Impact and relevance of transit disturbances on planning in intermodal container networks

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ABSTRACT

An intermodal container transportation network is being developed between Rotterdam and several inland terminals in North West Europe: the EUROPEAN GATEWAY SERVICES network. This network is developed and operated by the sea terminals of EUROPE CONTAINER TERMINALS (ECT). To use this network cost-efficiently, centralised planning by the sea terminal of the container transportation is required. For adequate planning it is important to adapt to occurring disturbances. In this paper, a new mathematical model is proposed: the Linear Container Allocation model with Time-restrictions (LCAT). This model is used for determining the influence of three main types of transit disturbances on the network performance: early departure, late departure, and cancellation of inland services. The influence of a disturbance is measured in two ways. The *impact* measures the additional cost incurred by an updated planning in case of a disturbance. The *relevance* measures the cost difference between a fully updated and a locally updated plan. With the results of the analysis, key service properties of disturbed services that result in a high impact or high relevance can be determined. Based on this, the network operator can select focus areas to prevent disturbances with high impact and to improve the planning updates in case of disturbances with high relevance. In a case study of the EGS network, the impact and relevance of transit disturbances on all network services are assessed.

Keywords: Intermodal planning, synchromodal planning, container transportation, disturbances

1 INTRODUCTION

In this paper, the effects of disturbances on the operational planning of container transportation in an intermodal network are studied. The *impact* is proposed as a measure for the severity of a disturbance. It measures the additional cost incurred by an updated planning because of the disturbance. Based on the properties of services with high impact, the network operator can focus on these types of services to prevent disturbances with high impact. The *relevance* measures the cost difference between a fully updated and a locally updated plan. Disturbances that show a high relevance must be handled with full updates as much as possible, whereas in the case of disturbances with low relevance, a local update of the planning suffices. These measures will be used to assess transit disturbances in a case study of the EGS network in North-West Europe. The concepts of container networks and the planning of intermodal container transportation will be introduced here[1], before outlining the contribution of this paper.

1.1 Development of Container Networks

A tendency of more integrated supply chains has sparked initiatives in North-West Europe to create inland transportation networks for containers (Groothedde *et al*., 2005, Van der Horst and De Langen, 2008, Lucassen and Dogger, 2012, Rodrigue and Notteboom, 2012, Port of Rotterdam, 2012). These container transportation networks are generally formed via cooperation between multiple barge service operators, rail service operators, and terminals. Veenstra *et al*. (2012) introduced the concept of an *extended gate*: a dry port for which the seaport can choose to control the flow of containers to and from that inland terminal. This control by the seaport distinguishes the extended gate from a dry port as defined by Roso *et al*. (2009) and introduces a central management for the intermodal container network. One driver for this development is the requirement for deepsea terminals in the port of Rotterdam to reduce trucking and to change the modal split of trucking/barge/rail from 55/35/10 in 2010 to 35/45/20 in 2035 (Port of Rotterdam, 2011). The extended gate concept has been implemented in the EUROPEAN GATEWAY SERVICES (EGS) since 2007, a subsidiary of EUROPE CONTAINER TERMINALS (ECT) that operates three deepsea terminals in Rotterdam. The network consists of these three terminals in Rotterdam and an increasing number of inland terminals in North-West Europe.

This study focuses on the transportation from the seaport terminal to a hinterland terminal (import) or vice versa (export), as organised by the seaport terminal. This is called *hinterland transportation*. In the network, the *intermodal transport* is carried out by three different *modes*: barge, rail and truck. Intermodal transportation is defined as *Multimodal transport of goods, in one and the same intermodal transport unit by successive modes of transport without handling of the goods themselves when changing modes* (UNECE *et al*., 2009). At terminals, containers can be switched from one transport mode to another. In this paper, an exchange at a terminal is called a *transfer*. Figure 1 shows a schematic view of three terminals. The figure shows five mode-specific *corridors* by which the terminals are directly connected. As multiple modes connect two terminals, multiple parallel corridors exist. Terminal A and C are indirectly connected via terminal B, and transport is possible using the corridors to B and then to C. A container that must be transported between A and C is part of the demand for the *connection* between A and C. The specific itinerary of a container, i.e. the services used, is called a *path*. Each of the used corridors is referred to as a *leg* of that path.

[1] adapted from earlier work by the authors (Van Riessen et al., 2013).

The *service* on a corridor between terminals is the movement of a vehicle from one terminal to another, travelling on a specific time and route. The number of services per time period on a certain corridor is called the *service frequency*. Here, the frequency denotes the number of services *per week* on a corridor.

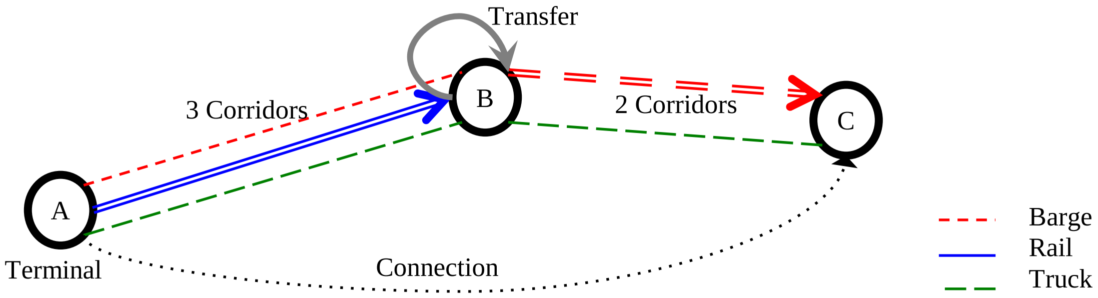


Figure 1. Container transport (schematic)

1.2 Planning of container network transportation

A driver for the development of transportation networks is to reduce cost by consolidating cargo on intermodal services. Crainic and Laporte (1997) signal that apart from low tariffs, customers also demand a higher quality of service. This quality of service consists of three parts: on-time delivery, delivery speed and the consistency of these aspects. As disturbances occur while executing the transportation, the transportation plan requires continuous adaptation. A central management of the network allows for central network planning. With *intermodal network planning*, the routing of containers with multiple consecutive services is possible, using intermediate transfers of the containers at network terminals. In this study the term *intermodal transfer* is used for a transfer between different modes. A container that has a path with two services uses such an intermodal transfer.

On top of intermodal planning, a network with centrally planned transportation can use *real-time switching* (Lucassen and Dogger, 2012). Real-time switching refers to changing the container routing over the network in real-time to cope with transportation disturbances, such as service delays or cancellations. The combination of these two aspects, intermodal planning and real-time switching, is referred to as *synchromodal planning*, a topic on the agenda of the Dutch *Topsector Logistiek* (2011). However, no unambiguous definition for synchromodality exists yet. In this research, synchromodality is considered as *intermodal planning with the possibility of real-time switching between the modes* or online intermodal planning.

In earlier work the authors studied the first part of synchromodal planning (Van Riessen *et al.*, 2013): the use of intermediate transfers in the intermodal planning. A new service network design model was formulated to consider the benefit of using additional corridors between inland terminals. It was shown that the use of paths with multiple consecutive legs and intermediate transfers reduced the transit cost by an equal amount as the increase in transfer cost. However, it was also shown that a reduction of the transfer price results in significantly more intermediate transfers and further reduction of transit cost.

In this paper we focus on the second part of synchromodal planning: the use of real-time switching. Occasionally, multiple services are disturbed simultaneously, e.g., because of snow, high water levels or strikes.However, this paper focuses on the more frequently occurring disturbances of single services, e.g., a train that is delayed because of shunting. Dealing with this kind of disturbances is daily practice for network planners. What type of disturbances must be prevented and how must containers be re-planned in case of a disturbance?

