Omega 54 (2015) 173–190

Contents lists available at ScienceDirect

Omega

journal homepage: www.elsevier.com/locate/omega

A tradeoff model for green supply chain planning: A leanness-versus-greenness analysis ☆

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ARTICLE INFO

Article history:
Received 20 August 2013
Accepted 27 January 2015
Available online 7 February 2015

Keywords:
Green supply chain
Environmental sustainability
Lean
Flexible
Agile
Nonlinear mathematical programming
Cross-entropy method
Case study

ABSTRACT

This article presents a tactical supply chain planning model that can be used to investigate tradeoffs between cost and environmental degradation including carbon emissions, energy consumption and waste generation. The proposed model also incorporates other aspects of real world supply chains such as multiple transport lot sizing and flexible holding capacity of warehouses. A solution methodology, the Nested Integrated Cross-Entropy (NICE) method, is developed to solve the proposed mixed-integer nonlinear mathematical model. The application of the model and solution method is investigated in an actual case problem. Analysis of the numerical results focuses on investigating the relationship between lean practices and green outcomes. We find that (1) not all lean interventions at the tactical supply chain planning level result in green benefits, and (2) a flexible supply chain is the greenest and most efficient alternative when compared to strictly lean and centralized situations.

1. Introduction

Governments and industries are seeking ways to decouple economic development and growth from commensurate environmental burden. This 'green growth' philosophy was a central discussion at the recent United Nations Conference on Sustainable Development, also called Rio+20. Decoupling economic growth and environmental degradation is not an easy goal to achieve. Yet at the national level, examples to grow without corresponding increases in environmental pressure do exist [16,71]. At the organizational level, efforts that have utilized eco-efficiency, ecological modernization and 'win-win' principles support the feasibility of achieving these goals [62,80].

Investigations on the phenomena of jointly improving organizational environmental and economic performance have tended to focus on empirical studies to show that green growth results are realistic and achievable [46,78]. However, such results do not inevitably occur without design, planning, and support. Research and development are required to help achieve these results and eventually contribute to decoupling economic and environmental growth [28].

Green or environmentally sustainable supply chain management (SCM) has been viewed as one area where organizations and industry can make significant contribution to both economic and environmental development [70]. Descriptive research utilizing empirical and case study research on forward sustainable supply chains (SCs) has seen substantial development over the past couple of decades. Normative, prescriptive, and quantitative modeling efforts on the forward SC have received significantly less attention [28], although reverse logistics planning has received considerable investigation [39,54]. The call for development and utilization of economic and optimization approaches to further socially supportive research such as sustainable SC research has continued [28,63]. We seek to contribute to this call for additional analytical and modeling normative research with our current study.

The specific focus of this study is on ecologically and economically balancing and optimizing material manufacture and movement across a multi-tiered SC. Our modeling effort is based on a real world situation that has actually encountered issues raised in this investigation. The complexity of the modeling effort limits how effectively these models can be solved. Efficient solution techniques are needed for solving complex green SC modeling efforts [32]. To address this complexity, we introduce a solution method, the Nested Integrated Cross-Entropy (NICE), that is able to find quality and relatively rapid solutions to the complex mixed-integer nonlinear model encountered in this study. The proposed model and the NICE solution procedure allows for investigating the locus of decision parameters that can prove useful to management seeking to balance the economic and environmental dimensions. One specific case situation, investigated in this paper, is studying various scenarios adjusting the leanness and flexibility (agility) of the SC.

☆This manuscript was processed by Associate Editor Geunes.

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http://dx.doi.org/10.1016/j.omega.2015.01.014
0305-0483/

We make several contributions to this important and growing field of green SCM. First, we introduce a multidimensional optimization model for tactical SCM that is applicable to real world situations. We then utilize a novel solution approach to provide quality solutions to this complex nonlinear problem within a relatively short model runtime. Our third major contribution involves the execution of this model to provide practical insights into the decision environment facing managers, focusing on critical issues related to the lean-and-green debate. These insights set the stage for additional investigation and model development in future research.

The remainder of the paper is composed of the followings sections. In Section 2 a background review of literature in this area and previous models which we use as a foundation is presented. Section 3 presents the mathematical model. Section 4 overviews the Nested Integrated Cross Entropy (NICE) solution method. Section 5 provides an execution of the model using real case data with results and initial analysis. Section 6 provides a discussion of the results with a focus on the issue of SC leanness-versus-greenness. Section 7 is the concluding section which includes a summary of the study and results, research and managerial implications, model and study limitations, and guidance for future research.

2. Foundational literature background

Green SCM has been defined as the explicit consideration of ecological dimensions in the planning, operations, and management of SCs [78]. Organizations are under varied and increasing pressures from a broad spectrum of stakeholders to manage their SC functions in more environmentally efficient and effective ways [13,24,69,79]. When adding the environmental and social concerns into modeling and management research effort, design, planning and management problems become geometrically more complex [49]. The research and modeling for SCM optimization in general is a relatively non-trivial exercise [22] and it becomes even more complex for greening of SCs due to the additional environmental variables and constraints. Organizations and researcher guidance is paramount to helping make practical and theoretical progress in this field.

