Computers and Operations Research 89 (2018) 369–384

Contents lists available at ScienceDirect

Computers and Operations Research

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

Sustainable agro-food supply chain design using two-stage hybrid multi-objective decision-making approach

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ARTICLE INFO

Article history:
Received 1 May 2015
Revised 16 October 2016
Accepted 25 October 2016
Available online 31 December 2016

Keywords:
Agro-food supply chain design
Sustainability
Decision-making
Multi-objective optimization
Analytical hierarchy process

ABSTRACT

Sustainability of agro-food supply chains has recently become the subject of greater interest from consumers, firms, governmental organizations and academia as the environment continues to deteriorate. One of the most critical factors influencing the sustainability of an agro-food supply chain is its network design. A particularly challenging aspect in this context is the broad range of influencing indicators associated with the Triple Bottom Line (TBL) of sustainability that need to be considered. However, many of these indicators could not be fully integrated or measured by single-step optimization problems. This paper presents a critical literature review of operational research methods for the design of sustainable supply chains. A novel two-stage hybrid solution methodology is proposed. In the first stage, a partner selection is performed using a hybrid multi criteria decision making based on Analytic Hierarchy Process (AHP) method and the Ordered Weighted Averaging (OWA) aggregation method. The result obtained in the first stage is used in the second stage to develop a multi-objective mathematical model to optimize the design of the supply chain network. This approach allows the simultaneous consideration of all three dimensions of sustainability including carbon footprint, water footprint, number of jobs created and the total cost of the supply chain design. The proposed approach generates a Pareto frontier to aid users in making decisions. Numerical experiments are completed utilizing data from an agro-food company to demonstrate the efficiency and effectiveness of the proposed solution methodology. The analyzes of the numerical results provide important organizational, practical and policy insights on (1) the impact of financial and environmental sustainability on supply chain network design (2) the tradeoff analysis between environmental emission, water footprint, societal implications and associated cost for making informed decision on supply chain investment.

1. Introduction

Growing environmental, social, and ethical concerns and increased awareness of the effects of food production and consumption on the natural environment have led to increased pressure from consumer organizations, environmental advocacy groups and policy makers on agro-food companies to deal with the sustainability of their supply chains. Interest in sustainability of supply chains has grown over the last decade. Achieving sustainability entails reaching a balance between economic growth, environmental protection and social conditions. A sustainable supply chain refers to the ways in which organizational innovations and policies in supply chain management are considered in the context of sustainable development [1,49]. It is imperative to consider sustainability in agro-food supply chain, since it relates to marked environmental and social impacts. In 2010, the International Resource Panel of the United Nations Environment Programme found that agriculture and food consumption are two of the most important drivers of environmental pressures including habitat change, climate change, water use and toxic emissions [34].

Most of the current research focuses on the improvement of individual firms or processes rather than the design of an entire supply chain. Although considerable effort has been put into researching efficiency and economic performance measures, there is very little research available concerning the influence of all three dimensions of sustainability and decisions on agro-food supply, which could, in turn, offer managers the prescriptive models required to create a sustainable agro-food supply chain. Some of the more rigorous attempts at Sustainable Supply Chain Management

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http://dx.doi.org/10.1016/j.cor.2016.10.012
0305-0548/

(SSCM) modeling have been conducted in 'closing–loop' or reverse logistics literature [21]. Yet, much of that literature has focused on cost-based measures or traditional financial metrics optimization, e.g. revenue generation or cost reduction. Interestingly, in many of these models, environmental measures play a minor role, if any, to operational and financial measures [66]. Some other research efforts have started to narrow the gaps in formal modeling literature by investigating specific aspects of SSCM [24,61]. Such modeling efforts are limited, not because of the insignificance of the work but because of the complexities involved in SSCM.

Agro-food supply chain network design becomes more challenging when sustainability is embraced in the traditional economic-oriented models. One of the main challenges in this context is the broad range of influencing factors associated with sustainability that need to be considered, many of which could not be fully integrated or measured in single step optimization problems. To achieve this goal, synergies must be created between economic growth, environmental protection and social conditions, with a multidisciplinary scientific and technical approach. Although there has been some work done to identify the attributes of sustainability in agro-food supply chain, little effort has been offered to come up with a holistic framework.