Not many models for the routing of containers in intermodal networks are available (Ziliaskopoulos and Wardell, 2000, Macharis and Bontekoning, 2004, Cho *et al*, 2010). Most existing approaches consider the routing of containers as a part of the more general network design problem. These models focus on static versions of the planning problem and do not have the possibility to incorporate online changes to the planning problem, nor do they allow us to measure the effect and size of a disturbance. This paper will present an alternative method that is able to quantify the effect of several types of disturbances. For that purpose, we propose a new model for finding the most cost-effective solution of the container transportation planning problem in the network: the Linear Container Allocation model with Time-restrictions (LCAT) and we propose a method to assess the effect of disturbances on the operational planning. The effect is quantified using two new measures: impact and relevance. The *impact* measures the additional cost due to the disturbance; a high impact indicates a disturbance that must be prevented. The *relevance* measures the difference in cost between an optimal planning update and a specific kind of local planning update; a high relevance indicates a disturbance that must be handled with a full update of the planning.

We focus on an operational planning level: the assignment of containers to services in a predefined service schedule. This planning level is in general carried out between 1-7 days before the time of departure of the transportation. Ideally, the central network-planning department could change the selected transit services for each container at any point in time. In practice however, some restrictions to the real-time changes in planning exist. Because of customs and port procedures, changes in the assignment of containers to a service can be made up to 6-9h before departure of that service.

1.3 Literature review

This section briefly reviews the relevant models in existing literature on the transportation planning of container networks (see Table 1). Several studies have been performed to find shortest or cheapest paths on a single container basis. The network is not optimised in general, but per order. Boardman *et al.* (1997) used a method that selects the cheapest path per container on a real-time basis. Ziliaskopoulos (2000) proposed a model that selects the least-time path, considering dynamic travel and transfer times. Cho *et al* (2010) used a weighted constrained shortest path problem to minimise time and cost for transports between two network nodes. These methods do not allow the network operator to do network-wide optimizations. Other studies use a network-wide optimization approach by modelling the transportation demand as flows through the network. Guelat *et al.* (1990) proposed a very general multi-commodity, multi-modal network flow model. There, each commodity represents the containers with a certain origin and destination. Crainic and Rousseau (1986) also proposed a multi-modal, multi-commodity network formulation. This type of model is the basis for the model proposed in this paper. A specific version of this type of model was also used by Caris *et al*. (2012) to design a barge service network. In that model, the goal is to select the optimal barge round trips between the port and the hinterland terminals, but their work is focused on small problem sizes (up to 3 inland terminals). Crainic and Kim (2007) provide a model for fleet management, referring to the problem of balancing empty containers. In these methods the transportation planning is a static sub problem of the network design and incorporating real-time disturbances is not considered. Some studies have explicitly focussed on the real-time influences on the operational planning, by incorporating these into the model. E.g., Ishfaq and Sox (2012) considered the effect of time-delays at hubs on the network performance, but this method does not provide methods for real-time planning updates. Our approach does not only measure the effect of a disturbance, but also provides the updated planning. In this study we compare the disturbance effect for two update methods: an optimal full planning update and a simple local planning update.

Table 1. Overview of existing container network models

	Objective	Method	Flows	Timing	Level
Boardman *et al.* (1997)	Lowest cost path per order	k cheapest paths (analytical)	Path	Pre-process k cheapest paths. Assign orders in real-time	Operational
Caris *et al*. (2012)	Minimise cost	Enumeration	Path	Offline	Tactical
Cho *et al.*(2010)	Lowest cost or shortest time	Dynamic programming	Arc	Offline	Operational
Crainic and Rousseau (1986)	Minimise cost	Optimal	Path	Offline	Strategic/ tactical
Crainic and Kim (2007)	Minimise cost	-	Arc	Rolling horizon	Strategic/ tactical
Guelat *et al.* (1990)	Minimise cost	Linear approximation approach	Path	Offline	Strategic
Ishfaq and Sox (2012)	Minimise cost	Heuristic	Arc	Offline	Strategic
Ziliaskopoulos and Wardell (2000)	Least-time route per order	Optimal	Path	Pre-process all shortest paths. Assign orders in real-time	Operational

1.4 Structure of the paper

The concepts of container networks and the planning of intermodal container networks were introduced in this section. The remainder of this paper is organised as follows. In Section 2, the LCAT model is presented. In Section 3 the methodology to determine the disturbance impact and relevance is introduced. The use of this method in a case study of the EGS network is subject of Section 4. The general implications of the case study are considered in Section 5. Finally, Section 6 gives the conclusion of the study.

2 PROPOSED MODEL

In this paper we propose a linear programming model that can be used to create an optimal solution of the container transportation planning problem in a network. The so-called Linear Container Allocation model with Time-restrictions (LCAT) is based on our earlier work (Van Riessen *et al.*, 2013) and has the following key characteristics: the model combines the allocation of containers to paths with capacity constraints on all corridors; the model allows for overdue delivery at a penalty cost; and, the model combines self-operated services with subcontracted transport. This model can be used to assess the effect of various disturbances in the network.

LCAT is solved offline, for a week of given demand of container transportation and a predefined service schedule. The demand of container transportation is categorised in cargo classes $c \in C$, based on the transport connection, mass category W_c, the time the container is available for transport $t^c_{\text{available}}$ and the due time t^c_{due}. The transport connection refers to the specific origin and destination for the demand.

For each connection, a set of suitable paths P_c is predetermined. The method to predetermine paths is independent of the mathematical model. Predetermining suitable paths could be done by listing all alternatives, by using expert knowledge or by another method. In this study an automated path generation method is used, based on a space-time graph of the service schedule, as described later in Section 3.1 The transit cost per TEU c_p , the number of transfers F_p and the time of departure and arrival T^p_D and T^p_A are known for each path.

LCAT uses two sets of decision variables: the number of TEU of cargo class c that is assigned to path p, denoted by x^c_p, and the number of TEU of cargo class c that is transported by a direct truck transport, denoted by v^c . Besides this, two sets of auxiliary variables are used: the number of TEU of cargo class c on service s, denoted by z^c_s, and the combined number of days that containers of cargo class c transported on path p are overdue, denoted by τ^c_p. With LCAT the objective J is formulated as:

$$J = \sum_{p,c} x^c_p \left(c_p + c_F F_p\right) + c_\tau \sum_{c,p} \tau^c_p + c^c_{dt} \sum_{c} v^c \,, \tag{1}$$

where the first summation represents the transit and transfer cost for the cargo classes c on path p, the second summation represents penalty cost of c_τ per TEU per day overdue, and the third term denotes the cost of direct trucking of cargo class c, with c^c_{dt} the cost per TEU of direct trucking cargo class c.

The total demand of cargo class c is denoted by d^c . This demand must be transported on one of the feasible intermodal paths or by direct truck. The cargo on the intermodal paths is translated to the number of TEU by mapping δ^p_s, which is equal to 1 if service s is part of path p or 0 otherwise. The maximum capacity of service s is denoted by u_s (TEU-capacity) and m_s (mass-capacity).

