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Green supply chain design: A mathematical modeling approach based on a multi-objective optimization model

Kartina Puji Nurjanni [a,b], Maria S. Carvalho [c], Lino Costa [c,*]

[a] Postgraduate Program of Industrial Engineering, Universitas Gadjah Mada, Bulaksumur, Yogyakarta55281, Indonesia
[b] Algoritmi Research Center, Department of Production and System, Universidade do Minho, 4800-058 Guimarães, Portugal
[c] Department of Production and System, Universidade do Minho, 4710-057 Braga, Portugal

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ABSTRACT

Increasing levels of industrialization of developed nations associated with globalization trends have been creating new challenges to supply chain management (SCM). For decades, the main focus of SCM has been on efficient ways of managing the flows through complex networks of supplier, producers and customers. More recently, and as a result of the exponential increase of energy and materials consumption rates of energy and materials, sustainable development arise as an urgent issue and new approaches to SCM are required to incorporate environmental and economic concerns in the design of supply chains. In this paper, a new green supply chain (GSC) design approach has been proposed to deal with the trade-offs between environmental and financial issues in order to reduce negative impacts on the environment caused by the increasing levels of industrialization. The new approach incorporates a closed loop network to accommodate the reprocessing paradigm of disposal products and a multi-objective optimization mathematical model to minimize overall costs and carbon dioxide emissions when setting the supply chain. Optimization process is performed using three scalarization approaches, namely weighted sum method, weighted Tchebycheff and augmented weighted Tchebycheff. Computational results are analyzed to identify the advantages and drawbacks of each approach. The model was tested in a case study and results allowed to identify the capability of the model to deal with the trade-offs between the costs and environmental issues as well as to identify its main limitation when addressing real size problems.

1. Introduction

The concept of sustainable development has become a key issue in many sectors all over the world, especially for industry which is often seen as one of the main causes of the environmental decay. It aims at "meet the needs of the present without compromising the ability of future generations to meet their own need", according with the report from the World Commission on Environment and Development (WCED, 1987). The industrial sector in developed countries, such as in United States, European Union and Japan, has been enforced to adopt green supply chains (GSC) because of government regulation on environmental subjects (Seman et al., 2012). Consequently, industries are required to redesign their SC in order to incorporate goals from all dimensions of sustainability: social, environmental and financial, the so-called, triple bottom line. The increasing concern on sustainable development triggered by the exponential growth of resource usage needs to be translated into new strategies to manage and operate supply chains. In the context of green supply chain (GSC), new approaches and models struggle to provide support to a more comprehensive decision making process able to incorporate environmental issues further to the traditional merely financial perspective.

In a simplistic way, the supply chain design problem consists of defining where and how to deploy assets (plants, warehouses, distribution centers) and how flows of materials (raw material, parts, final products) should be moved along the network of entities (suppliers, manufactures, distributors, retailers and customers) in order to enhance overall performance. Applied mathematical modeling that has been widely used to assess and optimize supply chain performance, can play an important role in developing sustainable alternatives in the design of complex supply chains. Previous researches on SC design optimization can be grouped into: single objective (SO) and multi-objective (MO).

Additionally, when looking at SC design modeling approaches put forward in the literature, it is still possible to aggregate them into two clusters, namely open loop (OL) optimization and closed loop (CL) networks optimization to incorporate reverse flows. The

* Corresponding author.
E-mail address: lac@dps.uminho.pt (L. Costa).

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reverse logistics deals mainly with backward flows such as, unused raw materials, packaging, and end-of-life (EOL) and end-of-use (EOU) products among others. In particular, the recovery of EOL products has been ignored by most manufacturers that face now new constraints imposed by an increasing number of legislation (both in European Union and USA) which sets targets in several dimensions: waste prevention, material recycling, disposal options, etc. (Salema et al., 2007). This new legal framework has been forcing a large number of companies to reconfigure their supply chains.

The literature review carried out in the context of this project allowed the identification of a gap in mathematical modeling research regarding GSC design optimization: to the best of our knowledge, there is no research work addressing the CL network design problem using a MO optimization model to address trade-offs between total costs and carbon dioxide (CO_2) emissions in the system. Therefore, in this paper a mathematical model is proposed to design a CL network able to integrate both direct and reverse flows to accommodate the reprocessing paradigm of disposal products such as those associated with EOL products. A mixed integer linear programming in an MO formulation is used to address costs and environmental impacts providing decision makers with a more comprehensive SC evaluation tool to select the most sustainable SC solution.

The rest of the paper is organized as follows. Relevant SC design literature is discussed in Section 2. In Section 3, a MIP model for the GSC design is provided, followed by computational results analysis and discussion in Section 4 and concluding remarks in Section 5.

