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Technical Paper

A reverse logistics network design

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ABSTRACT

The area of reverse logistics (RL) has recently received considerable attention, due to a combination of environmental, economic and social factors. Reverse logistics refers to the series of operations that initiate at the consumer level with the collection of products and terminate with the re-processing of these products at remanufacturing facilities. In the current work, we propose a mixed-integer linear program (MILP) to address the complex network configuration of an RL system, which decides on the optimal selection of sites, the capacities of inspection centers and remanufacturing facilities. Furthermore, we introduce important transportation considerations, by providing the option of using in-house fleet as well as outsourcing option and this constitutes one of the main contributions of our work. In addition, we take into account the initial investment, which limits investments to be made on fleet or center expansion in subsequent time periods. The model is tested on a real-life case and results are reported. The current work holds significant practical implications, as it can provide useful insights to decision makers from both governmental and private entities regarding important strategic decisions pertaining to the design of reverse supply chains.

1. Introduction

Recent environmental considerations have contributed to the adoption of different approaches with respect to supply chains. These include efforts for the minimization of the supply chain's carbon footprint [1], the adoption of renewable energy generation for powering the supply chain [2], or the implementation of carbon market trading [3]. Furthermore, in light of the high economic returns, special attention has been focused on recycling products [4,5]. In this direction, governments have enforced regulations that oblige companies to take back returned products [6]. Thus, it is crucial for companies to design reverse supply chains that are as efficient as the forward supply chains [7]. Aside from this, companies are encouraged to invest in the reverse supply chain as there may be financial benefits to remanufacturing used products [8,9]. As an overview of general approaches, several interesting works have focused on the drivers [10,11], as well as the barriers for the implementation of sustainable practices in the supply chain [12–15].

The challenge that arises for the RL networks is mainly due to the higher supply uncertainty that renders such networks more complicated than traditional forward logistics networks. In addition to this, investors bear a high risk when making decisions in the design phase of reverse production, due to the high costs associated with transportation, potential facility locations and other factors. For companies in reverse production and recycling, the initial investment is a crucial factor that affects all subsequent decisions: the layout of the transportation system and the optimal sites and locations of important infrastructures, such as inspection centers, remanufacturing plants and recycling centers. In fact, the majority of companies eventually expand their transportation systems, instead of opening new facilities, as it is more cost effective. They initially operate from a region that secures a higher profit, while outsourcing several operations until their business grows, which is when they choose to expand. Transportation, among others, is one of the operations that companies may choose to outsource. The primary reasons for outsourcing include labor cost savings, asset reduction as well as workload expansion. On the other hand, the reason for not opting for outsourcing is mainly related to loss of management control and disruption of company integrality [16].

Thus, in this paper, we address the important matter of network design for an RL system. Our focus has been concentrated on the transportation system of the RL network design with the objective of developing a model that closely simulates real life circumstances. Our new model was developed to include different transportation options that could be selected to transfer the items or goods from collection centers to inspection centers and take components from inspection centers to remanufacturing plants by using

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outsourcing or in-house fleet. Several important considerations have been accounted for. Firstly, the outsourcing can be done by using rented trucks for a specific cost per item per kilometer. Owning in-house fleet requires a higher budget in order to buy and operate the trucks, yet in the long run it is cheaper than outsourcing the trucks. Furthermore, the cost of each project cannot be unlimited and the amount of the initial investment must be defined to render the model more realistic. Every company can decide the size of the initial investment that they are willing to make at the initial period of time and the part of the revenue to be invested in the coming years. In this way, it is possible to devise an improved system that more accurately reflects real life circumstances and is therefore of higher practical value.

The structure of the paper is as follows: Section 2 provides an overview of the literature related to this field, while in Section 3 the model formulation is described. Section 4 illustrates a case study and results and discussion are presented in Section 5. Finally the conclusions and directions for future work are summarized in Section 6.

2. Literature review

Numerous models can be found in the literature that addresses problems pertaining to RL, for various industrial products and applications. Two research methodologies can be adopted for the RL network, namely case studies and quantitative models. The former approach involves analyzing a specific example of an RL network, by means of qualitative analyses, while the latter revolves around the development of an analytical model to describe the network. Due to the nature of the current work, this section will focus on presenting prevalent works that implement the quantitative methodology to address the RL design problem.