Objective J has to be minimised taking into account the following constraints:

$$v^c + \sum_p x_p^c = d^c \quad \text{for all } c \tag{2}$$

$$z_s^c = \sum_{p \in P_c} \delta_s^p x_p^c \quad \text{for all } c, s \tag{3}$$

$$\sum_c z_s^c \leq u_s \quad \text{for all } s \tag{4}$$

$$\sum_c W_c z_s^c \leq m_s \quad \text{for all } s \tag{5}$$

$$x_p^c T_D^p \geq x_p^c t_{\text{available}}^c \quad \text{for all } c, p \tag{6}$$

$$\sum_q x_p^c \left(T_A^p - t_{\text{due}}^c\right) \leq \tau_p^c \quad \text{for all } c, p \tag{7}$$

$$x_p^c, \tau_p^c, v^c, z_s^c \geq 0 \quad \text{for all } c, p, s \tag{8}$$

Here, constraint (2) ensures that all demand is met. By constraint (3), the auxiliary variable z_s^c is created. By constraint (4) and (5), the total number of TEU of the services is restricted to the available capacity. Constraint (6) ensures that a container is only planned on paths that depart *after* the time that the container is available: if the paths departure time $T_D^p \geq t_{\text{available}}^c$, then x_p^c can be any positive number. However, if $T_D^p < t_{\text{available}}^c$, than x_p^c has to be zero. Note that this time constraint is hard. Constraint (7) is the soft constraint for on-time delivery: τ_p^c measures the total number of days that containers of cargo class c on path p are late. Finally, constraint (8) is the nonnegativity constraint for the four sets of variables.

The next section will introduce the method in which the proposed model is used to determine the impact and relevance of disturbances in the network.

3 METHOD TO DETERMINE DISTURBANCE IMPACT AND RELEVANCE

The model proposed in the previous section is used in this paper to measure the effect of a disturbance on the operational planning. Three categories of disturbances are studied: late arrival, early arrival or cancellation of a network service. An experiment to determine the impact and relevance of a single disturbance consists of six steps (as seen in Figure 2):

1. Initialise experiment setting
2. Generate the sets of suitable paths P_c
3. Solve model (1)-(8) for an initial planning without any disturbances
4. Introduce a single disturbance and update the sets of suitable paths P_c
5. Solve the updated model twice: a full update and a local update
6. Determine *impact* and *relevance* of the introduced disturbance

The methodology used in step 2, path generation, and in step 5, solving the updated model, is described in more detail in Sections 3.1 and 3.2, respectively. Subsequently, the six step method is applied to determine the effect of disturbances in the EGS network in Section 4.

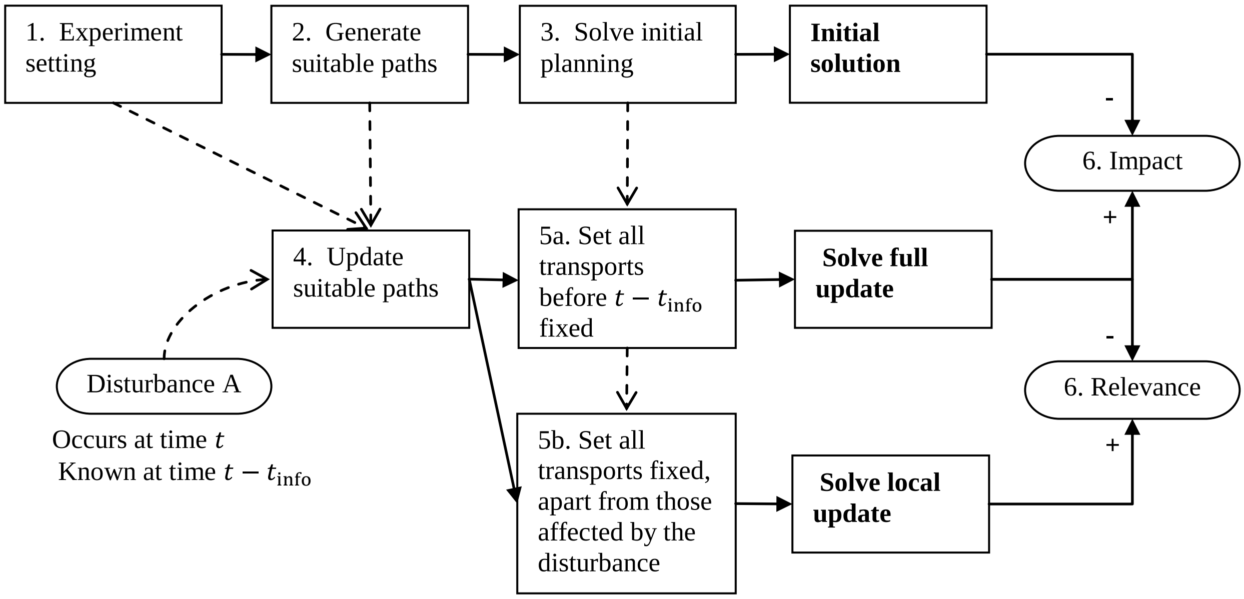


Figure 2. Schematic overview of the experiment setup

3.1 Path Generation

In earlier work we used a similar model that also required pre-processing the set of suitable paths (Van Riessen *et al*., 2013) for each cargo class. In that application, the set of suitable paths was using a shortest path method, based on the geographical arc lengths. So, all paths were determined in the space graph of the network. However, in the currently proposed model the planning is carried out on a specific service schedule. Hence, we require paths in the space-time expansion of the network and the service schedule. It is important that we do not miss relevant paths in our pre-selection, but the set must also be as small as possible, in order to limit the problem size and computation time. Several approaches could be used for generating the set of relevant paths: in existing networks, expert planners could denote all suitable container routes based on their practical knowledge. Or the model could use a list of all possible paths in the used service schedule. Alternatively, we propose to use an automated method to generate a relatively small set of paths P_c for each cargo class $c \in C$, using the following assumptions:

a) Only paths with a maximum of 3 legs are considered, as paths with more legs proved irrelevant (Van Riessen *et al*., 2013).
b) Paths with a detour of more than 10% in any of the transportation legs are ignored. This detour is measured as the difference in distance to the destination from both ends of a leg. Let T_{kD} denote the trucking distance from node k to the destination. Then, a path is considered to make a detour if $T_{iD} \geq 1.1T_{jD}$ in any of its legs (i, j). This rule is added to prevent paths with unrealistic detours; a little detour is allowed, though.
c) Only a leg directly to or from the hinterland terminal can be operated by truck. On intermediate legs containers can only be transported by barge or rail. This constraint is added as it does not make sense to make truck transfers. Note that direct trucking is modelled separately in the model; therefore it is not considered in the path generation.
d) Paths have a maximum duration of 8 days. In the case study, only commodities with a due time of 7 days or less were allowed, so, containers with a due time of 7 days could still be delivered 1 day overdue.

To generate the set of paths, the k shortest path method (Yen, 1974) was applied to a space-time graph of the network. Each node represents a barge or rail service; each arc (i, j) represents a feasible transfer from service i to service j at a terminal in the network. Each arc

(i,j) is assigned a value of $M + c_{\text{TEU},s}$, where $c_{\text{TEU},s}$ are the transit cost for one TEU on service s and $M$is a sufficiently large number. The method has generated all paths of three legs or less if the paths become larger than $4M$. After subtracting the multiple of M, the path lengths denote the transit cost. Subsequently, paths that do not comply with assumptions b)-d) are removed from the set and finally, the remaining paths are expanded with truck legs on the hinterland side, if applicable considering assumptions a)-d). For each path the transit cost per TEU c_p , the number of transfers F_p and the time of departure and arrival T_D^p and T_A^p are denoted. All cargo classes with the same origin and destination use the same set of suitable paths; the time restrictions are ensured separately in the model.

