Int. J. Production Economics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at SciVerse ScienceDirect

Int. J. Production Economics

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

Rail car fleet design: Optimization of structure and size

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ARTICLE INFO

Article history:
Received 3 September 2012
Accepted 1 May 2013

Keywords:
Fleet management
Fleet structure
Inventory
Safety stock

ABSTRACT

We develop a model to determine the optimal structure and size of a rail car fleet at a chemical company under uncertainty in demand and travel times as well as substitution between rail car types. First, we formulate an MILP model that accounts for the substitution relations between the types and minimizes the total direct rail car cost under given rail car availability constraints and a predefined maximum number of types. Second, based on the fleet structure obtained by the MILP model, the fleet size is computed by using an approximation from inventory theory that considers the existing uncertainties. Compared to the current approach of the rail car fleet management team, the model produces a reduction in safety stock of 120 rail cars and thus direct cost savings of 8% as well as further indirect cost savings due to a smaller number of rail car types, which reduces the switching effort of the rail cars on the storage tracks.

1. Introduction

In the chemical industry, rail cars represent an important means of transportation. Due to safety regulations many products are not allowed to be transported on the road. Moreover, rail cars can carry larger volumes than trucks. The product poses minimum requirements on a rail car with respect to material, valve model, heating, etc. The combination of these characteristics specifies a certain rail car type and determines its cost. Types with higher quality characteristics can be used as substitutes for lower ones and thus are more flexible.

At the company, which motivated this research, the task of the rail car fleet management team is to secure the supply with rail cars of an appropriate type while at the same time solve the trade-off between (i) minimizing the direct cost for rail cars and (ii) minimizing the number of different rail car types. The latter aspect is relevant because the smaller the set of rail car types, the easier it is to access a requested type on the storage tracks due to a sorted parking strategy. As the number grows, space limitations require a chaotic parking strategy, which increases the switching effort and thus causes higher indirect costs. Further, the smaller the set of types, the lower the required safety stock due to a larger risk pooling effect. These benefits have to be traded off against the higher costs for more flexible types.

Over the last decade, the fleet management team has invested considerable effort to reduce the overall cost and free up storage space on the site. In a first analysis of the rail car fleet, old and seldomly used types that could be easily replaced by others have been discarded. Thus, the number of so-called standard rail cars (which we will be focusing on in this paper) has been reduced from approximately 2600 to 1800. Similarly, the number of standard rail car types has been reduced from approximately 100 to 60. These tremendous improvements have been made possible through hard work, but without any support from sophisticated mathematical models. To realize further improvement and be well prepared for the future, management felt that such models are required.

In the light of the growing future business trend the rail car demand is expected to increase as well. Despite the already implemented reforms, it will not be feasible to meet these demands with the current order-filling strategy and structure of the rail car fleet. The limited space on the site simply hampers an increase in the number of cars. Moreover, as part of a new strategy the company considers to increase its rail car ownership. This is based on the insight that owning a rail car is much cheaper than leasing one, if the usage period is sufficiently large. It takes about 10 years for the investment in a rail car to amortize. In order to make a suggestion with regard to which types of rail cars to buy (*fleet structure*) and in which quantity (*fleet size*), a second thorough quantitative analysis is required.

In this paper we present the outcome of this second analysis. Together with the fleet management team mathematical models have been developed that take into account the existing trade-offs and are used as decision support for designing the rail car fleet.

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0925-5273/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ijpe.2013.05.008

This analysis is based on a new approach which combines mixed integer linear programming (MILP) models supporting substitution between the different rail car types with techniques used in inventory management theory to derive safety stocks in order to account for the existing uncertainties in demand and travel times of the rail cars.

The remainder of the paper is structured as follows. In Section 2, we briefly review the literature. The mathematical models are developed in Section 3. In Section 4, we apply the models to the real-world problem data. We conclude the paper in Section 5.

2. Literature review

Research on fleet sizing and structuring started in 1950s with deterministic models. Dantzig and Fulkerson (1954) determine the minimal number of tankers to meet a fixed schedule. Further research by Gertsbach and Gurevich (1977) and Ceder and Stern (1981) has led to the derivation of the well-known fleet size formula. While these deterministic models emphasize the spatial structure of the problem, the stochastic nature of demand and travel times is neglected.

The latter aspects are considered in Koenigsberg and Lam (1976), Parikh (1977), and Papier and Thonemann (2008), who make use of queueing models to account for the uncertainties. Koenigsberg and Lam (1976) analyze the effect of the fleet size on the mean delay time in a gas vessel cycle between two sea ports. Based on an $M/G/c$ queueing model, Parikh (1977) determines the optimal structure of a rail car fleet such that the service levels of all rail car types are nearly identical. Papier and Thonemann (2008) use an $M^x/G/c/c$ queueing model to explicitly account for customer order batching as well as seasonal demand.

