Master Thesis

Cargo consolidation in intermodal container transport

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Acknowledgements

Doing a master project is a tough task, which requires commitment, endurance and insights. During this process, I have received many types of valuable support. Foremost, I would like to give my thanks and gratitude to my thesis supervisor Prof. dr. Rob A. Zuidwijk, for giving me the fundamental to have a good start of the thesis. Next, I would like to give my sincere thanks to my daily supervisor dr. Behzad Behdani, for his patient guidance step by step and his sense of responsibility. Finally, I would like to thank dr. J.W. Rob Konings, for his invaluable comments and advice to improve my thesis.

During these two years, I have received the financial support from DRI Scholarship of TU Delft. Without this support, I would not be able to visit the Netherlands. Therefore, I would like to thank TU Delft for supporting me finishing the very interesting and enlightening TIL master program.

In these two years, I have also met lot of new friends: Fan Zhang, Rui Zhang, Rongwei Zou, Li Yuan, Shen Tian, Sien Liu, Yang Cao, Yunlong Li, Erik Gathier. They are always giving me help and bringing me fun. Therefore, a lot of thanks for them!

Finally, I would like to thank my lovely parents, for bringing me to this wonderful world and for giving me a lot of love. To them, I dedicate this dissertation.
Abstract

Container transport is currently growing fast and will continue to develop in the near future. However, some problems such as the road congestion, and negative environmental impacts due to container trucking, and the low utilization of container capacity are making the container transport less efficient. To deal with these problems, several new concepts regarding hinterland transport operations are presented and implemented by many seaports. The majority of these concepts aim to reduce the transport by roads and shift the cargo flows away from the congested roads to other transport modes including the waterways and railways. One promising new concept for improving hinterland accessibility is cargo-driven intermodal transport, which focuses on the consolidation of cargo flows. This concept may contribute to aforementioned problems by, e.g. improving the container weight capacity utilization and reducing the semi-loaded containers going the hinterland from the sea port.

Applying cargo consolidation in cargo-driven intermodal transport is expected to be beneficial for the society, but it remains unknown whether it will also provide benefits to the logistic service providers. In order to answer this question, an analytical optimization cost model is created to investigate the cost performance of cargo consolidation in this thesis. Further, a numerical case of container shipment between Port of Rotterdam and Tilburg is presented to experiment with the model. Based on the outcomes of the model, several conclusions are drawn in this work. As one important conclusion, applying cargo consolidation for container shipment between Port of Rotterdam and its hinterland is economically viable for a specific shipping distance. Furthermore, with a sensitivity analysis, the load factor of incoming containers and the unit truck cost are identified as most influential factors with overall largest positive impact on the total cost. Finally, with a Monte-Carlo simulation the impact of parameter variations on overall conclusions of this work have been found negligible.
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Chapter 1 Introduction

1.1 Problem statement: challenges in container transport

Container, which refers to a type of standardized load unit, was first introduced into freight transport in the late 1950s (Tomlinson, 2009). The transportation of containers is referred as “container transport”. In recent years, the expansion and intensification of globalization has spurred the demand for sourcing worldwide, which positively promotes the development of container transport. With this development, the top European ports all experienced a remarkable growth in container throughput in the last 20 years (see Figure 1), and the total volume of containers shipped on worldwide trade routes (excluding transshipment) will reach 177.6 million TEU in 2015, compared to the 28.7 million TEU in 1990 (Notteboom & Rodrigue, 2008).

In addition to maritime transport, as container helps to improve freight mobility in terms of higher handling and distribution efficiency (Rodrique, 2013), the application of containers in intermodal transport also increases. In US, the railroad container traffic volume increased from 8.24 million in 2009 to 10.17 million in 2011 (AAR, 2013), while European countries such as Germany, encountered a 1 million growth of railroad container units in 2011, compared to 2004 (Eurostat, 2012).