3.2 Solve updated model: full update and local update

In this study we consider the planning for one week. The solution of the model for one week network transportation planning is referred to as the initial solution, schematically shown in Figure 3a). The objective value of the initial solution as computed by (1) equals the cost of optimal operation of the network. This is denoted by $J^{\mathcal{I}}$ and the solution of the assigned containers is saved and referred to as $\acute{z}_s^c$.

In this study, we consider disturbances to barge and rail services: a late departure, an early departure or a cancellation. The estimated departure time of the service is denoted by t. A disturbance of service s is denoted by d_s. To handle an occurring disturbance, the planning has to be updated. This update can be calculated at the point in time where the information of the disturbance becomes available, denoted by $t - t_{\text{info}}$, where t_{info} denotes the *earliness of information*. The model can only consider cases where t_{info} is positive, i.e. where a disturbance is known in advance. The proposed model is aimed at the central network planning department, which can plan containers on a service up to 6-9h before departure. So, cases of incomplete information, i.e. were t_{info} is negative, are not considered.

We use two update methods in order to determine the impact and relevance. For both update methods, the set of suitable paths is updated in the same way: all paths with the disturbed service are removed and new paths using the disturbed service are generated, if possible. First, we consider the case where this update is determined optimally. This is considered a *full update*. To get the full update, all transports z_s^c departed before $t - t_{\text{info}}$ are set fixed to the values of the initial solution $\acute{z}_s^c$, indicated by the accent over z. These transports took place and cannot be rescheduled. This is shown schematically in Figure 3c).

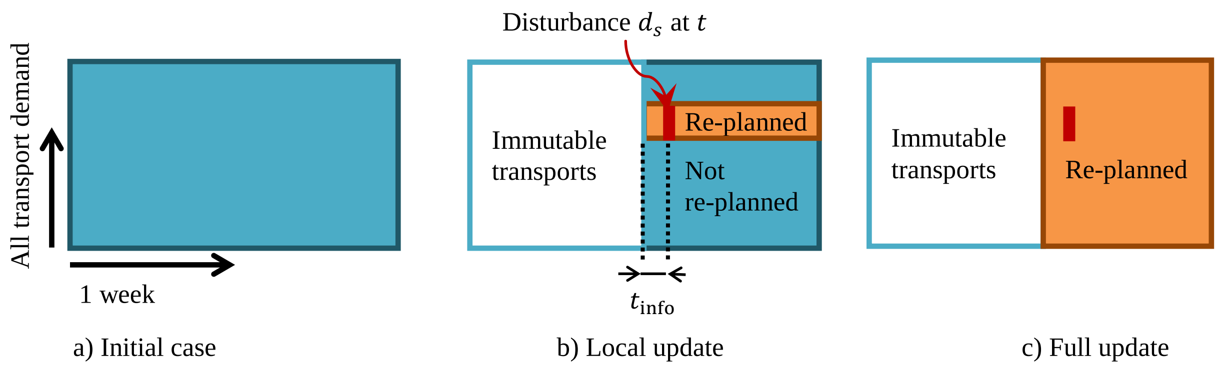


Figure 3. Initial solution and two update methods using LCAT

The objective value of the fully updated planning equals the transportation cost after the full update, denoted by $J_{d_s}^{\mathcal{F}}$. However, current practice is not to consider full updates, as the transportation planners do not have the tools available that are required for fully updating the planning. Instead, only containers planned on the disturbed service are re-planned; this is considered a *local update*. To compute this local update with our model, again all transports

z_s^c departed before $t - t_{\text{info}}$ are set fixed to the values of the initial solution $\acute{z}_s^c$. An additional constraint is added to ensure that all cargo classes c that are not planned on the disturbed service $\check{s}$ are not updated. Let $C_{\check{s}}$ denote the set of cargo classes and demand patterns that are planned on the disturbed service. Then the local update constraint is formulated as:

$$z_s^c \geq \acute{z}_s^c \qquad \forall c \notin C_{\check{s}}, s \neq \check{s} \tag{9}$$

where $C_{\check{s}} = \{c \in C | \acute{z}_{\check{s}}^c > 0\}$. Hence, only cargo classes from the disturbed service $\check{s}$ can be re-planned; these must be re-planned on the remaining capacity in the network. This is indicated by Figure 3b). The objective value of the locally updated planning equals the transportation cost after the local update, denoted by $J_{d_s}^{\mathcal{L}}$.

3.3 Measuring disturbance impact and relevance

To measure the effect of a disturbance d_s, the cost impact of a full update is denoted by $\mathcal{F}_{d_s}$ and of a local update is $\mathcal{L}_{d_s}$. These are defined as follows:

$$\mathcal{F}_{d_s} = J_{d_s}^{\mathcal{F}} - J^{\mathcal{I}},$$
$$\mathcal{L}_{d_s} = J_{d_s}^{\mathcal{L}} - J^{\mathcal{I}}.$$

The possibly higher cost of a local update is measured by the cost relevance:

$$\mathcal{R}_{d_s} = \mathcal{L}_{d_s} - \mathcal{F}_{d_s}.$$

As the local update is also a feasible solution for the full update, by definition it holds that $\mathcal{L}_{d_s} \geq \mathcal{F}_{d_s}$ and $\mathcal{R}_{d_s} \geq 0$. If $\mathcal{R}_{d_s}$ equals zero, it means that the full update does not result in a better solution than the local update. If $\mathcal{R}_{d_s}$ is positive, it indicates the value of using a full update instead of a local update for disturbance d_s.

The impact measures as defined here denote the absolute value of the additional cost after the update. Two additional measures are introduced to report the impact relative to the cost and volume per service:

$$\mathcal{F}_{d_s}^{\mathcal{C}} = \frac{\mathcal{F}_{d_s}}{c_{\check{s}}},$$
$$\mathcal{F}_{d_s}^{\mathcal{V}} = \frac{\mathcal{F}_{d_s}}{V_{\check{s}}},$$

where $c_{\check{s}}$ and $V_{\check{s}}$ denote the cost contributed to and the volumes assigned to the service $\check{s}$ in the initial solution, respectively. These are defined as

$$V_s = \sum_c \acute{z}_s^c,$$
$$c_s = V_s(c_{\text{TEU},s} + c_F) + c_{f,s},$$

With $c_{\text{TEU},s}$ the cost per TEU on service s, c_F the handling cost per TEU and $c_{f,s}$ the fixed cost for service s. In this study it is assumed that $c_{\text{TEU},s}$ equals 0 for self-operated services and $c_{f,s}$ equals 0 for subcontracted services. In both cases the transfer cost c_F apply, though. Hence, with the relative impact measures, the disturbance cost can be reported relative to the service cost or the service's transport volume.

In the next section we present a case study into the late arrival, early arrival, and cancellation of network services to show the use of the measures *impact* and *relevance*. Note that with this method it is also possible to study the effect of other changes in the set of feasible paths, as long as the part of operation carried out before the time of information does not change. Hence, the method can also be used to study the effect of changes in the expected transportation demand, changes in available capacity or delays at terminals.

4 CASE STUDY OF DISTURBANCES IN THE EGS-NETWORK

The proposed model and method to study disturbances is applied to a real-world case: the EUROPEAN GATEWAY SERVICES (EGS) network between three seaport terminals in Rotterdam and several hinterland terminals in North-West Europe. This container network is being developed by EUROPE CONTAINER TERMINALS (ECT). The planning updates in case of disturbances are time-consuming and possibly sub-optimal. In this cases study, the impact and the relevance of disturbances are determined. The results indicate what type of disturbance is the most costly and when a full update of the planning is most advantageous. In Section 4.1 the case is described. The results are reported in Section 4.2-4.4.

