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Closing loops in agricultural supply chains using multi-objective optimization: A case study of an industrial mushroom supply chain

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ABSTRACT

Environmental concerns and scarcity of resources encourage decision makers in supply chains to consider alternative production options that include preventing the production of waste streams, and simultaneously reusing and recycling waste materials. Until now, hardly any quantitative modeling approaches exist in literature on closing loops in agri-food supply chains. In contrast to closed-loop studies in discrete parts industry, in agri-food supply chains the value of the final product itself cannot be regained. However, the components used for production such as organic matter or a growing medium, can be recycled. In this paper, the consequences of closing loops in a mushroom supply chain are revealed. We propose a multi-objective mixed integer linear programming model to quantify trade-offs between economic and environmental indicators and explore quantitatively alternative recycling technologies. The model was developed to re-design the logistical structure and close loops in the mushroom supply chain. We found that adopting closing loop technologies in industrial mushroom production has the potential to increase total profitability of the chain by almost 11% while the environmental performance improves by almost 28%. We conclude that a comprehensive evaluation of recycling technologies and redesigning logistical structures requires quantitative tools that optimize simultaneously managerial decisions at strategic and tactical level.

1. Introduction

Resources become scarce, ecosystems are threatened, and the consequences of climate change have a large impact on the living environment. People become aware of environmental pressure, which in turn causes an increasing demand for sustainable food production. To become more environmentally friendly, food supply chains need to adopt innovative technologies that focus on using natural resources and materials to their full potential.

The concept of "closing loops", which refers to the integration of forward and reverse supply chain activities (Guide et al., 2003), is one of the options considered to ensure the sustainability of supply chains (Chaabane et al., 2012). This topic has been widely studied and has given rise to the field of Closed Loop Supply Chains (CLSCs) (Paksoy et al., 2011). In CLSCs, items no longer desired or used are taken care of and their value is (partly) recovered (Flapper et al., 2005). Examples of new logistical structures exist in which the concept of closing loops has been used and showed that resource use efficiency can be substantially improved. However, these examples mostly refer to returning products to original equipment manufacturers (OEM) in discrete parts industry e.g. car industry (van der Laan, 1997), refrigerators (Krikke et al., 2003), copiers (Krikke et al., 1999), and electronic equipment (Quariguasi Frota Neto et al., 2010). Value of OEM products can be regained after their use because these products consist of materials and components that are suitable for reuse. In agri-food chains, defined as supply chains that produce and distribute agricultural or horticultural products (Ahumada and Villalobos, 2009; Aramyan et al., 2006), raw materials used for production usually either disappear due to consumption or lose their value (e.g. due to product decay), and wasted food products can be valorised in other supply chains, e.g. for biofuel production or feed production. Thus in contrast to discrete parts industry, in a closed loop agri-food supply chain it is not the value of what is in the products that can be regained (in the same chain), but rather the components used for production, such as organic matter or a growing medium. Therefore, closing loops in agri-food chains may require a fundamental reconsideration of business processes and redesign of distinct logistical structures.

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To redesign an agri-food supply chain, decision support tools are needed that can optimize decision making at chain level. Additionally, these decision support tools should enable the assessment of multiple indicators. This can result in the calculation of trade-offs between conflicting objectives, which make decision makers aware of (individual) trade-offs and can facilitate the discussion and exploration of alternative logistical structures. Govindan et al. (2014) confirm that there are hardly studies in the CLSC literature that evaluate quantitatively the relationship between economic and environmental criteria simultaneously. Bell et al. (2013) emphasize the need for studies to demonstrate how closed loop technologies can lead to improved environmental performance. Moreover, in order to investigate the relation between economic and environmental criteria, Soysal et al. (2012) and Brandenburg et al. (2014) confirm the need for quantitative models on real-life case studies.

The research presented in this paper attempts to fill in these gaps. More specifically, we evaluate quantitatively a mushroom supply chain, in which farm waste materials are used for mushroom production. Horse and chicken manure are some of the ingredients that can be used for the production of substrate for growing mushrooms. Spent mushroom substrate, a material remaining after cultivating mushrooms can cause environmental burden, i.e. for instance in the Netherlands over 800,000 tons of spent mushroom substrate is produced annually (Phan and Sabaratnam, 2012), and need to be transported hundreds of kilometers just to be used as fertilizer. The activities related to disposal are neither economically nor environmentally attractive. The amount of mushrooms produced in the Netherlands constitutes to less than 9% of global mushroom production (Koopman et al., 2010). These figures demonstrate the magnitude of this waste stream worldwide. Simultaneously, the figures show the potential for improvement, as the economic and environmental performance could be improved substantially if only a minor part of the nutritious waste materials could be reused or recovered in the same chain for production. Amount of spent mushroom substrate can be reduced by extending production cycles, i.e. using the same substrate for more subsequent production rounds at mushroom production level. Such an option will reduce the amount of disposed substrate, however, always at the expense of the yearly production yield. Technological innovations provide potential for reusing and recycling parts of the spent mushroom substrate to close the loop in mushroom supply chains. The feasibility of these technological innovations including their impact on sustainability must be further investigated. It is therefore important to quantify the implications of valorisation of materials on the performance of a mushroom supply chain.