However, the fast developing container transport is at the same time encountering some challenges. The first challenge is the road traffic congestion entailed by container transport, especially around the port area. The reason for congestion is twofold. First, as many sea ports

![Figure 1 Throughput comparison among European ports, Hamburg-Le Havre Range (Jennings, 2006; PoR, 2012c)](image)

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lack in well-developed waterways and railroads (Visser, Konings, Pielage, & Wiegmans, 2007), trucking is currently the dominant mode for hinterland transport. Even for the ports like Port of Rotterdam which has abundant inland waterway resources, 56% of all containers (about 3.6 million TEUs) going to/from the port were still transported by road in 2009 (PoR, 2012b). Second, road capacity is comparatively small and is easily influenced by external conditions such as commuting peak and Working Time Directive of truck drivers. For instance, the road network accessing Port of Rotterdam is always overloaded at peak hours (PoR, 2011). And consequently, over 40% of vehicles (including container trucks) going to/from Maasvlakte suffer heavy delays (PoR, 2012a).

Moreover, the growing container road traffic brings many negative impacts to the environment. It is estimated that an export/import container will emit 5.6g CO$_2$/tonne-km if carried by a small containership (444 TEU) whereas 155g CO$_2$/tonne-km if carried by truck (Liao, Tseng, & Lu, 2009). Therefore in the Netherlands, 16% of the national CO$_2$ emission is concentrated in Rotterdam area (RCI, 2011), due to the massive port-related container trucking. In addition to GHG emission, container trucking also contributes a lot to the emission of air pollutants such as NO$_X$ and PM. Taking Port of Los Angeles as an example, in 2010 the emission of NO$_X$ and PM from heavy-duty trucks was twice of that from cargo handling equipment (Starcrest Consulting Group, 2011).

Furthermore, the low weight capacity utilization (WCU) of containers on laden trips greatly jeopardizes the efficiency of container transport. Take Port of Rotterdam as an example, based on 2009 and 2010 statistics, it is found that the average WCU was only 55%, which indicates that nearly half of the container weight capacity was wasted (see Appendix A). And as WCU and VCU are correlated with each other, a low WCU usually means a low volume capacity utilization (VCU). For example, a survey among 50 German haulage companies (including some container transport companies) has revealed that for heavy-duty trucks (> 40 tons) the mean weight and volume load factors are only 44.7% and 63.6% respectively (Léonardi & Baumgartner, 2004). As container truck constitutes a large part of the heavy trucks, it could be extrapolated that both volume and weight capacity of containers are somehow underutilized. Note that as weight capacity is used more often in industry due to its high measurability, volume capacity is not used in the thesis.

1.2 Solution illustration: cargo consolidation and its benefits

To deal with these challenges, a promising solution is to improve the capacity utilization of containers through cargo consolidation. To realize cargo consolidation, it is necessary to have a supportive facility – a decoupling center (DC) in or close to the sea port, where the cross docking at cargo level is enabled. With this facility, the consolidation could be done in the following way:

When a batch of containers (i.e. incoming containers) arrives at the terminal in the sea port, the logistic operator will decide, based on certain information, whether to shuttle these containers to DC for cargo consolidation, and how many containers to be shuttled. After the decision, some containers will be unsealed at DC so that the cargoes inside will be taken out for sorting and
accumulation, while the rest will be shipped directly from the terminal to the hinterland. When sorting and accumulation are finished, the consolidated cargoes will be reloaded to the outgoing containers and shuttled back to the terminal for shipment. And it will be guaranteed that through reloading, all the outgoing containers will achieve a high WCU in terms of a high container (weight) load factor.

The entire process flow of cargo consolidation and an overview of the logistic operations at DC are presented in Figure 2 and Figure 3 respectively.

