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On the design of closed-loop networks for product life cycle management: Economic, environmental and geography considerations

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ABSTRACT

The management of the product life cycle needs industrial synergies along large-scale networks to collect, recycle, reuse, and recover the end-of-life products. This paper provides a tool to assess the enabling economic, environmental, and transport geography conditions to design sustainable closed-loop networks for the management of a generic product along its life-cycle. The proposed tool is built through a mixed-integer linear programming (MILP) model for the strategic design of a multi-echelon closed-loop network. The product life cycle is handled via a cascade through seven stages, including raw material suppliers, manufacturing plants, distribution centers, retailers, collection nodes for waste and by-products, recycling centers, and landfills.
The model minimizes a cost-based and a carbon-based function to determine the optimal geographic location of the nodes of the network and the allocation of transport flows. The model is applied to a case study inspired by the furniture industry over the Italian geography and a multi-scenario analysis is illustrated. The resulting considerations on the economic, environmental performances of the network couple with the transport geography to provide guidelines for designer, logistics planners and regional geographers toward a circular economy scenario.

1. Introduction

In recent decades, connections between economic development, geography, transportation, and industrial goals are growing alongside the growth of global supply chains (Hesse and Rodrigue, 2004). The geography of freight flows produced by global consumers affects the cost of products and their environmental footprint. While the minimization of costs is largely the first driver in supply chain design, the assessment of environmental impacts associated with production and transport networks is elicited by government initiatives and regulations to sustain environmentally friendly practices and strategies, as well as reducing the externalities associated with industry and transportation.

Supply network design typically addresses the optimal location of facilities, distribution centers, and intermodal hubs based on the minimization of total network costs. Nevertheless, the economic and environmental sustainability of supply chains require the management of ever-scarcer natural resources through the reduction of waste and its recovery as a secondary material. The movement toward a zero waste supply chain has an environmental rationale and represents an increasing factor of competitiveness and economic sustainability by reducing dependency on raw materials and exploring valorization opportunities for end-of-life products. A systemic analysis of the cycle from production to consumption and from collection to recycling as a whole results in the design of sustainable processes for products and waste management, highlighting opportunities for both industry and social issues.

The management of product life cycle is supported by industrial synergies requiring large-scale integrated processes for the collection, recycling, reuse, and energy recovery of end-of-life products (e.g., by-products and packaging materials) to establish reliable and effective feed-stocks of secondary materials. With an increasing environmental responsibility felt by industrial actors, these synergies require innovative transport networks with a life cycle perspective that enables product reuse, recycling, and recovery.

Despite long-time interest in planning transport forward networks (Alumur and Kara, 2008; Melo et al., 2009; Manzini, 2012; Kelley et al., 2013; Bowen, 2014; Manzini et al., 2014; Reis and Leal, 2015) and in designing waste reversal chains (Chanintrakul et al., 2009; Jamsa, 2009), research efforts have only recently shifted to integrate forward and reverse chains into closed-loop systems (Akçalı et al., 2009). Increasing interest among scholars has led to research aiming to analyze the performance of the extended closed-loop system through the strategic location of facilities, hubs, and transport networks for both products (Rodrigue, 2006) and end-of-life products (e.g., waste, by-products, and packaging materials).

This paper analyzes the role of some economic geography decisions (e.g., spatial organization of industries, supply chain design, and establishment of transport infrastructure) in designing products according to a closed-loop scenario. When engineering new products, a designer ponders materials and sub-components mostly on the basis of economic

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constraints and technological performance. Environmental concerns are of increasing importance in design decisions. For instance, the adoption of recycled or recyclable materials shows movement toward a more environmentally friendly scenario. Incorporating transport and distribution issues or end-of-life considerations into the early stages of product design, however, is still an ambitious challenge for practitioners given the complexity and multidisciplinary nature of those aspects involved.

This paper provides a tool for the analysis of enabling economic, environmental, and transport geography conditions (e.g., availability of raw materials, location of intermodal infrastructure, and hubs) to design sustainable closed-loop networks for the management of products across their entire life cycle. The interdependency of economic and environmental performance within a closed-loop network is observed across multiple perspectives including that of the designer, logistics manager, and geographer.

The proposed tool is based on an original mixed-integer linear programming (MILP) model for the strategic design of a multi-echelon closed-loop network. The model includes all stages of a product life cycle from the cradle to the grave. The product life cycle is handled via a cascade through seven stages, including raw material suppliers, manufacturing, distribution centers, retailers, collection centers for waste and by-products, disposal centers (e.g., landfill), and recycling centers. Fig. 1 illustrates the analyzed network. This network assembles finished products using raw materials and subcomponents according to the product bill of materials (BoM). Flows of finished products generate waste at manufacturing facilities (i.e., by-products), distribution facilities (i.e., packaging materials), and on the retailer or consumer side (i.e., wastes and end-of-life products). Both finished and end-of-life products are processed and transported across the network to generate value for both the consumer and manufacturer in addressing the zero-waste goal (Winkler, 2011) at the minimum cost and with a minimum environmental impact.