The EGS network was described in Section 1. The network connects the Rotterdam seaport with hinterland terminals in North-West Europe via three modes: the network focuses on barge and rail transportation, but also considers trucking if necessary. The service schedule used in the study is adapted from the actual service schedule in this network, based on the results of our earlier study into the service schedule of the EGS network (Van Riessen *et al.*, 2013). The service frequencies (per week) on all corridors are shown in Figure 4. The schedule is created such that the possible transfer time at intermediate transfers is minimal. The schedule consists of 166 services per week in total, of which 38 are operated by EGS, and on 128 services transport can be subcontracted.

The set of suitable paths is generated according to the method described in Section 3.1. The total set consists of 13357 paths. The cost structure and transportation demand are equal to the studied case in the earlier study. The cost parameters in the study are based on the actual cost in the current operation of the EGS network. To protect the confidentiality of the data only the relative cost is reported. The cost per path is based on the cost per service per TEU ($c_{\mathrm{TEU},s}$). This is modelled with a linear approximation of the actual network cost and the corridor length l_s, i.e. $c_{\mathrm{TEU},s} = \alpha l_s + \beta$. On self-operated services no cost per TEU is used, but a fixed cost for the service. This fixed cost is not part of the operational planning problem. For each transfer a fixed cost c_F is used; for overdue delivery a penalty cost c_τ per TEU per day applies.

The expected demand is determined based on the historic transportation volumes. An analysis of the transportation on the EGS network in the period of January 2009 - June 2012 did not show significant periodic behaviour, so periodic demand fluctuations can be neglected. As the transported volume grew fast in 2010, the weekly demands were further analysed based on the period January 2011 - June 2012. The expected demand patterns for all cargo classes are based on the estimated normal distribution of transportation volumes in the period January 2011-June 2012. The parameters of the normal distribution of the weekly volume are determined for each cargo class. With this, ten 10-percentile subsets of the normal distribution are generated for each cargo class. The due time for the container is categorised in 1, 2, 4 and 7 days, based on estimates from EGS planning experts.

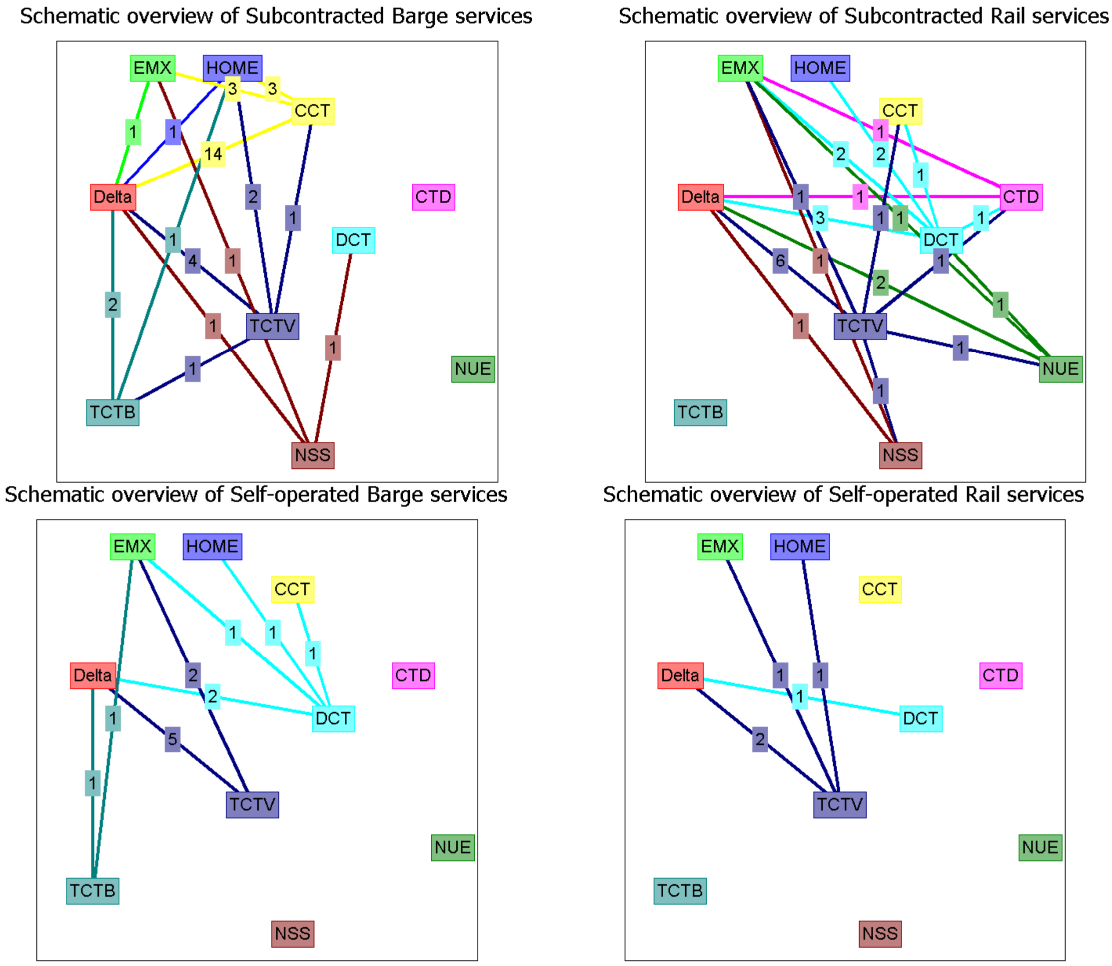


Figure 4. One-way service frequencies per week in the EGS case study

Once the initial solution is found, the impact and relevance of various disturbances is determined. The disturbances are considered one by one. All these experiments are also carried out for all ten demand patterns. The impact and relevance are averaged over the ten solutions to obtain the results. We distinguish two sets of experiments:

a) Cancellation of services
b) Out-of-schedule departures (early or late)

The experiments in set a) are carried out 3 times for each service in the service schedule, i.e. for the cases were the time of information is 6, 12 or 24h before departure time. Services that depart on the last day of the week are omitted because of end-of-horizon effects.

The results of experiment set a) allow us to distinguish between services with high impact and low impact. As the cancellation of a service is the most severe disturbance, the impact of a cancellation is the upper bound for the impact of out-of-schedule departures in experiment set b). So, for this experiment set we will focus on the set of services with high impact. The following disturbances are evaluated one by one for these services (Table 2).

Table 2. Experiments set b)

	Out-of-schedule departure time	Time of information
Late departure	$t \in \{6,12,24\}$	$t_{\text{info}} \in \{6,12,24\}$
Early departure	$-t \in \{6,12,24\}$	$t_{\text{info}} \in \{6,12,24 \mid t_{\text{info}} \geq -t\}$

Note that experiments in which the time of information is later than the time of departure are not feasible, as the model does not support situations with incomplete information. Hence, the early departure experiments are only carried out for $t_{\text{info}} \geq -t$, where the minus sign indicates a departure before the estimated time of arrival.

4.1 Initial solution

First, the initial solution is determined for the 10 demand patterns, see Table 3 for the average cost structure of the solutions. As most of the used data in this case study is confidential, only the relative cost structure for the weekly network is presented. This does not include the fixed cost for the self-operated services. The put the cost in some perspective, keep in mind that the average relative cost of operating a single service is $\frac{1}{166}$=0.6%. Table 4 shows the average modal split and service utilization. The demand patterns for the EGS network are not representative for the entire port's throughput, hence the low portion of trucking in the results. But the results show that barging amounts to two third of the transportation and rail transportation is used for 1 third. For both modes, the self-operated services account for more than ¾ of the transportation. Naturally, the utilization of the self-operated services is much higher than of the subcontracted services. Note that on these subcontracted services also transportation from outside of the network takes place.