**Process of Cargo Consolidation**

![Consolidation process flow](image)

*Figure 2 Consolidation process flow*
The expected outcome of the solution is a reduction of underutilized (semi-loaded) outgoing containers. To illustrate it, a comparison is provided in Figure 4. On the left, semi-loaded containers coming to the port are processed in a traditional way and shipped to the hinterland with much capacity being unexploited. However, on the right, as semi-loaded containers are allowed to be opened which enables the direct handling of cargoes, the capacity of containers could be fully utilized, resulting in less underutilized outgoing containers.
This outcome has several benefits. First, as the total amount of outgoing containers decreases, the demand for container trucking will also decrease. Consequently, there will be less road congestion and less negative environmental impacts, which correspond to deal with the challenges mentioned above.

Second, as fewer containers enter the hinterland, a reduction in the empty container movement could be achieved as well. The mechanism is shown in Figure 5. On the upper part of the graph, as cargo consolidation is not applied, the amount of containers going out of port remains the same as the amount of incoming containers. Hence, after cargo unloading at the final destination, there will be a large demand for repositioning the empty containers to the port. However, on the lower part of the graph, as cargo consolidation reduces the amount of outgoing containers, the amount of empty containers in the hinterland also decreases, which will entail less empty container movement.

Less empty container movement not only contributes to alleviate the road traffic congestion as well as the environmental pressure, but also helps to reduce the total operational cost in the supply chain. In 2010, worldwide port-to-port empty container traffic has reached 91.2 million TEU, leading to a repositioning cost of 38.4 billion dollar (ESPO, 2007; Jutta Wolff, Nico Herz, & Flamig, 2012). Therefore, if the amount of empty containers in the hinterland could be reduced by applying cargo consolidation, a dramatic cost saving could be achieved.

Third, as cargo consolidation helps to separate the urgent and non-urgent cargoes, the demand for container trucking will also decrease, which facilitates the modal shift towards barge and train. This is because when urgent and non-urgent cargoes are loaded together in a single container (see Figure 6), the container will be regarded as urgent and will be trucked to the destination to avoid the delay. However, when urgent and non-urgent cargoes are separated
with the help of cargo consolidation, it would be more appropriate to ship the non-urgent containers by a cheaper, cleaner but slightly slower mode, such as barge and train, and still ship the urgent containers by truck.

**Figure 6** Modal shift under cargo consolidation

### 1.3 Research question

Although cargo consolidation has many advantages especially for the society, it is still unknown whether the logistic service provider who applies the solution would be benefited and how could they be benefited. The focus on this perspective is indispensable, because if cargo consolidation adds too much operational cost, the profit-driven logistic service provider will not be fully incentivized to apply and/or invest on it. Moreover, as cargo consolidation leads to a trade-off between less transportation cost and more storage cost, a minimum operational cost might exist and would provide the logistic service provider with valuable guidance for its cost control. Therefore, an investigation in the cost performance of cargo consolidation is extremely necessary.

Moreover, as forwarding the containers from the port to the hinterland usually involves multiple transportation modes, the mode arrangement for hinterland container transport becomes an important issue. However, it is difficult to address the issue, as both the stochastic properties (e.g. stochastic arrival time) of containers and the time schedule (as well as cost) of transportation modes will influence the final decision of mode arrangement. And when cargo consolidation is involved, the situation will become more complicated, as the consolidation will create a cargo storage (i.e. time buffer) bringing more uncertainty in the container release time. Therefore, it is worthwhile to conduct a research on the mode arrangement for hinterland container transport under cargo consolidation.
Finally, as cargo consolidation and mode arrangement both require the support of logistics information, it is crucial to understand what type of information will help facilitate cargo consolidation and how the information will influence the mode arrangement.

Based on these considerations, the main research question of this thesis is formulated as:

**Under which circumstances can cargoes from different incoming containers arriving at the seaport be consolidated in outgoing containers to the hinterland, in order to reduce the total operational cost of logistics service provider?**

To support the main research question, four sub research questions are formulated:

- **Sub Q1.** What are the concept as well as the potential benefits of cargo consolidation?
- **Sub Q2.** What stochastic properties of cargo/container flows should be taken into consideration when applying cargo consolidation?
- **Sub Q3.** How to realize mode arrangement for the outgoing containers under cargo consolidation?
- **Sub Q4.** What kind of information is required to realize cargo consolidation and the mode arrangement?
- **Sub Q5.** Which cost items should be included in cargo consolidation?
- **Sub Q6.** How does the mode arrangement for outgoing containers affect the total cost?

