Transportation Research Part E 112 (2018) 142–160

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

Rail transportation planning in the chemical industry

Thomas Kirschstein

School of Economics and Business, Martin-Luther-University, Gr. Steinstr. 73, 06108 Halle, Germany

ARTICLE INFO

Keywords:
Rail inventory routing
Chemical industry
Multi-commodity network flows
Rolling horizon
Feasibility pump

ABSTRACT

Rail transports of raw and intermediate materials are cornerstones in chemical logistics. In this paper a multi-commodity rail inventory transportation planning problem for chemicals is proposed. The aim is to generate transportation plans for chemicals and rail cars such that product demands are fulfilled and total logistics cost is minimized. To solve the problem, heuristics based on a rolling-horizon decomposition are proposed. A case study illustrates the applicability of the heuristics. The results show that near-optimal solutions can be generated quickly by the heuristics. Thus, an instrument is offered to transport managers which helps them to optimize chemical logistics processes.

1. Introduction

Large and medium-scaled chemical companies typically operate networks of chemical production sites. Within such networks chemicals are handled as raw, intermediate, or final products. Typically, vast quantities of chemicals have to be shipped between production sites as well as supplier and customer locations. While shipments to customers are often realized by truck, particularly raw and intermediate chemicals are primarily shipped via pipeline, ship, or rail as the shipment quantities are large and the demand is comparatively stable.

Since most large-scaled chemical production sites have waterway access, raw materials are typically supplied via ship transports, but intermediate and minor raw chemicals are often transported via rail e.g. because the distribution structure is disperse and/or not all customers/suppliers have waterway access. Compared to pipeline and ship, rail transports are more flexible but require more organizational and technical efforts. As shipments in chemical production networks are closely interrelated with production processes at the sites, large- and medium-sized chemical companies often own or rent rail car fleets in order to manage rail transports by themselves (Closs et al., 2003). As a consequence, at chemical production sites often a rail infrastructure exists to shunt rail cars, compose trains, and transfer chemicals. As most basic and intermediate chemicals are liquids or gases, so-called rail tank cars (RTC) are used for rail transportation. While the shunting and handling of RTCs at production sites is managed by the chemical companies, the transport processes are typically managed and operated by rail freight service providers.

Hence, for most chemical companies the question arises how to manage their RTC fleets efficiently. This includes to determine shipments of RTCs and chemicals between production sites as well as to plan the stock levels of RTCs and chemicals at the sites. Thereby, logistics costs are to be minimized given the limited capacities of the logistics system.

Therefore, the paper at hand proposes an inventory rail transportation model to generate transportation plans for chemicals and RTCs such that capacity constraints are met, chemical demands are fulfilled, and total logistics cost is minimized. As large instances of the outlined planning problem turn out to be difficult to solve to optimality by standard solvers like CPLEX, tailor-made heuristics are proposed. The performance of CPLEX and the proposed heuristics are evaluated by means of computational experiments based on a real-world case study. The computational experiments shed light on the performance of all solutions approaches under different

---

E-mail address: thomas.kirschstein@wiwi.uni-halle.de.

https://doi.org/10.1016/j.tre.2018.01.001
Received 7 June 2017; Received in revised form 28 November 2017; Accepted 1 January 2018

conditions. Hence, decision makers are able to identify the most suitable solution approach depending on the structure of a problem instance.

The paper is organized as follows: The relevant literature is reviewed in Section 2 followed by the problem description outlined in Section 3. Section 4 formulates the problem as a capacitated fixed-charge, multi-commodity network design model. Afterwards, heuristics are described in Section 5 which are evaluated by computational experiments described in Section 6. The paper finishes with a conclusion.

2. Literature review

The planning problem introduced above bears characteristics of inventory routing problems (IRP). Andersson et al. (2010) provides a comprehensive overview on industrial applications of IRPs. It is pointed out that no literature on rail IRPs could be found. This is because in a rail IRP no vehicles (offering transport capacity) are to be tracked over time as in traditional IRPs. In contrast, transport capacities are offered by rail cars such that the vehicles (i.e. trains) have a variable capacity. As rail car transports have to be planned along the product flows, it is more appropriate to call the outline problem a rail inventory transportation problem (RITP). Within the class of IRPs, maritime inventory routing problems (MIRPs) are the most similar to the RITP. MIRPs often occur in similar industries (like chemical or oil producing industry). Moreover, the management of ship and train transports is quite similar: Both are means of mass transportation, require specialized infrastructure for loading and unloading, and are capable of multi-product transportation (e.g. in contrast to chemical trucks).