The next sections assess the experiments with disturbances. The resulting impact and relevance of cancellations are presented first, followed by the impact and relevance of out-of-schedule departures.

Table 3. Average cost structure of initial solutions for 10 demand patterns

Subcontracted	Transfers	Late	Direct truck
21.3%	60.1%	17.5%	1.0%

Table 4. Average modal split and utilization over 10 demand patterns

	Model split		Utilization
Trucking		1.8%	-
Subcontracted barge	15.3%	65.7%	20%
Self-operated barge	50.5%		53%
Subcontracted train	6.6%	32.5%	17%
Self-operated train	25.9%		75%

4.2 Impact and relevance of service cancellations

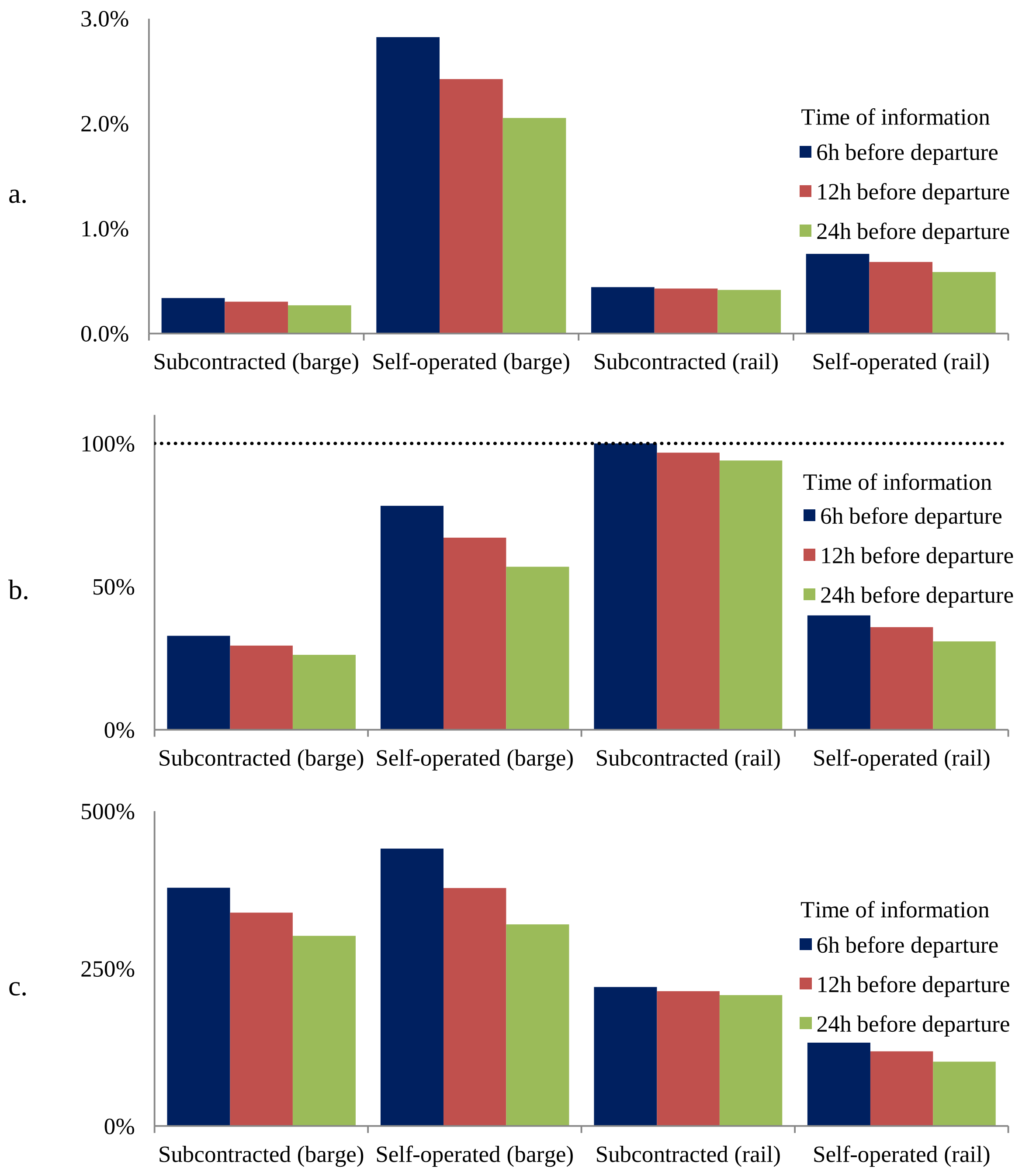
In the first set of experiments, three experiments per service are carried out, for the 143 services departing on day 1 to day 6 of the week, amounting in a total of 429 experiments.

In Table 5, the average impact and relevance are show as a percentage of the initial objective value. The disturbance with the most severe impact is the cancellation of a self-operated service. This disturbance results on average in 2.4% additional: the equivalence of the cost of about 4 average services. Secondly, disturbances on self-operated services have an impact that is higher than disturbances on subcontracted services. For barges, the impact of cancelling self-operated services is 8 times more costly than the cancellation of subcontracted services. Also, cancellations of self-operated services are more relevant than of subcontracted services. Table 5 also shows the relevance as percentage of the impact. This shows that the use of a local update result on average in 6-16% additional impact, depending on the type of service that is cancelled. However, the absolute value of the relevance is not very large with respect to the total transportation cost.

Table 5. Average impact and relevance of cancellation

	$\frac{\mathcal{F}_{d_s}}{J^{\mathcal{I}}}$	$\frac{\mathcal{R}_{d_s}}{J^{\mathcal{I}}}$	$\frac{\mathcal{R}_{d_s}}{\mathcal{F}_{d_s}}$
Subcontracted barge	0,30%	0,03%	10%
Self-operated barge	2,43%	0,19%	8%
Subcontracted train	0,43%	0,03%	6%
Self-operated train	0,68%	0,11%	16%

In Figure 5, the impact of the cancellation of a service is presented with respect to the time of information. Figure 5a shows the full impact as percentage of the initial objective value. Figure 5b en 5c show the relative impact w.r.t. the service volume and service cost, respectively. If a disturbance is identified earlier, the planning update is less restricted, and hence, the impact must decrease with increasing t_{info}. This is indeed the case in all three parts of Figure 5. However, barges show more cost reduction by early information than trains, especially for self-operated services. The absolute impact of self-operated barges is a lot higher than the impact of self-operated trains (Figure 5a). For confidentiality reasons, the values of Figure 5b are normalised to the maximum value in the figure. It shows that the impact per TEU is also higher for self-operated barges than self-operated trains. However, for subcontracted services, the impact per TEU is lower for barges than for trains. The highest impact per TEU is found for cancellation of subcontracted rail services. Finally, Figure 5c, shows impact measured relative to the cost contribution of the disturbed service in the initial solutions. This relative impact is higher for barges than for trains.



a. Full impact $\frac{\mathcal{F}_{d_s}}{J^{\mathcal{J}}}$ b. Impact per TEU $\mathcal{F}_{d_s}^{\mathcal{V}}$ (normalised)   c. Impact per service cost $\mathcal{F}_{d_s}^{\mathcal{C}}$

Figure 5. Average impact (per type of service) of cancellation of a service

4.3 Impact and relevance of early and late departures

From the experiments with service cancellations, we select 25 services that showed the highest impact per TEU, $\mathcal{F}_{d_s}^{\mathcal{V}}$. Out of these 25 services, all services with an absolute impact $\mathcal{F}_{d_s}$ of less than 0.1% of the total network cost are omitted. By doing this, we focus on services of various sizes for which the planning update shows the largest differences. This results in a total of 17 services, for the second series of experiments. In the second series of experiments, 9 experiments for late departure and 6 experiments for early departure are carried out; a total of 255 experiments.

