

# A CONSOLIDATION MODEL FOR CARGO-DRIVEN INTERMODAL TRANSPORTATION

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## ABSTRACT

Accessibility of main sea ports by road has become increasingly difficult due to rapid growth in container throughput. To deal with this challenge, new ways for handling containers and distribution of cargo flows are needed to define and implement. One possibility is going beyond container transportation and considering cargos inside the containers in the design and operation of transportation networks. Consequently, by consolidation of cargo flows, the utilization of container capacity can be improved and the number of transportation fleet will be reduced. This idea is further discussed in this paper and a mathematical model for the operation of such a consolidation center is presented.

**Keywords:** Consolidation, intermodal transport, cargo, containerization.

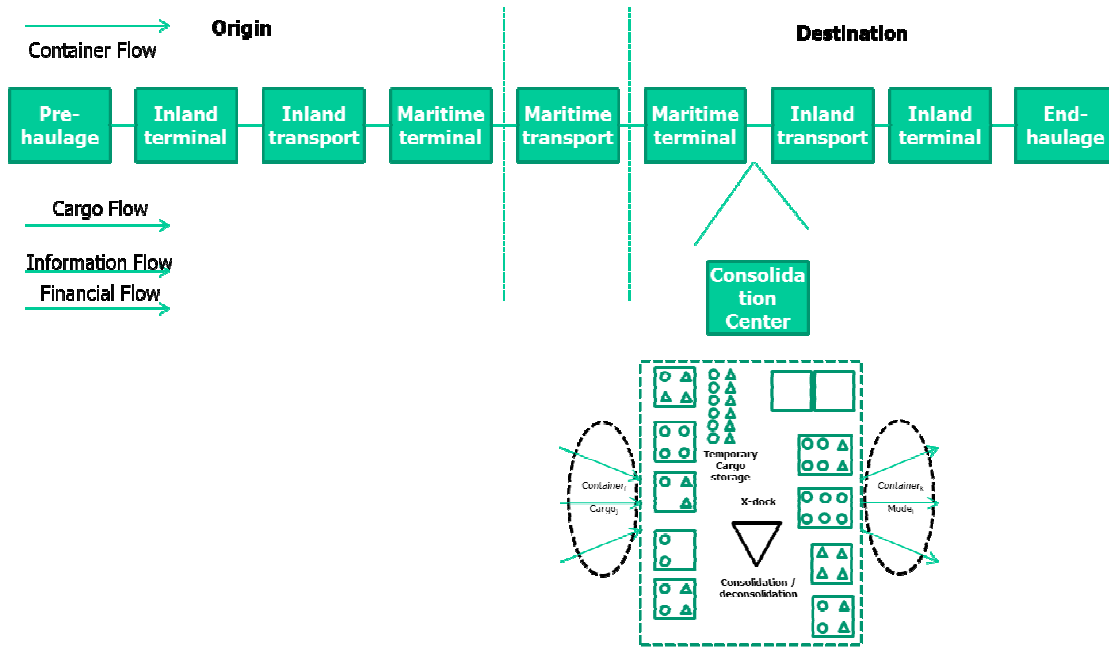
## 1 INTRODUCTION

In the last two decades, the main sea ports around the world – especially, European ports - have experienced a remarkable increase in their container throughput. This rapid increase has adversely impacted the accessibility of ports by roads as the capacity and quality of the hinterland transport cannot accommodate the increase in container throughput. This is even more challenging since freight transport to and from the main ports is expected to grow significantly over the coming years (Notteboom and Rodrigue, 2009). To deal with these challenges, new cargo handling concepts are needed to study and implement which minimize the use of land and road infrastructure. One possibility is improving the utilization of container capacity by having cargo consolidation in a cross-docking facility located in (or close to) maritime terminal. Such a cross-docking facility may also facilitate switching to other less-costly modes of transportation by creation of economies of scale.

Several studies have shown the under-utilization of container capacity in the European road networks and support the premise of such a consolidation process. A survey among 50 German haulage companies by Léonardi & Baumgartner (2004) has shown that the mean weight and volume load factors for road transportation are around 44.2% and 59.3% respectively. Another study shows that the average weight-based utilization on laden trips in UK is decreased from 62% in 1997 to 57% in 2003 (McKinnon, 2007). The decrease in utilization rates can be partly explained by more tendencies towards lean and Just-in-Time inventory management. These studies demonstrate the potential for improving the utilization of containers and suggest that the focus on moving containers from one point to another point has to be complemented by a focus on the cargo inside the containers. Meanwhile, some new initiatives like Rotterdam Cool Port has already started evaluating new freight distribution networks by having a decoupling point in the container terminal (Port of Rotterdam, 2013).