This paper intends to address this gap. Indeed, very few papers so far have considered all three dimensions of sustainability in designing an agro-food supply chain using an optimization approach. Decision-making tools and techniques can help organizations make more effective and informed sustainable agro-food supply-chain design decisions. To help advance this research and further integrate sustainability into agro-food supply chain network modeling, this research proposes a two-stage hybrid solution methodology. First, this will perform a partner selection of an agro-food supply chain with a number of sustainability indicators (Stage I), and second this will formulate a mathematical model with multiple objective functions to optimize the design of the supply chain, and generate a Pareto frontier to aid users in making decisions (Stage II). To the best of our knowledge, this paper is the first to take into consideration water footprint, CO_2 footprint and the number of jobs created along with economic cost in terms of multi-objective optimization for designing sustainable four echelons supply chains. Furthermore, this research investigates the application of the proposed method using an illustrative case study to show the efficiency and effectiveness of our approach.

The remainder of this paper is organized as follows. In Section 2, a systematic review of operational research tools and methods for the design of sustainable supply chains is presented. From a performance perspective, we make a distinction between papers focusing on a single criterion and papers that focus on multiple criteria. Section 3 presents the hybrid two-stage approach to design the sustainable agro-food supply chain. A multi-criteria decision-making method is presented in the first stage, followed by the mathematical formulations and the solution method used in the second stage. Section 4 presents a case study of an agro-food supply chain to illustrate the application of the proposed methodology. Managerial implications are also discussed in this section. Finally, the paper concludes with a note about future research in Section 5.

2. Background and literature review

2.1. Sustainable agro-food supply chains

Despite the agro-food sector's importance for the development of any economy, the study of agro-food supply chains has received little attention in the literature. One of the main reasons for this neglect may be characteristics of agro-food products and processes. Agro-food supply chains are complex systems involving multiple firms usually working together within specific industry sectors to satisfy an increasingly globalized market demand for food products. Recently, consumers have become more inquisitive and there is growing concern over food attributes such as quality, integrity, safety, diversity and sustainability. To meet these requirements, companies have begun to incorporate sustainability concerns in the management of their operations in line with corporate social responsibility [28–30]. Thus, the design and management of agro-food supply chains has become extremely important in determining where a competitive advantage could be gleaned for the companies and/or industries involved [16]. The agro-food supply chain refers to a series of activities from production to distribution that brings agricultural or horticultural products from the farm to the kitchen table. The roles in an agro-food supply chain usually include the sectors responsible for producing the raw materials (farmers), processing and transforming raw materials into products, and ultimately distributing and delivering final products to the final consumers [5].

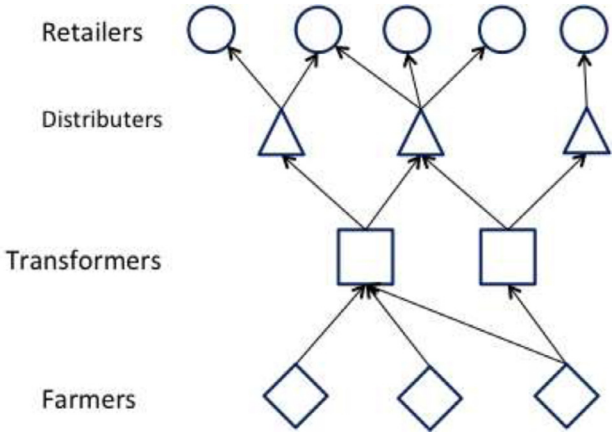

Fig. 1. Structure of the supply chain considered in this paper.

As is the case with any supply chain, the agro-foods supply chain is a network of different sectors working together in different processes and activities in order to bring products and services to the market, with the purpose of satisfying client' demands. However, what distinguishes the agro-food supply chain from other supply chains is the importance of indicators such as food quality, safety, weather-related variability and limited shelf life of products [62]. These indicators make the agro-food supply chain more complex and harder to manage than the others.

The network of the supply chain considered in this paper is shown in Fig. 1. This supply chain consists of four levels: suppliers who are farmers, transformer sites, distributor sites, and clients who are retailers. The developed multi-objective linear supply chain model aims to select effective suppliers from a candidate set of suppliers, and to locate a given number of effective transformers, and distributors to satisfy the demands of the clients. This is done in order to minimize the overall supply chain cost considering economic, environment, and social aspects, subject to suppliers', transformers' and distributors' capacity constraints.

The agro-food industry is one of the biggest users of road freight and the volume of road freight transport is growing constantly (accounting for over 80% of goods moved in the UK), with obvious disadvantages in congestion, safety and pollution. Large Goods Vehicles are responsible for around 25% of the Europe's road transport CO2 emissions [48].

In EU the food and drink sector contributes to 20%–30% of all environmental impacts [8]. According to [63], food systems contribute 19%–29% of global anthropogenic greenhouse gas (GHG) emissions, releasing 9800–16,900 Mega-tones of carbon dioxide