Figure 6 shows the results of these experiments. It can be seen that the impact increases with more severe disturbances (earlier, later). As can be expected, the impact of out-of-schedule departures is lower than the impact of the cancellation of the selected services (indicated by the dotted lines). The effect of departing too early or late is similar; however, early departure has a slightly larger impact than late departure. Practice learns that early departures of barges do occur: as barges decide last-minute on the route in the Rotterdam area, they may arrive early or late compared to the times as expected several days in advance. The time of information has not much influence on average. The average impact is only slightly lower if the time of information is earlier.

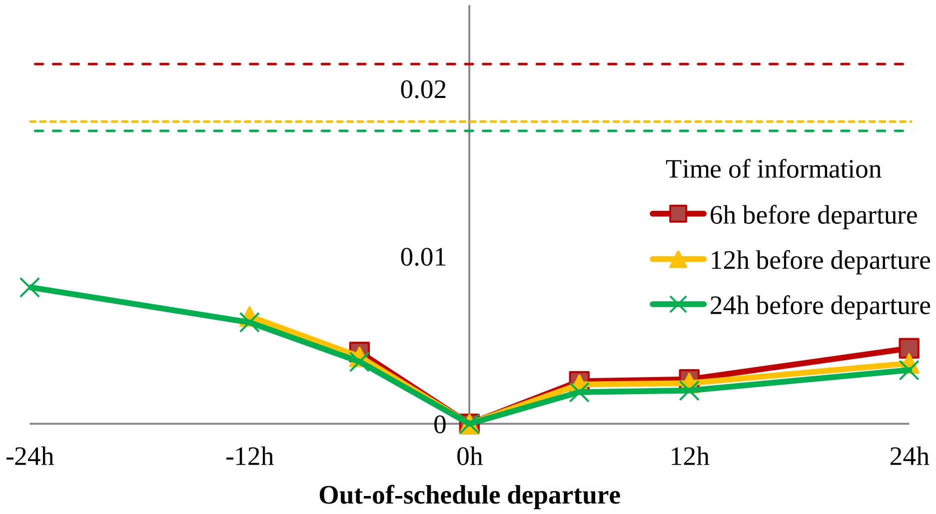
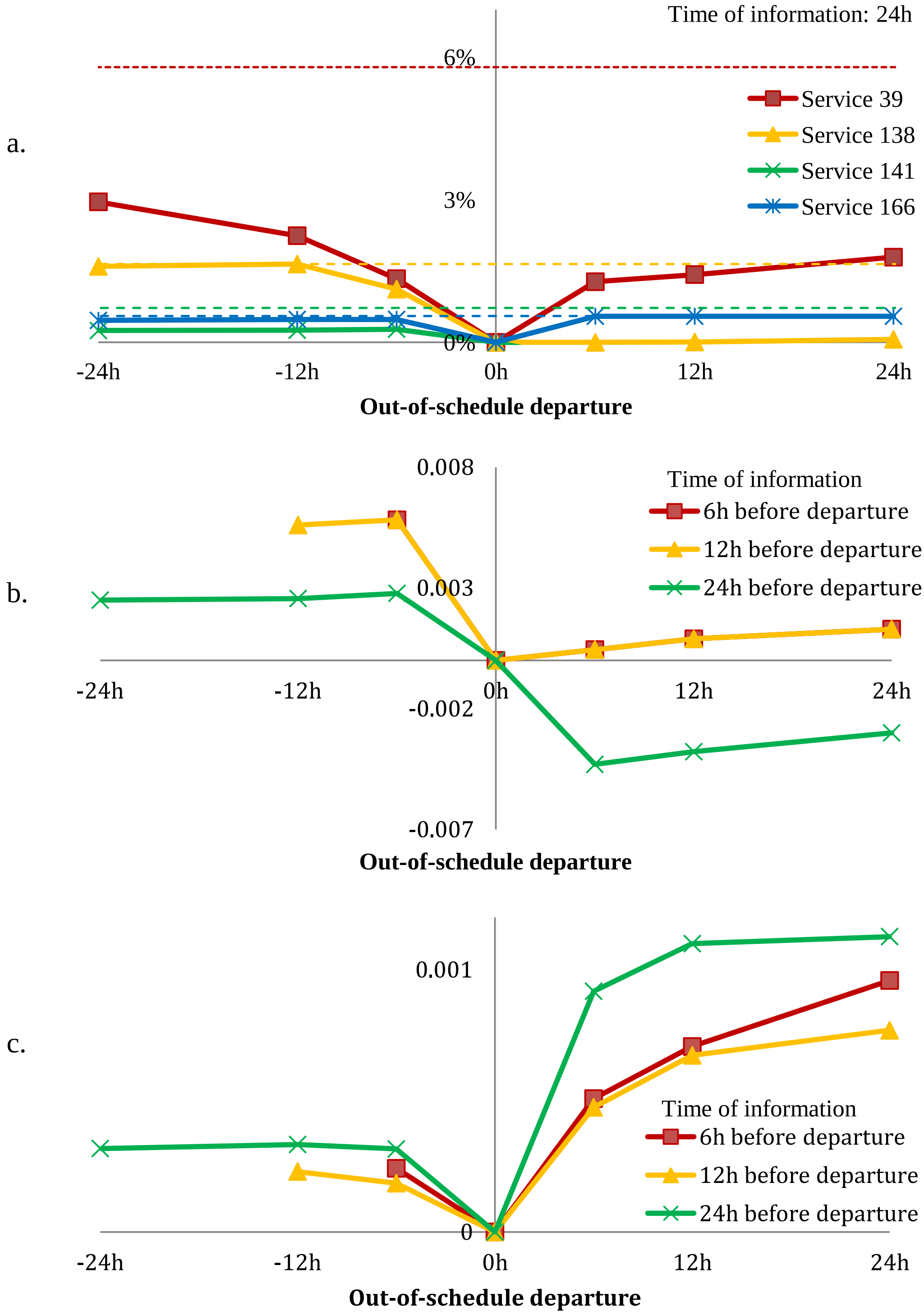


Figure 6. Impact $\frac{\mathcal{F}_{d_s}}{J^{\mathcal{J}}}$ of early and late departure (dotted line: cancellation)

These results are not consistent for all selected services, though. Figure 7a shows the impact of out-of-schedule departures for four different services, where the time of information is 1 day in advance. It shows that, per service, the impact of early and late departure can differ:

- Early or late departure can have impact similar to cancellations (e.g., services 138 or 166), but that is not necessarily the case (e.g., service 39).
- For service 141, the out-of-schedule departure results in a negative impact, i.e. a cost reduction. This means that a delayed departure time results in cost reductions in this case
- Figure 7b shows the results for service 141 in more detail. It shows that early information can be very beneficial in some cases: if the delay of service 141 is known 1 day in advance, a cost reduction is possible, but if the delay is known half a day in advance or less, it will have a cost impact.



a. Four example services: impact $\frac{\mathcal{F}_{d_S}}{J^{\mathcal{J}}}$ (dotted line indicates cancellation impact)

b. Service 141: impact $\frac{\mathcal{F}_{d_S}}{J^{\mathcal{J}}}$ for various $t - t_{\text{info}}$

c. Average relevance $\frac{\mathcal{R}_{d_S}}{J^{\mathcal{J}}}$ of selected services

Figure 7. Results for out-of-schedule departures

Figure 7c shows the relevance of full updates in case of out-of-schedule departure. Note that a negative relevance is impossible by definition: the solution of the local update is also a feasible solution of the full update. Clearly, a full update is more relevant in case of late departure than in case of early departure. Also, the relevance is not linear with the earliness of information. The relevance is highest for the case where the disturbance is known 1 day in advance. However, the case where $t - t_{\text{info}} = 6\text{h}$ shows a higher relevance than the case where $t - t_{\text{info}} = 12\text{h}$.