### 1.4 Research methodology

The methodology used in this thesis consists of four steps. In the first step, some problems faced by the current container transport are identified with the help of scientific findings and government statistics. After that, a solution – improving the WCU through cargo consolidation – is proposed to deal with these problems. Based on the solution, a research question is formulated as stated above to guide the whole thesis. Subsequently, an analytical cost model is formulated to investigate the cost performance of the solution, which is the essence of this thesis. Finally, a numerical case is created to implement the model and an analysis based on the modeling results is presented to answer the research question and make some recommendations for the future research. The whole methodology is visualized in Figure 7.
1.5 Thesis outline

Corresponding to the methodology in Section 1.4, the thesis is structured as five chapters. In Chapter 1, problem definition and research questions are presented. In Chapter 2, a literature review is provided illustrating how this thesis contributes to the existing studies. In Chapter 3, details about the analytical cost model are discussed. In Chapter 4, a cost analysis based on a numerical case is conducted. And in Chapter 5, the final conclusion of the cost analysis and some recommendations are given.
Chapter 2 Literature Review

In this chapter, first, an overview of the previous works concerning analytical cost model for cargo consolidation, logistic information utilization and mode planning in intermodal container transport will be presented. Subsequently, how this thesis contributes to the current studies and the some literature that is more relevant for the thesis will be discussed.

2.1 Previous studies

2.1.1 Shipment consolidation

Cargo consolidation is in fact a combined application of shipment/freight consolidation and cross docking in intermodal container transport. Both shipment consolidation and cross docking enable the consolidation of several small shipments with the same destination into a single, larger shipment (Boysen & Fliedner, 2010; Brennan, 1981; Hall, 1987; Higginson & Bookbinder, 1995). The former focuses more on making full truck loads (FTLs) to achieve economies of scale in outbound transportation, whereas the latter is mainly about shipment sorting and minimizing the intermediate/temporal storage through synchronizing the inbound and outbound trucks (Apte & Viswanathan, 2000; Boysen & Fliedner, 2010). The Figure 8 and Figure 9 adapted from Apte and Viswanathan (2000) has clarified the difference in the focus between these two concepts.

![Figure 8 Principle of shipment consolidation](image-url)
Recent studies regarding cross docking mainly focus on the truck scheduling problems, which determine where and when the trucks should be processed at the dock doors (Boysen & Fliedner, 2010). However, as this thesis attempts to demonstrate how changes in container WCU will contribute to reducing the total operational cost at a strategic-operational level, this sort of literature seems rather irrelevant. Therefore, more efforts have been devoted to studying the literatures concerning shipment consolidation.

The first systematic discussion on shipment consolidation appeared in M. J. Beckmann (1953) and M. Beckmann, McGuire, and Winsten (1956), where a train could transfer its small loads to another big one heading for the same destination in the railway-switching yard. Subsequent studies from Schuster (1979) analyzed the economics of shipment consolidation, illustrating its potential benefits in cost performance. However, until 1976, there was virtually no report of sophisticated mathematical techniques in the technical literature (House & Jackson, 1980).

Some of the early academic treatments focus on analyzing the impacts of shipment consolidation, which are mainly realized by computer simulation (Sila Çetinkaya & Bookbinder, 2003). For instance, Masters (1980) and Cooper (1984) both used a Monte Carlo-based simulation to study the impacts of major variables in the order-consolidating system, while Closs and Cook (1987) established a dynamic simulation to address the freight consolidation in multiple-staged distribution system where small shipments are involved.

