among the three pillars of sustainability: economic, environmental and social. Additional case-studies of different sectors as well as uncertainty analysis on the main parameters affecting these decisions should be included in future studies.

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