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Sustainable supply chains: An integrated modeling approach under uncertainty☆

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ABSTRACT

This work presents ToBLoOM – Triple Bottom Line Optimization Modeling, 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.

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 26,000:2010 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 tac-

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tical (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 analyzed 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 modeling 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 continue 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 modeling 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 microtime that allows for more detailed planning on attaining this satisfaction [14]. Cardoso et al. [7] analyze the integration of reverse logistics activities under demand uncertainty, considering the maximization of the expected net present value as the objective function and modeling 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] analyze 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