However, most of the later research is focused on determining the timing of dispatching the consolidated shipments (Bookbinder & Higginson, 2002). Jackson (1985) reported a practitioner survey, where three common consolidation policies were identified: time policy (dispatch every $T_0$ periods), quantity policy (hold until the shipment amount reaches $Q_0$) and time-and-quantity policy (dispatch according to time or quantity policy which is satisfied earlier). It was found that the time policy was adopted most frequently. To further evaluate these policies, especially on the timing issue, Higginson and Bookbinder (1994) made a simulation to compare their relative costs and delay performance. However, it is pointed out that the optimal value may not be
among the tested values used for the simulation (Sila Çetinkaya & Bookbinder, 2003).

To find the optimal dispatching policy, deterministic analytical research such as the work presented by Blumenfeld, Burns, Diltz, and Daganzo (1985) applies the concept of Economic Shipment Quantity (ESQ), i.e. the optimal number of items, orders, or weight that minimizes total cost. Deterministic ESQ could also be adapted for analyzing the long-run average performance in a stochastic environment. For example, Higginson (1995) discussed when the ESQ is an adequate substitute for a probabilistic analysis of dispatch timing.

Compared to the deterministic approach, stochastic approach has gained more attention recently, as they could incorporate more realistic factors. Stochastic approaches have evolved into many different forms. Brennan (1981), Sila Çetinkaya and Bookbinder (1997), Sila Çetinkaya and Bookbinder (2003) and Mutlu, Cetinkaya, and Bookbinder (2010) used Renewal (Reward) Theory to model and evaluate a stochastic consolidation problem. Renewal (Reward) Theory generalizes the Poisson process, which is usually applied to describe the stochastic shipment arrival. Higginson and Bookbinder (1995) used a Markov decision process to set load dispatch policies. Markov decision process is realized by setting probabilistic functions for a current state to transit to a future state. Powell (1985) and Powell and Humblet (1986) applied the bulk-queuing theory with the option to cancel scheduled vehicles if the load is too small. Besides, Stidham (1977) and Gupta and Wyskida (1972) dealt with it by introducing a stochastic clearing system, where the cumulative quantity enters the system will be “cleared” intermittently and instantaneously.

Besides, Sila Çetinkaya (2005) analyzed the shipment consolidation policies in the context of integrated inventory and transportation decisions. She categorized the policies as pure consolidation policy and integrated consolidation policy. Many previous researches such as Bookbinder and Higginson (2002) and Sila Çetinkaya and Bookbinder (2003) belong to pure consolidation strategy. For integrated policy, a typical example is the study from Sila Çetinkaya and Lee (2000), where a joint inventory replenishment and outbound shipment scheduling problem of a supplier operating under a Vendor Managed Inventory (VMI) agreement are considered simultaneously.

2.1.2 Mode planning in intermodal container transport

Intermodal freight transport refers to the movement of goods in one and the same loading unit or vehicle, which uses successive, various modes of transport (road, rail, water) without any handling of the goods themselves during transfers between modes (ECMT, 1993). As the loading unit/vehicle is usually acted by containers, the term “intermodal freight transport” is often understood the same as “intermodal container transport”.

In recent years, the intermodal freight (container) transport has emerged as a new transportation research application field, but still in a pre-paradigmatic phase (Bontekoning, Macharis, & Trip, 2004). To have a better overview of the problems which are often encountered in this field, Macharis and Bontekoning (2004) provided a classification matrix to categorize the existing literature in intermodal freight transport (see Figure 10). According to
this matrix, mode planning is usually attributed to terminal operators, as they are responsible for the transshipment operations from road to rail/barge, or from rail to rail, from barge to barge. But in this thesis, mode arrangement should be accomplished by the logistic service providers, as they attempt to efficiently exploit the intermodal services on the hinterland container transport and function as an intermodal operator. Moreover, as the mode planning here considers cargo consolidation which usually involves a time period of weeks, the planning should belong to a tactical level problem.