The objective of this paper is to evaluate the economic and environmental performance of closing loop technologies at chain level in a mushroom supply chain. A multi-objective (mixed integer) linear programming model is developed to support production and distribution planning decisions by optimizing material flows in a closed loop mushroom supply chain. The mushroom supply chain provides an example of an agri-food supply chain in which not the product itself, but the medium for growing the product can be reduced, reused, or recycled. We demonstrate how environmental and economic performance of alternative closed loop logistical structures can be evaluated in a multi-objective context. To the best of our knowledge, this paper presents the first decision support model to optimize flows of materials with respect to economic and environmental objectives in a closed loop agri-food supply chain. Deriving a set of Pareto-optimal solutions allows to obtain insights in the environmental costs of activities in a mushroom supply chain.

The paper is structured as follows. Section 2 presents an overview from literature in the related areas, i.e. closed-loop supply chains, and the use of multi-criteria decision making models in agri-food supply chains. Section 3 introduces a mushroom supply chain in which possibilities exist to close material loops. We propose a multi-objective decision support model that can be used to quantify the benefits of closing loops. Section 4 presents the results of the model applied to the real-life mushroom supply chain. Section 5 focuses on the generalizability of the case study to create a framework for closed-loop agri-food supply chains. The main conclusions are summarized in Section 6.

2. Literature review

A vast body of literature exists that focuses on improving the environmental performance of supply chains (SCs) (Brandenburg et al., 2014). Reduction of environmental impact, however, often requires sacrifices in terms of economic performance in a SC, and only a limited number of initiatives for environmental friendly production have proven to be profitable (Quariguasi Frota Neto et al., 2008). Assessment of alternative options requires the consideration of multiple criteria, because any (re)design of a SC usually involves trade-offs between different conflicting objectives (Wang et al., 2011). Multi-objective optimization has already been used to address different decision problems in SCs and to test the efficiency of various SC configurations and operating strategies (Aramyan et al., 2011; Ramudhin et al., 2010).

One of the environmental issues in SCs is associated with the amount of waste produced and in response, the recovery of products is drawing attention of researchers and practitioners (Paksoy et al., 2010). Commonly, the aim is to regain the incorporated value of some products once their use has ended, instead of land filling or incinerating the remains (Dekker et al., 2012). Regaining value of a product typically involves reverse logistic activities, such as reuse, repair, recycle and remanufacture (Chaabane et al., 2012; Paksoy et al., 2011; Jayaraman, 2006). Reverse logistics, therefore, includes the activities all the way from used products (i.e. no longer required by the user), to products that are reusable in a market (Fleischmann et al., 1997). Applications of reverse logistics in literature include e.g. hi-tech products (Eskandarpour et al., 2013), computer hardware (Ravi et al., 2008), electronic equipment (Quariguasi Frota Neto et al., 2009), plastic recycling (Senthil et al., 2014), or tire recovery (Dehghanian and Mansour, 2009). Reverse supply chain activities improve supply chain management by giving the advantage of closing the material loop of products from resource extraction, through production, use, and end-of-life (Paksoy et al., 2010).

A Closed Loop Supply Chain (CLSC) is defined as a chain in which both forward and reverse logistics are combined. In a CLSC flows of materials are circular and finished products do not become waste after their use, but instead are disassembled, reused, remanufactured, or recycled into a source of raw materials (Hassini et al., 2012). Examples of CLSC optimization models including economic and environmental criteria can be found for instance in automotive industry (Kannegiesser et al., 2014) or electronic equipment (Quariguasi Frota Neto et al., 2010).

Within the context of agri-food supply chains the sustainability discussion focuses on emissions related to all activities in the supply chain, including the reduction of waste (Bloemhof and van der Vorst, 2014). Amorim et al. (2012) present a multi-objective model to minimize the costs, and maximize the remaining shelf life of a perishable product. Akkerman et al. (2009) study sustainable production and distribution of industrially prepared meal elements, while taking into account products' quality degradation. To ensure the product's quality, its enthalpy levels in the developed mathematical model must be below a given threshold when delivered to customers. Soysal et al. (2014) study a beef logistics