There is a rich body of literature on MIRPs starting with industrial case studies (Christiansen and Nygreen, 1998; Ronen, 2002) which is still growing. Basically, modeling approaches can be distinguished into discrete and continuous time models. For the former class see e.g. Agra et al. (2013a,b), Rakke et al. (2011), Ronen (2002), Song and Furman (2013) and for the latter see Agra et al. (2014), Al-Khayyal and Hwang (2007), and Siswanto et al. (2011). Typically, MIRPs are modeled based on vehicle routing problems enhanced by inventory balancing constraints where the core component is the transporter offering transport capacity. In general, MIRPs are particularly difficult to solve because comparatively large but few ships are available. Moreover, traveling times are typically long. Meeting demand requires careful planning which is even more complicated when storage and transport capacities are limited. Thus, even finding feasible solutions is often difficult (see e.g. Agra et al., 2013b).

In rail transportation a more complex situation is met since rail transportation is a complementary task requiring traction (i.e. locomotives) and carriers (i.e. RTCs). The traction is usually provided by a rail operator who is also responsible for the detailed routing and scheduling of rail transports. The rail cars, on the other hand, are often provided and managed by the shippers such that detailed routing and scheduling decisions can be separated from the distribution and inventory management decisions.

Rail operators offering freight transport services often face a similar distribution and inventory management problem as the shippers of chemicals. Problems of this kind are called “empty rail car distribution problems” (Du and Hall, 1997) where a set of (empty) rail cars is to be re-positioned among a set of rail yards to meet incoming transport orders subject to the available set of locomotives and transport relations. Such problems are typically formulated as multi-commodity network flow models (see e.g. Du and Hall, 1997; Holmberg et al., 1998, 2008; Joborn et al., 2004; Narisetty et al., 2008; Wang et al., 2008). Here, discrete time intervals are used to model the temporal and spatial dimension of the system under study. Transportation times are reflected by a number of time intervals which elapse during the shipment. Obviously, this is a notable simplification of real-world conditions and a drawback of all time-discrete models. In this case, however, the simplification does not severely interfere the modeling since traveling times in trans-regional rail freight networks are typically quite long. Time intervals are often set to 24, 12, or 8 h (Newman and Yano, 2000). Additionally, integrating demand and rail car handling procedures further complicate the problems. Lawley et al. (2008) proposes a discrete time-space network flow model for recurring bulk rail car deliveries. Here, rail car transport demands have to be fulfilled considering transport times as well as limited train and handling capacities. However, the goods themselves and their corresponding stocks are not considered explicitly. Similarly, Gedik et al. (2014) considers travel times as well as time-varying track segment capacities and rail yard capacities to determine optimal train flows in a rail network with capacity disruptions. A stochastic rail car fleet sizing and allocation problem is addressed by Milenković et al. (2015). Here, given the stochastic demand of rail transport orders, an optimal size and allocation of different types of rail cars is to be found considering rail yard capacities and (partially) interchangeable rail cars. A case study from chemical industry for a tactical rail car fleet sizing problem is provided by Kallrath et al. (2017). Here, it is to decide about the optimal number and size of rail car fleets based on a given set of transport orders. A MINLP is proposed which could be solved for up to 3 rail car types. For larger fleets of up to 5 rail car types a linearized version of the MINLP is used.

The problem proposed here differs from related rail transportation problems as it explicitly considers the stocks of multiple commodities to be transported. Besides, it takes into account time-varying rail yard and train capacities. In contrast to IRPs, it is not necessary to model the routes of trains. However, block trains with limited capacity w.r.t. weight and length are booked at fixed charges. Moreover, the RTCs used for transportation are limited and need to be repositioned in order to satisfy demands. All together, a challenging optimization problem results which can be labeled as a fixed-charge, multi-commodity rail inventory transportation problem (FC-MC-RITP).

3. Problem description

In the following, we assume a network of chemical production sites which are interconnected by rail links. At the production sites, a set of chemicals is handled, i.e. they are produced and/or consumed such that a net deficit or surplus for each chemical at each site