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<td>Intermodal operator</td>
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<td>Mode Planning with Cargo Consolidation</td>
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Figure 10 Matrix for categorizing common literatures in intermodal freight transport

According to Macharis and Bontekoning (2004), very few researches discussed the strategic and tactical issues faced by intermodal operators. Even in the paper of Caris, Macharis, and Janssens (2008), who updates the literature review based on Macharis and Bontekoning’s findings, there are no further discussions.

Among the limited studies, Cullinane and Toy (2000) made a content analysis to explain what attributes are usually considered in Stated Preference (SP) experiments of freight route/mode choice. It is found that cost, speed of the mode, and transit time reliability appear most frequently in the related articles. Similarly, García-Menéndez, Martínez-Zarzoso, and De Miguel (2004) emphasized the role of cost, transit time, and frequency of shipments as determinants of mode choice through estimating a freight transport demand function using a Conditional Logit model.

Moreover, mode choice decision is usually regarded as the mere route choice decision for specific trajectories between the starting and ending point (Macharis & Bontekoning, 2004). For example, Boardman, Malstrom, Butler, and Cole (1997) used the least-cost path criterion to find the best (i.e. least cost) combination of transportation modes (truck, rail, air, barge) between a given origin and a corresponding destination in a multimodal network.

However, the application of co-modal transport (Groothedde, Ruijgrok, & Tavasszy, 2005) is neglected in these works. Co-modality facilitates the use of different transport modes, on their
own and in combination, to obtain an optimal and sustainable utilization of freight transport resources (BMT, 2011). More specifically, it involves both slow and less costly transport modes such as barge and rail to carry the (containerized) cargoes of less value, and the fast and flexible trucking option to execute shipments under time pressure (Zuidwijk & Veenstra, 2010). This co-modality is important, because urgent cargoes are obviously not suitable for consolidation and need fast hinterland transport to avoid delays, while the non-urgent cargoes could not only conduct cargo consolidation but also exploit cheap transportation modes to minimize the total operational cost.

An application of co-modality in model planning could be found in the work of Zuidwijk and Veenstra (2010). The co-modality is realized by setting a “container release time” at the destination sea port, so that the containers arrive at the port before this critical time will be shipped by barge, while the ones that arrive later will be shipped by truck. However, although the authors include the delay cost for cargoes, the co-modality is not fully motivated by the urgency of cargoes. And cargo consolidation is also not considered.

2.1.3 Role of information in transport

The use of information plays a crucial role in controlling the supply chain dynamics. For example, Lee, Padmanabhan, and Whang (1997) found that the “bullwhip effect” in supply chain could be alleviated by information sharing among the supply chain actors. Tan (1999) further evaluated the impact of demand information sharing on supply chain network structures, product structures and demand mix. And Li, Shaw, and Tan (2000) quantified the benefits of demand and inventory information sharing on reducing demand uncertainty. These findings all indicate that logistic information has added value.

However, the general methods to assess the value of information (VOI), such as GEOSS Benefit Assessment and GMES Benefit Assessment, are not discussed too much in the literature. The basic concept behind these methods is a simple “benefit chain” (EuroGEOSS, 2012). In the benefit chain (see Figure 11), a certain piece of information will be obtained as a result of improved data system. This information will lead to improved decision making which has better economic benefits. And the value of this information will be calculated as the difference between the economic benefits brought by this information and the incremental cost to obtain this information (Fritz, Scholes, Obersteiner, Bouma, & Reyers, 2008).

![Figure 11 Benefit chain in the assessment of VOI, from (EuroGEOSS, 2012)](image-url)
An application of this principle in transportation field appears in the work of Zuidwijk and Veenstra (2010). In their work, different logistic information is revealed to shippers for container mode planning. As the information varies, the planning behavior changes accordingly and results in different cost. And by comparing the cost, the value of specific information is obtained.

