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A mathematical model of inter-terminal transportation

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ABSTRACT

We present a novel integer programming model for analyzing inter-terminal transportation (ITT) in new and expanding sea ports. ITT is the movement of containers between terminals (sea, rail or otherwise) within a port. ITT represents a significant source of delay for containers being transshipped, which costs ports money and affects a port's reputation. Our model assists ports in analyzing the impact of new infrastructure, the placement of terminals, and ITT vehicle investments. We provide analysis of ITT at two ports, the port of Hamburg, Germany and the Maasvlakte 1 & 2 area of the port of Rotterdam, The Netherlands, in which we solve a vehicle flow combined with a multi-commodity container flow on a congestion based time–space graph to optimality. We introduce a two-step solution procedure that computes a relaxation of the overall ITT problem in order to find solutions faster. Our graph contains special structures to model the long term loading and unloading of vehicles, and our model is general enough to model a number of important real-world aspects of ITT, such as traffic congestion, penalized late container delivery, multiple ITT transportation modes, and port infrastructure modifications. We show that our model can scale to real-world sizes and provide ports with important information for their long term decision making.

1. Introduction

Around the world, ever larger ports are being constructed to keep up with the growth of containerized shipping. Ports routinely contain multiple terminals serving container ships, railways, barges and other forms of hinterland transportation. Containers are often transferred between terminals when they are transshipped between different modes of transportation. The movement of containers between terminals, which is called *inter-terminal transportation* (ITT), represents not only an operational problem for port authorities and terminal operators to deal with, but also a strategic one to be considered during the planning of new terminals and container ports.

The correct choice of the layout of terminals and the transportation connections between them, as well as vehicle type and the number of vehicles, represent expensive and critical decisions that ports must make. The goal of an efficient ITT system is to minimize the delay of containers moving between terminals, so as to reduce and, ideally, eliminate the delayed departure of containers. To this end, we introduce an optimization model based on a time–space graph to determine optimal flows of vehicles and containers in ITT scenarios in order to assist port authorities in their decision making process.

We use an abstract view of ITT operations using a time–space graph with maximum arc capacities and node throughput to model vehicles as flows through the network with transportation demands given as a multi-commodity flow. We focus on minimizing the overall delay experienced by containers, an important consideration for port planners, as the costs of delaying outgoing shipments are usually very high.

Previous work in the area of strategic analysis of ITT primarily deals with simulating inter-terminal operations at the Maasvlakte area of the port of Rotterdam and analyzing the resulting delay of the pickup and delivery of containers (Ottjes, Duinkerken, Evers, & Dekker, 1996, 2006, Duinkerken et al., 2006). In contrast to this work, we optimize the flows of containers through the network in order to provide port planners with a better estimation of the cost of using particular vehicles, roadway designs, new infrastructure or traffic planning. Thus, this paper provides the following novel contributions:

1. the first fully defined mathematical model of ITT,
2. two exact approaches for minimizing ITT delivery delay,
3. congestion modeling in the setting of vehicles servicing a multi-commodity flow.

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This paper is organized as follows. We first provide an overview of ITT in Section 2, followed by a brief literature review in Section 3. We then present our mathematical model in Section 4, as well as our method for constructing the time–space graph and a two-step solution approach for solving our integer programming (IP) model. We provide computational results in Section 5, showing that our model not only provides useful information about ITT, but also that it can be computed by CPLEX in a reasonable amount of time. Finally, we conclude in Section 6 and discuss directions for future work.

2. ITT

ITT involves the movement of containers between terminals in a port. There are several types of terminals, including waterside terminals that have a quay where container ships and barges can dock and transfer containers, rail terminals where containers can be loaded onto rail cars, as well as hinterland terminals which can be set far inland and deal with barge, rail or truck transportation. ITT traffic generally consists of either sea-to-sea transportation, i.e., containers being transshipped between vessels, or land-to-sea/sea-to-land transportation, in which containers originating from overseas (the hinterland) are carried to (from) the hinterland by another mode of transportation such as a barge or train.

At first glance, ITT might seem avoidable, either through scheduling container vessels that will transship containers to arrive at the same terminal, or by placing key logistics components of a port all in the same location. However, in nearly every mid to large sized port some amount of ITT is required, due to the fact that avoiding ITT would involve building rail, barge, and container ship connections all in one place, and there simply is not enough space.