Mixed integer linear programming (MILP) formulations are widely employed in this context. In the work of [17] the authors address the problem of plastics' recycling in the Netherlands. They aim to minimize transportation cost and environmental impact and they test various scenarios in order to find the optimal separation strategy. Gomes et al. [18] also propose an MILP that aims to decide on the optimal locations for collection and sorting centers. The selection is performed simultaneously under what is defined as tactical network planning. This work was inspired by the European Union directive for electric and electronic waste.

Alumur et al. [19] present a highly flexible generic MILP model that can be used for different recovery products and can be extended further to include more settings. The model was developed to determine the optimal sites and capacities of inspection centers and remanufacturing plants in the RL network design. A case study in the context of RL network design for washing machines and tumble dryers (large household appliances) in Germany has been used. Alumur et al. [19] estimate the revenues from selling the components of washing machines and tumble dryers from [20]. One important assumption made by [19] is that all the components of the disposal products can be reused. Aside from the notable formulation, the authors also propose a very useful classification through a table of summarized modeling features and assumptions of existing literature.

Other works that implement MILPs include [21–27]. Furthermore, a mixed integer nonlinear programming (MINLP) formulation is proposed by [28], as the authors incorporate certain dynamic aspects such as lead time and inventory positions. The resulting model is complex and that is why they implement a single product single level network and solve it using a genetic algorithm (GA). Giri and Sharma [29] solve the problem with algorithms developed for sequential and global optimization.

A different formulation is developed by [30], who choose a mixed integer goal programming (MIGP) model to aid in better management of the paper recycling logistics system. The authors examine the relationship between multiple objectives in a recycled paper distribution network, such as reverse logistics cost, product quality improvement and wastepaper recovery benefits. Furthermore, their model determines strategic decisions, such as facility location, as well as tactical decisions such as routing and recyclable product flows in a multi-item, multi-echelon and multi-facility context. Multi-objective optimization was also implemented by [31], in order to enhance the control policies with respect to returned products.

On another note of classification, the RL and closed-loop network model can be distinguished into generic and stochastic models. By closed-loop we refer to the network that considers both the forward and reverse supply chain, at the same time. Contrary to the generic model, the stochastic network accounts for various uncertainties.

For example, uncertainty associated with transportation costs and waste generation is accounted for by [32]. The authors develop a comprehensive model for reverse logistics planning that considers multiple facility echelons, multiple commodities and a choice of varying technologies, aside from stochasticity. A two-stage bi-objective mixed-integer stochastic programming formulation is presented, which makes strategic and tactical decisions on the first and second stage, respectively, with the objective of minimizing cost as well as negative impact. Other stochastic models are developed by [25,26,28,33].

At this point, it is worth describing the characteristics of the problem addressed in the current work, which is an extension of the work done by [19]. We also choose to develop an MILP to model the problem of selecting optimal locations for inspection centers and remanufacturing plants, as well as delivering each product from a collection center to an inspection center and from there to a remanufacturing plant. The important contribution of our work is highlighted through the consideration of two transportation options for delivering the products across the reverse supply chain. These options include using in-house fleet or outsourced trucks. In addition, we consider that every project is limited by a certain budget, in the sense that an initial investment amount is proposed for the first year with possibility of reinvestment up to a certain percentage of the revenue in the next year. Based on the classification of [19], and to the best of our knowledge, our model is the only one that introduces transportation options and investment considerations.

3. Mathematical formulation

Regarding the description of the developed model, Fig. 1 represents the proposed RL system where the "products" of upstream holders are either collected, or dropped by the consumer at the collection center at each site or city which is near the municipality. Municipalities assume the sources for the supply of "products" in the model. Subsequently, the returned products are sorted in the collection center as per their condition, before being sent either to a recycle/disposal center or to an inspection center. Afterwards, at the inspection center, the inspected items can be sent to external remanufacturing plants or be disassembled. The reusable parts can be sent to remanufacturing plants and these parts cannot be reused at recycling centers. At the remanufacturing plant, the incoming parts from inspection centers can be reused again to create new products and then resold to a secondary market and the damaged parts can be sent to recycle or disposal centers. The remanufacturing plant can purchase new parts to replace the damaged ones from external suppliers. The transportation to recycle/disposal centers