Regarding product designers, cost minimization is undeniably the most important goal, even for logistics planners. Recent research considers environmental impact when planning a supply chain and addresses the growing challenge of climate change (Paksoy et al., 2011; Mallidis et al., 2012; Marletto and Sillig, 2014). Above all other pollutants, carbon dioxide is renowned as the main stressor of climate change (Chapman, 2007). The costs and carbon dioxide emissions associated with facility establishment, product manufacturing, warehousing and transportation activities, waste collection, recycling, and disposal are accounted for by the proposed model in two objective functions (i.e., cost-based and carbon-based, respectively).

This model minimizes the objective functions independently by determining both the optimal geographic location of the nodes of a closed-loop network and the optimal allocation of transport flows of products and end-of-life products. The resulting considerations of the economic and environmental performance of a network, coupled with the observed geography of transport activities, provide guidelines for designers, logistics planners, and regional geographers in movement toward a circular economy scenario.

The remainder of this paper is organized as follows. Section 2 presents a review of the state-of-art on closed-loop network models. Sections 3 and 4 illustrate network assumptions, problem formulation and limitations, a description of constraints, and a comparison between the two objective functions. Section 5 presents a case study inspired by the furniture and home decoration industry in Italy. Inspired by the findings of this case study, Section 6 explores the interdependency between product design and the logistic network. This paper highlights how the economic and environmental performance of a closed-loop network is affected by the product design phase, proposing a tool to integrate these decisions at the strategic level. Section 7 presents the conclusions and proposes further developments.

2. Literature review

The design of closed-loop networks is gaining importance in the operation literature (French and LaForge, 2006; Akçalı et al., 2009). To compare this paper with the state of the art literature, Table 1 classifies the most recent and relevant models for the design of closed-loop networks. The models are characterized for the number of planning periods, the type and the number of the layers of the network, the objective function of the model, and the presence of constraints that enable the assembling and disassembling of products according to their bill of materials. While multi-period models aid the scheduling and planning of the supply chain operations, single-period models enable

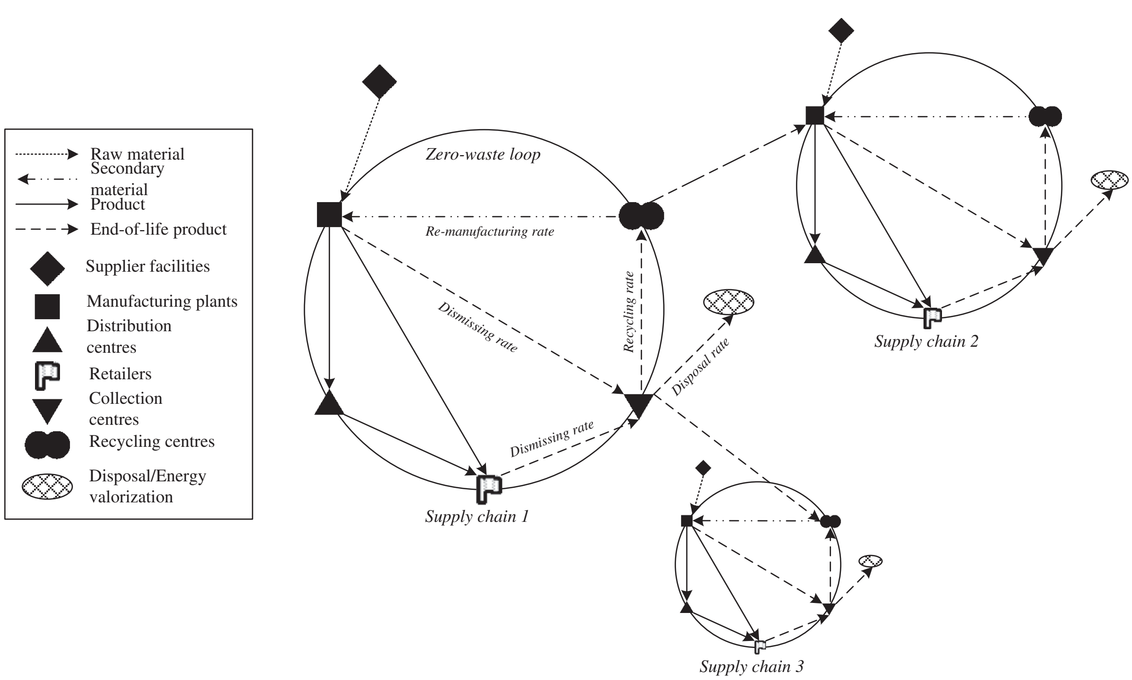

Fig. 1. Closed-loop network.