There are, therefore, two important problems within the topic of ITT. The first is the purely operational problem of dispatching and routing vehicles to move containers between terminals on a day to day basis in an already constructed port. The second problem is a strategic planning problem for new ports and the expansion of existing ports, which involves several key questions:

1. Is the planned infrastructure sufficient to handle ITT forecasts?
2. What types of vehicles and how many of them are necessary to handle ITT containers?
3. What kind of delays will be experienced, on average, given a particular infrastructure and vehicle configuration?

In this paper, we provide an optimization model that assists in answering these questions, as well as supports port and terminal authorities in examining the impact of new infrastructure, such as tunnels or bridges, on the overall delay experienced by ITT containers. Thus, while we primarily address the strategic planning issues, our model is also capable of dispatching and routing vehicles in the operational problem at a high level.

2.1. Vehicle types

We consider a range of types of vehicles for ITT that each comes with pros and cons that must be evaluated by decision makers.

2.1.1. Automated Guided Vehicles (AGV)

AGVs are driverless vehicles that can carry up to one forty-foot container or two twenty-foot containers, and have no lifting capabilities of their own. This means that AGVs require cranes for (un) loading operations. Current AGV systems are only allowed in areas where there are no humans in order to prevent accidents. However, this is likely to change as safer AGVs are developed.

2.1.2. Automated Lift Vehicles (ALV)

ALVs, like AGVs, are also driverless vehicles that can carry two twenty-foot containers or one forty-foot container. As their name implies, ALVs have lifting capabilities and do not require external assistance to transport containers. This makes ALVs significantly more versatile than AGVs. However, they generally travel slower.

2.1.3. Multi-Trailer System (MTS)

MTSs consist of several container carrying trailers, that can generally transport up to five 40-foot containers. MTSs require cranes to load them as in the case of AGVs. MTSs are not automated and require a human to drive a tractor unit that pulls the trailer. While this allows more flexibility in the places an MTS can travel, the coupling time of the tractor unit to the trailer can result in a slower turn-around time for the vehicles than AGVs or ALVs. This process is described in detail in Duinkerken, Dekker, Kurstjens, Ottjes, and Dellaert (2006).

2.1.4. Barges

Barges can be used to transport large quantities of containers between terminals all at once and are driven by humans. Barges are loaded slowly and travel slowly, but have an advantage over road vehicles in that waterways tend to offer shorter connecting distances between terminals than roads, as well as being less congested. Additionally, barges have high capacities in comparison to land based vehicles, and are generally able to carry 40–50 containers.

2.2. Infrastructure

In order to solve the steep logistical challenges of ITT as container volumes around the world substantially increase, new infrastructure ideas must be considered. The construction of ropeways, monorails, dedicated lanes, tunnels and bridges to connect ports to shunting yards/hinterland logistics centers or to avoid bottlenecks could provide answers for effective ITT. For example, the cost of tunnels and ropeways were considered for connecting the port of Hamburg to hinterland transportation depots in Daduna, Stahlbock, and Voß (2012). Although ropeways using current engineering technology were found to be infeasible to carry the weight of fully loaded containers, it shows that with new ideas come new challenges for evaluating their effectiveness. Our goal is to be able to take any potential infrastructure change into account in a general model.

3. Literature review

Copious studies simulate and optimize container movements within container ports and terminals; see (Steenken, Voß, & Stahlbock, 2004; Stahlbock & Voß, 2008a). A particular focus has been placed on intra-terminal simulation and optimization (see Angeloudis & Bell (2011) for an overview), considering primarily AGV and ALV dispatching and routing (e.g. Briskorn & Hartmann, 2006; Grunow, Günther, & Lehmann, 2007; Nguyen & Kim, 2009; Jeon, Kim, & Kopfer, 2010). AGVs and ALVs were compared in Vis and Harika (2005) to determine which could be used to unload ships fastest, with ALVs being shown to require less overall vehicles and cost. Vehicle dispatching within a container terminal has been considered in, e.g., Bish et al. (2005), Lee, Chew, Tan, and Wang (2010), and as an integrated component of unloading vessels in Chen, Langevin, and Lu (2013). A comprehensive review on vehicle routing applications on container terminals can be found in Stahlbock and Voß (2008b). A handbook on terminal planning is Böse (2011).

Intra-terminal transportation is characterized by its short distances and lack of external traffic interaction. This stands in sharp