## 2 MODELING FOR CARGO-DRIVEN INTERMODAL TRANSPORTATION

Generating logistics value considering the cargo within the containers and using the cargo level information to make better-informed decisions for the design/operation of a logistical network is termed “cargo-driven intermodal transportation” in this paper. To operationalize this idea, the cargo (and container) flows must be (de)consolidated in a de-coupling point located in (or close to) maritime terminal. Such a facility can be a substitute for inland terminals and distribution centers (Fig. 1). The containers are shipped to the consolidation center; the cargos in these containers and the ones that are already stored are integrated and loaded into available containers. Subsequently, the loaded containers are consolidated and put on barges (or other transport vehicle) to be sent to inland terminals or to final destination.



**Figure 1.** Cargo de-coupling center to operationalize cargo-driven transportation

This cargo consolidation process can improve the efficiency of container/cargo handling process in three different ways:

- Full containers with cargos for different destinations can be delivered to the cross-docking facility and after de-consolidation, the loaded containers can be sent to the final destinations.
- The “urgent cargo” flows to one destination can be separated from “non-urgent cargo” flows. Subsequently, the containers with “non-urgent cargo” can be delivered by slow transport modes (e.g., barge) and the containers containing “urgent cargo” can be sent by truck. As a result, decoupling the “urgent cargo” from “non-urgent cargo” may significantly reduce the cargo transport by road to the hinterland.
- “Semi-loaded container” flows can be reduced by combining the container flows in the de-coupling center.

Based on these ideas and to manage the operation of such a consolidation center, a planning model is developed and studied for illustrative cases in this research (Appendix A).

For this model, the set of cargos in the de-coupling center and a set of (semi)-full containers are given for a specific time horizon (e.g., for one week). Then, the objective is to determine (i) which incoming containers must be opened, (ii) which cargos must be loaded in

which (semi-)full containers, and subsequently (iii) which containers must be transported by each modes of transport (i.e., truck or barge).

The formulation of presented model (including the parameters, variables, constraints and objective function) is discussed in detail in Appendix A.

### 3 CONCLUSION

Design, planning and control of logistics networks at the cargo-level (together with container level) can be a promising idea and create logistics value. To operationalize such an idea, a mathematical model for “cargo-driven intermodal transportation” is presented in this paper. This model allows planning the operation of a cargo de-coupling center and is evaluated with illustrative cases. The next step in the future works concerns applying the model to a real case.

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## Appendix A: Mathematical Model.

The proposed formulation requires the following indices, sets, parameters, and variables:

### Indices

i = cargo  
j = destinations  
t = event time  
c = (semi-)full container  
l = new containers  
f = cargo family

### Sets

$I$  = set of all cargos in the CC  
 $\bar{T}$  = set of time points = {1, 2, ..., T}  
 $I^f$  = set of all cargos belong to the same family “f”  
 $I^j$  = set of all cargos for the same destination “j”  
 $\bar{C}$  = set of (semi-)full containers  
 $I_c$  = set of cargos in container “c”  
 $\bar{K}$  = set of all cargos in (semi-)full containers:  $\bigcup_c I_c$   
 $L$  = set of new containers  
 $BD \subset \bar{T}$  = set of barge delivery time

### Parameters

$\mu_i$  = expected time of arrival of cargo “i”  
 $\sigma_i$  = due date of cargo “i”  
 $\gamma_{ij} = 1$ , if container “i” is going to destination “j” and zero otherwise  
 $\mu_c$  = expected time of arrival of (semi-)full container “c”  
 $W^{min}$  = minimum allowed capacity for container  
 $W^{max}$  = maximum allowed capacity for container  
 $TDT$  = time of delivery by truck  
 $TBT$  = time of delivery by barge