2. Literature review

SO optimization for OL network in SC research was performed by Abdallah et al. (2010), Che et al. (2010), Ramudhin et al. (2010); Yang et al. (2010) and Zhang and Liu (2013) in which financial indicators are chosen as an optimization target. Even though financial indicators have been selected by these researchers, Abdallah et al. (2010) and Ramudhin et al. (2010) had also included the negative environmental impact in the scheme of carbon trading by converting the amount of excess carbon into a penalty cost. Therefore, the optimization targets were formulated as a SO function in the form of total cost. Combination of financial indicators with other operational performance indicators in a MO formulation have also been widely applied as optimization goals in SC researches in OL network, for example: cost, customer service, and utilization of capacity (Altiparmak et al., 2006); cost, delivery time and quality (Che and Chiang, 2010); profit and supplier defects (Franca et al., 2010); cost and lead time (Cardona-Valdés et al., 2011) and (Moncayo-Martínez and Zhang, 2011); cost, lead time and lost sales (Liu and Papageorgiou, 2013).

Furthermore, there is a few number of approaches combining financial and environmental issues explicitly in OL multi-objective frameworks to address the supply chain design problem: Wang et al. (2011), Jamshidi et al. (2012), Pozo et al. (2012), Sabio et al. (2012), and Giarola et al. (2011). Sabio et al. (2012), Pozo et al. (2012), and Giarola et al. (2011) developed multi-objective approaches incorporating both financial and environmental metrics in the chemical industry area. Sabio et al. (2012) proposed a framework for optimizing hydrogen supply chain including eight environmental indicators combined to produce a damage factor. They used MILP and Principal Component Analysis (PCA) to detect redundant environmental indicators. A similar PCA statistical approach was used by Pozo et al. (2012) to identify the most relevant environmental metrics. In Giarola et al. (2011), a MILP framework was proposed to optimize environmental a financial performance indicators in multi-period and multi-echelon biofuels supply chain. Jamshidi et al. (2012) combined total cost and environmental effect components in a multi-objective approach and used a memetic algorithm to solve it. Wang et al. (2011) developed the concept of environmental protection and defined a total cost function which includes the investment associated with the protection. The total cost is combined with total CO_2 emissions in a MO approach which is solved using the normalized normal constraint method. None of these works addresses the CL supply chains problem.

The SC research to optimize CL supply chains using a SO formulation was proposed by Sheu et al. (2005), Salema et al. (2007), Salema et al. (2009) and Pishvaee et al. (2011) that use also a financial indicator to measure the SC performance. In CL network design approaches, an MO model was proposed to identify several trade-offs such as profit and cost (Shi et al., 2011) and profit, level of satisfaction and fill rates of customer demands (Ozkir and Basligil, 2013). A more detailed review of the state of the art on GSC design optimization models can be found in Nurjanni (2013). A summary of available SC mathematical models is given in Table 1 which classifies different research contributions on SC network design according with the type of network, the type of model and number of dimensions of the objective function and main performance indicators used.

Even though utilization of GSC as research topic has long been performed, a further research in this area is still required to cover special case situations and to address some research gaps such as supply chain design incorporating direct and reverse flows further to incorporate trade-offs between financial and environmental performance indicators providing an effective support to decision makers in a context of sustainable development. More recently, some authors have been extending the sustainability concerns to incorporate lot sizing issues and new haulage-sharing strategies combining costs and environmental issues in integrated approaches. Andriolo et al. (2014) identify the importance of considering the total cost function coupled with emission consequences, and to create new approaches in modeling lot sizing activities in the context of closed-loop supply chains. In Andriolo and Battini (2015), a methodology based on a multi-objective optimization approach is used to evaluated the costs and savings in a new haulage-sharing lot sizing model in which two partners are cooperating in sharing transportation paths and handling units. To the best of our knowledge, there are no equivalent integrated approaches addressing the CL supply chain design problem.

3. Mathematical Model

According with national and international regulatory frameworks, the GSC concept has been translated by industrial companies into a set of strategic decisions and operational practices some of them with impact outside their direct ownership, across the whole supply chain. It is the case of the close loop supply chain, moving units of product from the final consumer back to the recycling and reuse of raw materials. Even though GSC research has long been introduced, more research developments in this area are still necessary due to its wide scope. In fact, although several authors have been dealing with CL supply chains, there are a very limited number of contributions able to assess the negative impact of supply chains options in the environment.

In this paper a mathematical model is developed to optimize SC performance, incorporating both financial and environmental performance indicators, in a GSC network design. In fact, further to a total cost (TC) measure to account for all the financial expenses in a particular SC design, environmental performance is evaluated