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Analysis, modeling and solution of the concrete delivery problem

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Abstract

This paper describes a specific local search approach to solve a problem arising in logistics which we prove to be NP-hard. The problem is a complex scheduling or vehicle routing problem where we have to schedule the tours of concrete mixer vehicles over a working day from concrete-producing depots to concrete-demanding customers and vice versa. We give a general mixed integer programming model which is too hard to solve for state of the art mixed integer programming optimizers in the case of the usually huge problem instances coming from practice. Therefore we present a certain local search approach to be able to handle huge practical problem instances.

Keywords: Ready-mix; Ready-made; Concrete; Vehicle routing; Vehicle scheduling; Concrete delivery; Concrete distribution

1. Introduction

Scheduling concrete mixer vehicles to deliver concrete from concrete-producing depots to concrete-demanding customers introduces some new combinatorial challenges from the viewpoint of traditional vehicle routing and scheduling problems. Besides the sheer size of usual practical problem instances of the concrete-producing/delivering industry we have to take into account constraints and properties that are not considered in standard vehicle routing and scheduling problems.

Most of the additional constraints necessary come directly from the material to deliver. Ready-mixed concrete is a perishable product, which has several ramifications for our problem. First, concrete may only reside in the concrete mixer vehicle for a certain amount of time before it looses quality for the customer and eventually hardens and can even destroy the barrel resulting in disproportional maintenance costs. Second, it is not advisable that vehicles transport a non-full load of concrete, because this could result in an increased rate of hardening of the concrete. This property prevents delivering concrete to more than one construction site before refilling the vehicle at a depot (delivering more concrete to a construction site than the demanded amount poses usually no problem or costs). Finally, if more than one delivery of concrete is necessary to satisfy the demand of the corresponding customer then the temporal spacings between the consecutive deliveries may not exceed certain limits (time lags) as the concrete could partially harden at the construction site before the subsequent supplies arrive.

Besides above mentioned complications for the scheduling part directly induced by the perishability of concrete, typical concrete delivering scenarios differ further from standard vehicle routing problems in the following aspects. Usually, we cannot expect total homogeneity of the vehicles. In our considered practical applications the available vehicle fleet contains concrete mixer vehicles capable of only transporting 2 m^3 of concrete to vehicles that can deliver 8 m^3. The demands of construction sites often exceed the vehicle capacities and thereby require chains of subsequent deliveries. Furthermore, there exists usually more than one depot and there is enough concrete demand

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during a given working day calling for decisions from which depot to deliver to which customer.

Altogether we have a highly complex scheduling problem at the intersection of several research areas, such as logistics, supply chains and just-in-time production. We will try to investigate the concrete delivery problem in a general form, but still being able to solve problem instances coming from practice. For this aim this paper is organized as follows. In Section 2, we will give a short review on existing papers on the subject. From Section 3 on we will formulate a general model of the concrete delivery problem by first defining a notation for the input parameters of the problem. Section 4 continues with the definition of a network flow model based on the input data and results eventually in a mixed integer programming model (MIP) which describes formally the general concrete delivery problem that we consider and could be used to solve such problem instances. In Section 5 we present a certain general local search approach, which we utilize to solve our problem in Section 6. The paper finishes in Sections 7 and 8 where the computational results are given and conclusions drawn.

2. Related work

The logistical problems arising in concrete delivery seem to represent a rather young research field. Following are most publications in this area that are known to us.

Durbin researches in his dissertation [6] the concrete delivery problem both practically and theoretically. The result is a decision support system which is used in practice and incorporates different models described in his thesis. The problem he considers is a special case of ours as it assumes homogenous vehicles. He mostly uses time-space networks as foundation of the MIP models which contain time-fixed but different possibilities of deliveries.

In [11], Naso et al. give a non-linear model for a rather general concrete delivery problem, which they solve using genetic algorithms.

Feng et al. study in [7] a concrete delivery problem with a single depot arising in Hong Kong. The problem is also solved with genetic algorithms.

Matsatsinis investigates in [10] mainly another aspect of concrete delivery which we do not consider here, the routing of pumps, which is basically a multi-depot vehicle routing problem with time windows. In this problem, besides the concrete deliveries, some customers need a pump on the construction site for the time of the deliveries. These pumps need to be routed alongside the concrete deliveries, so that when the deliveries arrive at the customers a pump is already set up there.

Finally, Tommelein and Li explain in [13] concepts underlying a just-in-time production system with the example of concrete delivery, "which is a prototypical example of a just-in-time construction process". In contrast to the preceding publications, this one does not have an operations research focus and is rather conceptually motivated, but covers some interesting aspects of the practical problem.

So far it is not surprising that mostly heuristical methods have been investigated in the rather short scientific history of concrete delivery research, because the problem instances arising in the real world are huge and the theoretical problem itself is very complex.

3. Problem parameters and notation

Since the concrete delivery problem that we consider is similar to the vehicle routing problem with time windows (VRPTW), we have based our notation especially on [5], which contains the prevalent notation for VRPTW problems (for an overview over VRPTW problems and the plethora of algorithms we refer to [3,4] besides the aforementioned paper). Thus, we will simply call the concrete mixers just *vehicles* and the construction sites *customers*.

We consider a static model where all data are available at the beginning of the working day. The *working day* is a (possibly but not necessarily integer) time interval $T = [\tau_1, \tau_2]$. All times of the model have to be contained in this set. At the beginning of the working day there are sets $C = \{C_1, \ldots, C_n\}$ of n concrete-demanding *customers* and $D = \{D_1, \ldots, D_m\}$ of m concrete-producing *depots*. To deliver the concrete from the depots to the customers the vehicle fleet $K = \{K_1, \ldots, K_p\}$ of p *vehicles* can be used. Every vehicle $k \in K$ starts its tour on the considered working day at location $O(k)$ and has to be at a (possibly different) location $F(k)$ at the end of the working day. The set O and F define the set of p *starting locations* $O(K_i)$ and *ending locations* $F(K_i)$, respectively. All of these customers, depots and starting and ending locations correspond to actual *locations* in the practical problem. The time it takes to move a vehicle between two of these locations and the related cost are obtained through the *travel time function* $t : (C \cup D \cup O \cup F) \times (C \cup D \cup O \cup F) \to \mathbb{Z}$ and the *travel cost function* $z : (C \cup D \cup O \cup F) \times (C \cup D \cup O \cup F) \to \mathbb{Z}$, respectively. We assume, that the functions t and z respect the triangle inequality and are vehicle independent up to a setup cost $\alpha(k)$.

All customers $c \in C$ have a positive *demand* (of concrete) $q(c) \in \mathbb{Q}^+$. If we do not deliver the full demand $q(c)$ to customer c *penalty costs* $\beta(c) \in \mathbb{N}$ accrue. Besides the travel time a vehicle arriving at customer c requires a service time $s(c) \in \mathbb{N}_0$ for parking, unloading, cleaning up the vehicle, etc. until the delivery is finished. Service times are mainly determined by the customer while different vehicles have no significant effect. We say vehicle k *supplies* customer c at time t synonymously to that the service time of vehicle k at customer c begins at time t. Deliveries to customer c have to respect a (hard) *time window* $[a(c), b(c)]$ of c. That means a delivering vehicle has to start supplying customer c in the time interval $[a(c), b(c)] \cap T$. The customer might also demand that the first delivery (supply) of the day must not start later than at time $b'(c)$ (*first delivery deadline*). Furthermore the customer can request that