### Variables

$X_{it}$  = binary, if cargo “i” is sent at time “t”  
 $Y_{ic}$  = binary, if cargo “i” is assigned to (semi-)full container “c”  
 $Y_c$  = binary, if container “c” is opened  
 $Y_{il}$  = binary, if cargo “i” is assigned to new container “l”  
 $T_{mt}$  = binary, if container “m” is sent by truck at time “t”  
 $B_{mt}$  = binary, if container “m” is sent by barge at time “t”  
 $TA_m$  = time of arrival of container “m”  
 $TD_m$  = time of departure of container “m” from CC

On the basis of this notation, the mathematical model for the cargo-driven intermodal transportation planning involves the following constraints:

#### Cargo Allocation Constraint:

$$\sum_t X_{it} = 1 \quad \forall i \in I \quad (A-1)$$

This constraint states that every cargo in the consolidation center must be sent at one point of time in the planning horizon.

#### Cargo Allocation to Containers:

$$\sum_c Y_{ic} + \sum_l Y_{il} = 1 \quad \forall i \in I \quad (A-2)$$

$$\sum_i Y_{ic} \leq MY_c \quad \forall c \in \bar{C} \quad (A-3)$$

Constraint (A-2) indicates that each cargo must be assigned to one (semi-)full container or a new container. Of course, assigning a cargo to a (semi-)full container is only possible if that container is decided to open (as discussed in the following constraints).

**Container opening decision:**

$$H(1 - Y_c) \leq \sum_{i \in I_c} \gamma_{ij} \quad \forall j \in J, \forall c \in \bar{C}, H: |I_c| \quad (A-4)$$

$$(1 - Y_c)(\bar{\sigma}_c - \sigma_i) \leq \Delta \quad \forall i \in I_c, \bar{\sigma}_c: \max \sigma_i \quad (A-5)$$

$$\sum_t X_{it} = Y_c \quad \forall c \in \bar{C}, \forall i \in I_c \quad (A-6)$$

$$\sum_{c' \in \bar{C}, c' \neq c} Y_{ic'} + \sum_{l \in L} Y_{il} = Y_c \quad \forall c \in \bar{C}, \forall i \in I_c \quad (A-7)$$

$$1 - Y_{ic} \leq Y_c \quad \forall c \in \bar{C}, \forall i \in I_c \quad (A-8)$$

Constraints (A-4) and (A-5) describe the rules for opening a container. Opening a container will cause extra opening costs – as shown in the objective function (equation A-23). However, if cargos inside one container are for different destinations, the content of that container must be de-consolidated. Equation (A-4) states that if the summation of  $\gamma_{ij}$  is lower than H (i.e., at least one of cargos is heading towards a destination other than “j”), then that container must be opened. The other condition for opening a container is described by equation (A-5). This constraint entails that if the difference between maximum of due date for cargos inside each container is greater than  $\Delta$ , then that container must be opened.

Constraints (A-6) and (A-7) express the necessity to assign the cargos to other containers if one container is opened. If a container is not opened ( $Y_c = 0$ ), then  $Y_{ic}$  is equal to one as described by equation (A-8).

**Container Loading Constraints:**

$$Y_{mj} \leq \sum_{i \in I} \gamma_{ij} Y_{im} \quad \forall j \in J, \forall m \in L \cup \bar{C} \quad (A-9)$$

$$(1 - Y_{mj}) \leq \sum_{i \in I} (2 - \gamma_{ij} - Y_{im}) \quad \forall j \in J, \forall m \in L \cup \bar{C} \quad (A-10)$$

$$W^{min} \leq \sum_{i \in I} Y_{im} w_i \leq W^{max} \quad \forall m \in L \cup \bar{C} \quad (A-11)$$

Equations (A-9) and (A-10) define the destination of each container based on cargos that are loaded in that container. Clearly, all cargos loaded in each container must be for the same destination which is checked by constraint (A-13) in the model. Therefore, only for one destination, both  $Y_{im}$  and  $\gamma_{ij}$  (for all cargos) are equal to one and subsequently, for that destination, equations (A-9) and (A-10) enforce the value for  $Y_{mj}$  to be one. Meanwhile, the value of  $Y_{mj}$  for other destinations must be zero as required by equation (A-9).

Equation (A-11) describes the capacity constraints for each container; the weight of total cargos that are loaded in one container is bounded by the minimum and maximum capacities of a container.

