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The impact of food perishability issues in the vehicle routing problem ☆

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ABSTRACT

Highly perishable food products can lose an important part of their value in the distribution process. We propose a novel multi-objective model that decouples the minimization of the distribution costs from the maximization of the freshness state of the delivered products. The main objective of the work is to examine the relation between distribution scenarios and the cost-freshness trade-off. Small size instances adapted from the vehicle routing problem with time windows are solved with an ϵ-constraint method and for large size instances a multi-objective evolutionary algorithm is implemented. The computational experiments show the conflicting nature of the two objectives.

1. Introduction

Product perishability may manifest itself in a whole set of difference forms. Products subject to perishability range from daily newspapers that lose their value soon after the day they are reporting, to flowers that look wilted sometimes even before reaching stores, or blood used for transfusions. This last example sparked the study of the perishable inventory (Millard, 1960). Decision models valid for this broad range of perishable products should capture their specific nature distinguishing, for example, between products with and without *best before dates* (Amorim, Meyr, Almeder, & Almada-Lobo, 2011). Highly perishable products have an important role in the operational distribution process, particularly in the vehicle routing planning task. Examples of this kind of products are fruits, vegetables and prepared meals. In this category of goods, the quality changing imposed by the perishability phenomenon is noticeable by the entity receiving the products during the planning horizon. Hence, in this paper, the decreasing value that customers attribute to a decreasing freshness state is acknowledged.

Let us focus on the prepared meals segment to exemplify the particularities of this vehicle routing problem that delivers highly perishable goods. Consider a company specialized in gourmet prepared meals based on a very busy city that services daily hundreds of customers. Moreover, this company runs an own fleet of refrigerated trucks to perform the distribution of the products. The meals are ordered on the day before and customers are very demanding in terms of expected delivery time and freshness of the food received. Hence, if a customer orders duck with sauce, he is expecting that when he receives the meal, it will seem as the sauce was just made and poured above the duck. On the other hand, if the customer orders an assortment of cheeses, he will be less sensible to how much time the product stayed in the truck before reaching him.

This operational distribution planning task fits into the vehicle routing problem (VRP) class of problems. In specific, we are dealing with a VRP with time windows (VRPTW) that has to consider the perishable nature of the products delivered. This hard problem (Savelsbergh, 1985) is to be modelled using a multi-objective framework in which distribution costs are minimized and the freshness of the products delivered to the customers is maximized simultaneously. The first objective reflects explicitly the need of reducing operation costs and the second one expresses the intangible customer value stemming from product freshness, which the company wants to grasp when designing their routes.

In order to investigate the impact of product perishability in the distribution process a set of empirical hypotheses are postulated, relating distribution scenarios and the cost-freshness trade-off. The customers' typology, time windows width and perishability intensity are varied through these distribution scenarios. To test these hypotheses an ϵ-constraint method is employed to solve exactly the well-known Solomon instances (Solomon, 1983) with 25 customers. Afterwards, the findings are validated for the instances with 100 customers using a multi-objective evolutionary algorithm (MOEA) as the exact methods fail to generate feasible solutions.

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The remainder of this paper is as follows. In the next section a brief literature review is performed, and the mathematical formulation that models this problem is then presented in Section 3. Section 4 formulates the hypotheses that establish the possible influences of distribution scenarios in the cost-freshness trade-off. In Section 5 the methodology used to test the hypothesis for small and large instances is described. Afterwards, in Section 6 the results obtained through the computational experiments are shown. Finally, the Conclusions section resumes the main findings of this work and gives some hints for future research.

2. Literature review

The VRP field of research is very vast and proficuous. The same applies for the VRPTW extension. In this review, the focus will be kept on papers dealing with the VRP for perishable goods. The readers are referred to Laporte (2007) or Eksioglu, Vural, and Reisman (2009) for more general VRP problems.

Some literature focus on different distribution problems related with perishable food products but without considering explicitly the degradation of quality (losing of freshness) during transportation. In fact, these models could be most of the times applied to products without a perishable nature. The work of Tarantilis and Kiranoudis (2001) concentrates on the distribution of fresh milk and formulates the problem as a heterogeneous fixed fleet VRP. The same authors (Tarantilis & Kiranoudis, 2002) solve a real-world distribution problem of fresh meat as a multi-depot VRP. Faulin (2003) implements a hybrid algorithm procedure that uses a combination of heuristics and exact algorithms to find a solution to a VRP with constraints enforcing narrow time windows and strict delivery quantities. According to the author, these delivery scenarios are usually the case in the agribusiness industry.

