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A metaheuristic for the multimodal network flow problem with product quality preservation and empty repositioning

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ABSTRACT

We study a transportation planning problem with multiple transportation modes, perishable products, and management of Reusable Transport Items (RTIs). This problem is inspired by the European horticultural chain. We present a Mixed Integer Programming (MIP) optimization model which is an extension of the Fixed-charge Capacitated Multicommodity Network Flow Problem (FCMNFP). The MIP integrates dynamic allocation, flow, and repositioning of the RTIs in order to find the trade-off between product freshness requirements, and operational circumstances and costs. We furthermore propose an Adaptive Large Neighborhood Search (ALNS) algorithm with new neighborhoods, and intensification and diversification strategies. We then provide detailed computational analysis on its properties, compare its results with a state-of-the-art MIP solver, and provide practical insights.

1. Introduction

Perishable supply chains are international businesses and the horticultural industry of the Netherlands is an example. Everyday, around 400,000 types of cut flowers and plants, with an average daily turnover of more than 8 million Euros (FloraHolland, 2015), are transported from around the world to the auction houses in the Netherlands, to get auctioned, sold, and further transported throughout Europe and beyond. Kenya, Ethiopia, Israel, Belgium, Germany are among the top producers of these products, and United Kingdom, Netherlands, Germany, France, Italy, Poland, and Russia are among the top European markets.

These perishable products are fragile, have short shelf-lives, and travel long and in different climates. Temperature fluctuation and long handling time have a direct influence on their deterioration. To ensure freshness of the products, they are traditionally transported by either air or road, and in temperature-controlled environment. However, their market is growing, and adding more air and road vehicles results in more expensive transportation, and causes various social and environmental issues such as congestion and pollution. The horticultural supply chain of the Netherlands is aiming to lower related logistics costs in 2020 by 15%, equivalent to 64 million Euros (FloraHolland, 2015).

The challenge of finding the optimal transportation fleet plan is added to other operational issues such as resource management. An optimal transportation of perishable products needs synchronized flow with minimum waiting and handling. In the horticultural supply chain, this is highly dependent on the availability of Reusable Transport Items (RTIs). An RTI is an empty loading unit which can have different sizes ranging from a small box to a large 45-feet container. Their number

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is limited, and their shortage results in quality decay of the products awaiting them, and therefore, in less profit. Returning or repositioning these units is costly and does not bring any direct profit. As a result, solutions integrating the forward flow of loaded RTIs with the backward flow of empty ones are needed to minimize the system-wide costs.

A cheap, diverse, flexible, and environmentally friendly transportation, ensuring freshness of the products while offering a competitive price, requires consolidation and switching from air and road to other modes of transport. *Multimodal transportation* has gained a lot of attention over the last 50 years (SteadieSeifi et al., 2014). Other industries are not unfamiliar with the opportunities that it offers. In perishable supply chains though, switching to slower modes means an increase in transportation time, which furthermore might decrease the product quality. Finding the trade-off between minimizing operational costs and product quality preservation becomes an interesting research subject, which is the target of our research.

Our contributions are as follows. In this paper, we study the long-haul transportation of perishable products. In order to include product preservation requirements, we present a mode-space-time network where all types of multimodal operations such as holding, handling, transshipment, and transportation are included. We model the problem as a Mixed-Integer Program (MIP), where we add new sets of constraints to the classic Fixed-charge Capacitated Multicommodity Network Flow Problem (FCMNFP). These constraints include a product quality measure based on temperature and travel time, and enforces a maximum limit on the products after which the products are spoiled. Moreover, we integrate the forward flow of loaded RTIs with the backward flow of empty ones via a set of special constraints. Based on a given demand, these constraints automatically assign and move the needed empty RTIs. Balakrishnan et al. (1997) have shown that the capacitated fixed-charge network design problem is NP-hard. Our problem incorporates additional resource management constraints which add further complexity to the problem. The number of decision variables goes very quickly beyond what can be solved to optimality with a state-of-the-art MIP solver. Therefore, in this paper, we build upon the literature and propose an ALNS algorithm with new operators, improved scoring mechanism, and extra strategies, to solve this problem.

In the remainder of this paper, Section 2 gives an overview on the literature of transportation of perishable products, as well as asset management issues in transportation, and the related solution algorithms. Section 3 describes the problem, and presents its MIP formulation. In Section 4, the proposed solution algorithm is explained and in Section 5, its performance is analyzed and compared with a state-of-the-art solver. Finally, in Section 6, we give some concluding remarks and describe potential future work.

2. Literature review

Planning transportation of perishable products in the literature is identified by extra preservation constraints or penalty costs. We can group transportation problems into long-haul transportation, and last-mile (or first-mile) transportation.

Last-mile (or first-mile) distribution problems are traditionally modeled as Vehicle Routing Problems with Time Windows (VRPTW) and the goal is to find the optimal load, delivery routes, and departure times of the fleet of vehicles. Doerner et al. (2008) study the Pickup and Delivery Problem (PDP) of blood products with strict time windows. Hsu et al. (2007) model a food distribution planning problem with stochastic and time-dependent travel times and time-varying temperature. Osvald and Stirn (2008) also address distribution of fresh vegetables with time-dependent travel times, but add a quality degradation based cost function to the objective function. Tarantilis and Kiranoudis (2001, 2002) study the distribution of fresh milk with a heterogeneous fixed fleet, and the distribution of fresh meat in a multi-depot network, respectively. They consider strict time windows for delivery of the products. Derigs et al. (2011) and Mendoza et al. (2011) study distribution planning problems for food and petrol where the products are incompatible and they should be separated and allocated to separate trucks, while customers order them simultaneously, resulting in excessive transportation costs.

On long-haul transportation of perishable products, Reis and Leal (2015) propose a MIP model for a soybean shipping chain planning problem where choice of transportation mode is included in the model besides decisions for annual crop purchase. Since their real-world application deals with significant uncertainty related to crop production, they define several combinations of scenarios for this uncertainty and apply their MIP model to each scenario in order to give insights for their decision makers. Studying long-haul transportation of perishable products is slowly getting more attention.

In this paper, we add to this literature of long-haul transportation of perishable products by incorporating management of resources, here RTIs, into our multimodal planning problem, which is missing in Reis and Leal (2015). An optimal transportation comprises the optimal and timely utilization and operation of its resources, called assets. *Assets* can be RTIs, vehicles, crews, power units, engines, etc (SteadieSeifi et al., 2014). Positioning, balancing, allocating, repositioning, and rotation of assets are the subject of asset management.

Repositioning of vehicles has been widely investigated in the literature, mostly addressed as Service Network Design (SND) problems. SND problems with cyclic service design account for returning of empty vehicles to their service starting location. Pedersen et al. (2009), Andersen et al. (2009a, 2009b, 2011) present comprehensive studies on formulating SND problems with vehicle repositioning and their computational differences. Moccia et al. (2011) propose a column generation heuristic for a rail and road transportation system with both consolidated and dedicated services. Thiongane et al. (2015) introduce new constraints to the fixed-charge capacitated multicommodity network design problem, where commodity volume is not splittable, and there is a limit on the number of arcs that each commodity can travel between its origin and destination nodes. They propose different formulations and several relaxation methods to solve them. Li et al. (2016) formulate a SND problem with heterogeneous vehicles, but decompose it into two interdependent sub-problems of a fixed-charge capacitated multicommodity network design problem, and a vehicle assignment problem (VAP). Unlike most of the SND