List et al. (2003) formulate a large stochastic programming problem to determine the optimal fleet size under uncertainty in demand, travel times, and further operational aspects. Due to its complexity, the model easily becomes intractable for large problems, however.

Besides the pure fleet-sizing problem, several authors address the interdependency between the fleet size and the management of empty and loaded vehicle flows (see, e.g. Beaujon and Turnquist, 1991; Cheung and Powell, 1996; Wu et al., 2005, and references therein). Due to the complexity of the problem, most works assume either deterministic demand or deterministic travel times in order to obtain a solution. For the solution of a stochastic version of the problem, Köchel et al. (2003) propose a simulation optimization approach.

In the application that motivated this research, we also face stochastic demand and travel times as well as customer order batching. In addition and in contrast to the previous works (except for Wu et al., 2005), substitutions between different rail car types are possible. This prevents us from directly applying any of the existing above-mentioned approaches. Through the substitution aspect the problem is also related to transshipment models in inventory theory. The possible upward substitution between different rail car types can be interpreted as a unidirectional lateral transshipment as explained and analyzed in, e.g. Axsäter (2003) and Olsson (2010). For a general overview on transshipment models see Paterson et al. (2011). However, those models do not readily fit either for the following reasons. They make certain assumptions with respect to the lead (travel) times or the demand arrival process, which are not satisfied in our real-world problem setting. Most importantly, however, they rely on enumerative solution methods, which for our real-world problem size with up to 20 substitution possibilities, are prohibitively time consuming.

Therefore, we develop a different solution approach, which is easier to solve in our view, but still accounts for all relevant problem aspects. We use a combination of deterministic MILP models and stochastic models originating in inventory management theory. In the deterministic part of our model we account for the substitution possibilities. The outcome of this first solution step is the fleet structure. Based on the deterministic solution, the existing uncertainties concerning demand and travel times are dealt with in a second step, the fleet-sizing part of the model, which is based on an approximation from inventory theory.

3. Model

3.1. Problem description and notation

The goal of the analysis is to provide a suggestion for the "optimal" design of the rail car fleet. As such, the planning problem is tactical/midterm in nature rather than operational/shortterm. The focus is not on how to reach a close-to-optimal solution as fast as possible and provide a detailed implementation plan. It is on what the "optimal" solution looks like in the first place. Therefore, the current rail car fleet design of the company can be neglected in the analysis, i.e. we basically assume that we can design the fleet from scratch.

When deciding about the structure and size of the fleet, the fleet management team has to consider and trade off various aspects. First, the supply of the appropriate rail cars needs to be secured. In terms of the mathematical model, this aspect translates into the requirement that (i) all orders within the planning horizon are to be satisfied in a deterministic model formulation or (ii) a high level of service needs to be provided in a stochastic inventory model formulation.

Second, this service is to be achieved at the lowest possible cost. For each rail car of a certain type, we have a specific direct cost. This cost is incurred once for the entire planning horizon, if the rail car is used at all irrespective of the actual timespan that it is in use. This kind of modeling appropriately reflects the majority of the existing leasing contracts.

Third, not only the direct costs for rail cars are to be minimized, but also the number of different rail car *types* is to be kept at a low level in order to save indirect costs. Due to space restrictions, a large number of different types requires a chaotic parking strategy on the storage tracks. This causes a considerable switching effort for providing rail cars of a certain type. A reduction in the set of types to only a few would enable a sorted parking strategy where each type is parked on a separate track facilitating the handling. In addition, a type reduction also has a positive effect on the direct rail car cost. The risk pooling effect can be exploited to a larger extent, which results in a lower overall safety stock requirement.

Fourth, substitution between different rail car types is feasible. The transported product poses minimum requirements on certain rail car characteristics (material, valve model, heating, etc.). These characteristics define a rail car type. Types with higher quality characteristics can be used as substitutes for lower ones and thus are more flexible. On the other hand, a more flexible type is more expensive, in general. This flexibility aspect is very important when it comes to the structuring and sizing of the fleet.

Fifth, due to market restrictions not all rail car types are available in an unlimited quantity. Some types are no longer produced or are very expensive to produce. Therefore, only the number of rail cars currently circulating in the market is considered "available".

Before we develop an optimization model that takes all of the above-mentioned aspects into account, we first describe the current planning and execution approach of the fleet management