Concerning the articles modelling perishability explicitly, Osvald and Stirn (2008) extend a heuristic proposed by the first author in a previous work to solve the problem of distributing fresh vegetables in which perishability represents a critical factor. The problem is formulated as a VRPTW with time-dependent travel times. The objective function minimizes the distance and time travelled, the delay costs for servicing late a customer and the costs related to perishability. In this model, the perishability costs are calculated by multiplying the load transported in each arc by the time needed to do it. Hsu, Hung, and Li (2007) consider the randomness of the perishable food delivery process and present a stochastic VRPTW model that is further extended to consider time-dependent travel times. The objective function of this work is very similar to that of Osvald and Stirn (2008), but the calculation of costs due to perishability is done in a stochastic manner. The authors attribute probability density functions to determine the chances of having spoiled products due to the opening of the vehicle door and to the travel time. The problem is solved by a heuristic procedure. Chen, Hsueh, and Chang (2009) integrate production scheduling with the VRPTW for perishable food products. In the distribution part, they consider a value decay on the products distributed that will influence the price paid by the retailer to the transporter. This model has a stochastic nature by defining the demand through a probability density function. Afterwards, the integrated model is solved in an iterative scheme in which the VRP part is solved by a constructive heuristic followed by an improvement one.

In Table 1 we compare our work against the closest papers in the literature, in terms of modelling characteristics (type of VRP considered, number of objectives, perishability behaviour and number of products), solution methods and instances tested.

From the literature review, it is clear that incorporating the perishability factor explicitly in the formulations seems to be of great advantage (Akkerman, Farahani, & Grunow, 2010) since the customers' point of view is also taken into account. In our work, a multi-objective framework is used to tackle this phenomenon and, hence, to give to the decision maker a whole set of equally efficient solutions, evidencing the trade-off between supply chain optimization and customer service related to the freshness aspect. Furthermore, in the experiment design, the goal is to provide new insights into the relation between distribution scenarios and the aforementioned trade-off.

3. Mathematical formulation

This section aims to present a formal definition of the Multi-Objective Vehicle Routing Problem with Time Windows dealing with Perishability (MO-VRPTW-P). The formulation and notation is based on the VRPTW formulation proposed in Cordeau, Desaulniers, Desrosiers, Solomon, and Soumis (2001).

The MO-VRPTW-P trades-off the optimal design of routes and the freshness state of the delivered products. A set K of identical fixed capacity vehicles indexed by $k = 1, \ldots, m$ initially located at a depot are available to deliver perishable food goods to a set N of customers $i, j = 1, \ldots, n$ through a set of arcs A. The number of vehicles m is enough to always guarantee a feasible solution. The VRPTW structure can be defined on a direct graph $G = (V, A)$ with $V = N \cup \{0, n+1\}$, where the depot is simultaneously represented by the two vertices 0 and $n+1$ and, therefore, $|V| = n+2$. Each possible arc (i, j) has an associated time and cost that is related to the euclidean distance of the vertices that it connects to. Each customer has a demand that needs to be satisfied for a certain number of products. Without loss of generality, these products are of identical size, and they have different deterministic shelf-lives. It is assumed that as soon as the vehicle departs the depot, all products that it is carrying are at their maximum freshness. Moreover, customers want their requests available within a strict time window and they need a certain time to be served. From a modelling point of view we will just account for the shelf-life of the products within a customer order that deteriorate the most. Thus, by maximizing the freshness of the products delivered, it is ensured that the worst case is tackled for each customer and, therefore, all the other products still have some remaining shelf-life when delivered.

A feasible solution for this problem implies a collection of routes that correspond to paths starting at vertex 0 and ending at vertex $n+1$. These routes have to ensure that each customer is visited exactly once satisfying simultaneously its demand and time window. Furthermore, it is not admissible that any of the

Table 1
Comparison of the VRP related works dealing with perishability.

Author	VRP-type	Number of Obj.	Perishability behaviour	Products	Solution method	Instances
Chen et al. (2009)	STW	1	Random	Multiple	Heuristic	Solomon (1983)
Osvald and Stirn (2008)	HTW; TD	1	Deterministic	Single	Heuristic	Solomon (1983)
Hsu et al. (2007)	STW; TD	1	Random	Single	Heuristic	Tailor-Made
This paper	HTW	2	Deterministic	Multiple	MOEA	Solomon (1983)

STW: soft TW, HTW: hard TW, TD: time dependent travel time.