One important factor in improving the tractability of the modeling for greening the SC is an explicit definition of the boundaries and flows of the problem [61]. In this paper, we clearly define an important boundary to include forward SC participants including manufacturers, warehouses, and end-users. The flows in the model include materials, energy, and waste flows. Models for evaluating and optimizing environmental and economic performance of organizational operational activities can range from machines in a production center [66], to a large global closed loop SCM system [36]. But, even the most comprehensive surveys show that the relative investigation of green SC topics with analytical modeling and optimization is secondary to qualitative and empirical studies [28,63,64]. Although some emergent analytical modeling research for green SCM does exist, a vast majority of literature focuses on cost minimization objective and relatively fewer articles incorporate multiple objectives and explicitly integrate economic and environmental goals [7,45].

Our modeling effort in this paper fits within the tradeoff mode of modeling literature. The literature that seeks to jointly model environmental and financial/business objectives is not extensive. Recent reviews have been completed by Fahimnia et al. [28], Brandenburg et al. [7], Tang and Zhou [68], and Dekker et al. [14]. Most of this literature focuses on cost minimization as a financial objective. Profit maximization is the only other financial objective which requires consideration of sales revenue and pricing. Managing greenhouse gas emissions has been the most common environmental objective. This is not surprising given the greater global focus on carbon emissions as the primary contributor to climate change. Some of the bi-objective models focusing on cost and carbon emissions minimizations have been presented by Ferrati et al. [30], Nagurney and Nagurney [47], Pinto-Varela et al. [52], Abdallah et al. [1], Wang et al. [72], Elhedhli and Merrick [18], Chaabane et al. [11], Pishvaee and Razmi [53], Fahimnia et al. [25], Fahimnia et al. [29] and Zakeri et al. [77]. But, not all emissions studies are only on carbon. For example, Nagurney and Nagurney [47] use general emissions in a strategic network design problem, where a variety of emissions, even solid wastes, are used to design a green SC network. Some other studies, such as Pinto-Varela et al. [52] and Yeh and Chuang [76], utilize a set of green scoring or ecological indicators that are broader in perspective than carbon emissions alone.

The preponderance of this literature uses numerical experiments or simulated data to validate the developed models (see for example Ferretti et al. [30], Nagurney and Nagurney [47], Pinto-Varela et al. [52], Abdallah et al. [1], Wang et al. [72], and Elhedhli and Merrick [18]). Only some of the more recent studies have incorporated real data from organizations and industry (Fahimnia et al. [25], Fahimnia et al. [27], Fahimnia et al. [29], Mallidis et al. [43]; Pishvaee et al. [53]; [77]). There are also case or sector specific models such as that of Ferretti et al. [30] who present SC cost and environmental expressions for molten aluminum substitution into the SC. Even though specific to a particular industry case, the expressions can help set the foundation for other industries.

Apart from these initial classifications, the published works can also be evaluated using the level of planning and analysis. The tradeoff between cost and emission performance has been a major focus in strategic SC decision making. Such modeling efforts may include green infrastructure modeling [34], green SC network design, particularly in closed-loop situations [11,18,67] as well as studies with a narrower focus on specific SC operations such as green supplier selection [4,41,76] and transport mode selection [35]. These models only capture a broad, strategic dimension and thus the levels of analysis present very aggregate solutions. Integrating tactical and operational product level considerations in these modeling efforts is relatively immature (see for example Fahimnia et al. [26], Fahimnia et al. [29], and Pan et al. [50]).

We also realize that multi-objective SCM modeling efforts result in major complexity and that a model, to be accepted by industrial practitioners and researchers, needs to arrive at quality solutions in a relatively tolerable length of time. The opportunity to investigate various scenarios and parameters requires improved solution procedures. The use of linear solvers such as CPLEX has made this possible where small and medium size problems can be presented in a linear form [15,22,31,33]. Alternatively, various heuristics methods have been proposed for tackling large and nonlinear models that are difficult or impossible to solve optimally using the standard solvers [20,23,37,48,75]. The design of such heuristics is generally problem specific and a generic heuristic method may not fit the purpose for solving all ranges of combinational optimization problems [21].

As evidenced by the many issues and potential dimensions of green SC research, this study aims to address, in some form, the various gaps and limitations in the current literature. We clearly bound our decision environment to focus analysis on a critical aspect of the SC which includes the production, storage, and delivery of products, the three core elements in almost all SCs. Our explicit focus is on the forward SC, which has received less modeling investigation than reverse logistics aspects of environmentally oriented modeling [64]. We also focus on tactical SC planning which has received less modeling attention compared to strategic design of networks [27]. In addition, we provide a more comprehensive evaluation of environmental factors (by considering carbon emissions, energy and wastes as model objectives) and jointly balance these efforts against economic concerns. Balancing these dimensions can help organizations decide how far they should take each based on organizational, community, and competitive pressures and requirements, a very important step towards decoupling economic growth and environmental degradation at the SC level. Finally, we take advantage of the binary and nonlinear