**Cargo Uniformity Constraint:**

$$\sum_{i \in I, f} Y_{im} \leq M(1 - Y_{im}) \quad \forall i \in I^f, f \neq f, m \in L \cup \bar{C} \quad (A-12)$$

$$\sum_{i \in I, f} (Y_{im} - \gamma_{ij}) \leq M(2 - Y_{im} - \gamma_{ij}) \quad \forall i \in I \cup K, m \in L \cup \bar{C} \quad (A-13)$$

$$|Y_{im} \sigma_i - Y_{im} \sigma_i| \leq \theta + (2 - Y_{im} - Y_{im})M \quad \forall i \in I \cup K, m \in L \cup \bar{C} \quad (A-14)$$

These constraints represent the uniformity of cargos inside each container. Constraint (A-12) evaluates if all cargos in each container belong to the same family of cargos. In many cases (especially for conditioned cargo such as fruit), not every cargo type can be loaded into the same container. Equation (A-13) represents the evaluation of final destination for all cargos loaded inside each container. Finally, in constraint (A-14), the uniformity in the cargo due date is checked; only if the due date for two cargos “i” and “i” is lower than  $\theta$ , they can be loaded in the same container.

**Container-mode Allocation:**

$$\sum_t T_{mt} + \sum_t B_{mt} = 1 \quad m \in L \cup \bar{C} \quad (A-15)$$

$$\sum_{m \in L \cup K} B_{mt} \leq BC_{tj} \quad \forall t \in BD_j, \forall j \in J \quad (A-16)$$

$$\sum_{m \in \bar{L} \cup \bar{C}} B_{mt} = 0 \quad \forall t \in BD_j, \forall j \in J \quad (A-17)$$

These constraints express the allocation of containers to different modes of transportation. Every container must be transported by barge ( $B_{mt}$ ) or truck ( $T_{mt}$ ) to the final destination. Sending containers by barge is only possible in some specific time points which are defined by barge departure time to destination “j” ( $BD_j$ ).

**Timing Delivery Constraint:**

$$TD_m = \sum_t T_{mt} t + \sum_t B_{mt} t \geq \mu_i Y_{im} \quad \forall m \in \bar{L} \cup \bar{C} \quad (A-18)$$

$$TA_m = \sum_t T_{mt} (t + TDT) + \sum_t B_{mt} (t + BDT) \leq \sigma_m \quad \forall m \in \bar{L} \cup \bar{C} \quad (A-19)$$

$$0 < \sigma_m \leq Y_{im} \sigma_i + M(1 - Y_{im}) \quad \forall i \in I, \forall m \in \bar{L} \cup \bar{C} \quad (A-20)$$

$$TD_i \leq TD_m + M(1 - Y_{im}) \quad \forall i \in I, \forall m \in \bar{L} \cup \bar{C} \quad (A-21)$$

$$TD_m + M(Y_{im} - 1) \leq TD_i \quad \forall i \in I, \forall m \in \bar{L} \cup \bar{C} \quad (A-22)$$

Equation (A-18) checks if the departure time of one container is after arrival time of cargos assigned to that container. Constraint (A-19) indicates that the arrival time of container must be before its due date. The due date of a container is the minimum of due date of cargos assigned to that container (which is define by equation A-20). Equations (A-21) and (A-22) define the time of departure for each cargo.

**Objective Function:**

**min total cost =**  
*cargo/container holding cost + transportation cost +*  
*consolidation (handling) cost*

$$\begin{aligned} \text{total cost} = & \sum_c (TD_c - \mu_c) CoHC + \sum_i (TD_i - \mu_i) CaHC + \sum_{m \in \bar{L} \cup \bar{C}} \sum_t T_{mt} TC + \\ & \sum_{m \in \bar{L} \cup \bar{C}} \sum_t B_{mt} BC + \sum_c Y_c COC + \sum_i \sum_c Y_{ic} LLC + \sum_i \sum_l Y_{il} LLC \end{aligned} \quad (A-23)$$

The first term in the objective function describes the storage cost for (semi-)full containers in the de-coupling center. The second term is, however, the cost of storing cargos in the consolidation center. Transportation cost by truck and barge are defined by third and fourth terms respectively. Fifth term is the cost of opening container in the de-coupling center. Finally, two last terms are the cost for loading cargos in the containers.