Table 6 shows the impact and relevance as percentage of the initial objective value. The impact and relevance of cancellations for the selected services are also denoted. It shows that the cancellation of a service often has a much higher impact than an early or late departure, but a similar relevance. This indicates that a cancellation is costly, regardless of the update method. Table 6 also shows the relevance as percentage of the impact. This shows that the relative relevance is also higher for delays than for early departures. I.e., a full update offers a larger cost reduction for delays than for early departures, relatively.

Table 6. Impact and relevance of out-of-schedule departures (selected services)

Disturbance	$\frac{\mathcal{F}_{d_s}}{J^{\mathcal{J}}}$	$\frac{\mathcal{R}_{d_s}}{J^{\mathcal{J}}}$	$\frac{\mathcal{R}_{d_s}}{\mathcal{F}_{d_s}}$
Cancellation *(selected services)*	1.90%	0.02%	1%
24h early	0.82%	0.03%	4%
12h early	0.62%	0.03%	5%
6h early	0.40%	0.02%	6%
6h late	0.23%	0.06%	28%
12h late	0.24%	0.08%	35%
24h late	0.38%	0.10%	25%

5 DISCUSSION

The LCAT model was developed for use in intermodal networks with barge and/or rail services. In the case in which an urgent delivery is required, the model is able to select a truck delivery. The case study of the EGS network showed the use of the LCAT model for planning in an intermodal container network. It was used to assess the impact and relevance of disturbances of the network services.

The LCAT model can also be useful for other ports around the world in which developments of using more intermodal services take place. We will consider ports that are similarly situated on the estuary of a river: Rotterdam and Antwerp are connected to the Rhine, Hamburg is situated at the Elbe. Le Havre is located at the Seine, Shanghai at the Yangtze river. New Jersey (and New York) is located on the Hudson River estuary. To assess the value of the LCAT model for these ports, the model splits at these reference ports. The modal splits of these ports are shown in Table 7, based on a comparison study between several reference ports by the Dutch Ministry of Transport in 2009. Significant volumes of containers are transported to the hinterland with intermodal rail or barge services from these ports.

Table 7. Modal split of hinterland transportation in 2007 (Kolkman, 2009)

	Hinterland transportation volume (1000 TEU)	Truck	Barge	Rail
Antwerp	7824	57%	33%	10%
Rotterdam	8200	59%	30%	11%
Hamburg	5390	64%	2%	34%
Le Havre	1880	86%	9%	5%
New Jersey	Unknown	87%	<1%	12%
New Orleans	Unknown			
Shanghai	Unknown	89%	10%	1%

All the ports mentioned in this section are located in populated urban areas, where trucking of containers results in increasing congestion and emission of green house gasses. These developments provide an incentive for more transport using intermodal services (barge and rail). With more possible modes and routes, the efficient planning of the container transportation requires network wide optimization, such as with the LCAT model. The LCAT model is especially suitable for planning of heterogeneous cargo classes on heterogenous routes: the model can handle the simultaneous planning of classes with different origins, destinations, mass categories and due times on pre-processed paths. The pre-processing of paths enables to use the model for complex transport chains. E.g., in this paper we studied a case of intermodal transportation to and from the sea terminal in Rotterdam. Other than that, the use of preprocessed paths allows for planning of various complex transport chains. For instance, in Shanghai large volumes of containers have to be transported between the hinterland and the new port island Yangshan. Containers from shore are transported here via truck over a 32km bridge, or via barge. Barges can pick-up containers from other Shanghai terminals that are connected to inland routes. But alternatively, barges also travel directly between Yangshan and hinterland locations up the Yangtze river such as Nanjing (450km) or Wuhan (1100km). The LCAT model is suitable for combining these different routes in one network planning problem to use all intermodal possibilities efficiently.

6 CONCLUSIONS AND FUTURE RESEARCH

In this study the new Linear Container Assignment model with Time-restrictions (LCAT) is proposed. LCAT adds two new aspects to existing models for operational planning: overdue delivery at a penalty cost and the combination of subcontracted and self-operated services. Truck transportation can be selected as fast alternative for the intermodal services, but is expensive. An automated method is proposed to find a relatively small set containing all suitable paths. This method is a good starting point to generate relevant paths in similar cases of a network between a sea terminal and several hinterland terminals. Furthermore, two new measures are introduced to quantify the effect of disturbances: impact and relevance. The impact measures the additional cost of a disturbance. The relevance measures the difference between the cost of a full or local update. A high relevance for a specific type of disturbance suggest the use of a full update if that type of disturbance occurs. A low relevance indicates that the local update method of this study performed almost as well as the full update.

Generally, the relevance is low, compared to the total transportation costs. Hence, the use of full updates does not result in large cost reductions compared to local updates. Based on the case study, 6-16% more impact can be prevented if full updates are used. Full updates may be unwanted for other reasons. Full updates are currently not used in the EGS network and the development and implementation of real-time planning methods for full updates is costly. Secondly, during full updates, large amounts of containers may be rescheduled. The cost of rescheduling containers is not taken into account in this study. On the other hand, the local planning method in this study can be improved to give planning results even closer to the optimal full update. Further research is required to develop improved methods for partial updates, suitable for manual planners. With improved manual methods for partial updates, the relevance of disturbances can be further decreased. This eliminates the necessity of full updates and implementing automated planning methods. One improvement may be that the local update re-plans containers on all services on the disturbed corridor. The current local update can only change the paths of containers on the disturbed service. This extension of the local update will allow bumping: postponing containers planned on future services to allow containers of the disturbed service to arrive on time.

The case study of the EGS network was based on data from ECT. The research presents ECT with several interesting results. The results support the following conclusions regarding the EGS network:

- Where possible, use fixed schedules for departures. This reduces the late schedule changes causing early and late departures compared to the initial planning. ECT tries to do this, for instance on the service to CCT Moerdijk. This research supports that effort.
- The results indicate on what disturbances must be focused. Disturbances with a high impact must be reduced as much as possible.
- Simultaneously, the planning department must give additional attention to disturbances on barges or self-operated services. These showed high relevance; cost reduction can be attained with more elaborate planning updates, or even a full update.

Note hereby the following practical limitations of the model. The model uses a linearised cost structure. Container commodities are represented as a continuous flow. Also, the historic demand may differ from the future demand. Several operational limitations at the terminal are not incorporated in the model, such as custom restrictions, available quay and crane capacity and security issues. This study does not consider the joint influence of multiple disturbances simultaneously, e.g., because of snow, high water or strikes.

Further research consists of extending the LCAT model to incorporate two situations that occur regularly in practice. Firstly, sometimes a self-operated service is skipped if demand is low. Secondly, services often make multiple consecutive stops on a route. These routes can easily be implemented in the path selection. However, depending on the actual demand, some stops may be skipped to reduce transit time and cost. Including that in the planning problem requires an extension of the LCAT model.

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