However, some recent studies indicate that not all the logistics information gives added value for supply chain management, and the use of information might even become detrimental (Ketzenberg, Rosenzweig, Marucheck, & Metters, 2007). Therefore, the assessment of VOI in supply chain needs to consider not only the completeness, timeliness, and reliability of the information, but also consider the physical flows, information flows and, to some extent, commercial transactions where the information works (Ran, Veenstra, Ming, Lei, & Zuidwijk, 2010; Strong, Lee, & Wang, 1997).

### 2.2 Contribution of the thesis and relevant works

In the cost model, a modified time policy (release the consolidated cargoes every $t_0$) is applied to cargo consolidation. It is different from the traditional time policy, as the container release time $t_0$ will represent the departure time of a barge which carries the containers to the hinterland. Through this modification, the co-modality planning is realized. Therefore, the biggest contribution of this thesis is showing the possibility of combining the co-modality planning and cargo consolidation in a context of container transport.

Moreover, the concept to assess the value of specific information presented by Zuidwijk and Veenstra (2010) is also used in the model of the next chapter to investigate what type of information will influence cargo consolidation, and how the accuracy of information will affect the mode arrangement. From this perspective, the thesis makes a contribution to the evaluation of VOI in intermodal container transport as well.

Finally, the thesis will supplement the studies in the category of “intermodal operator-strategic/tactical level” for intermodal freight transport.
Chapter 3 Cost Models

In this chapter, a cost model is presented for the following cost analysis. The model consists of two parts. In the first part, four different scenarios where cargo consolidation is/isn’t applied are created. For each of them, the optimal total operational cost is formulated analytically. However, as some of the assumptions in these scenarios are overly simplified, a general case is provided to illustrate the costs of cargo consolidation in a more realistic environment. The structure of the model is depicted in Figure 12.

![Figure 12 Structure of the cost model](image)

To clarify the model, Chapter 3 is organized as the following five sections. In the first section, the background of the model will be discussed in detail. In specific, a fabricated storyline will be first presented to help better understand what has been taken into consideration in the model. After that, a description of the modeling scope and some basic assumptions will be presented. In the third section, the scenarios in the model will be introduced. Particularly, the consolidation policy and the cost structure in each scenario will be discussed. In the fourth section, the analytical cost functions in the four scenarios will be presented. And in the last section, the cost functions of the general case will be presented.

3.1 Story of modeling

To make the model more understandable to the readers, a story is given as follow:

A logistic operator is making an operational plan which has a fixed planning horizon – one week – to ship the containerized cargoes from the sea port to the hinterland. In this weekly plan, the operator has to arrange the transportation modes for container shipment. In particular, he/she will decide how many containers to be shipped by barge and/or by truck. Besides, the operator would like to apply cargo consolidation in the plan, as the consolidation facilities (i.e. decoupling center) is available. When a plan is created, the operator is required to present a cost estimate for implementing the plan and minimize the cost if possible.

Before each planning, the operator is given some logistic information as a resource, which turns out to have a large impact on the planning outcomes. Therefore, the employer of the operator would like to know what kind of information contributes to making a better plan and to
facilitating the application of cargo consolidation. To complete this task, the operator is asked to do the planning with different information given, and compare the implementation cost of different plans.

3.2 Modeling scope and basic assumptions

3.2.1 Modeling scope

According to the description of cargo consolidation in Section 1.2 and Section 3.1, the main scope of modeling (see Figure 13) is set from the container arrival at the port (i.e. incoming containers) to the container departure (i.e. outgoing containers), including the mode arrangement for the hinterland transport. In addition, the repositioning of empty containers from the hinterland back the sea port is also considered in the model, making it a more complete system.

Moreover, the model is limited to two types of cargoes (i.e. Cargo 1 and Cargo 2) and two hinterland destinations (i.e. A and B) at the same time. Note that incorporating more cargo types and/or more destinations is theoretically possible, but it will make the model too complex to solve.

Furthermore, as cargoes are sorted by destination at the decoupling center, the consolidation process as well as the shipment process is actually independent for the cargoes sending to two destinations. Therefore, in order to illustrate the model in a simpler way, only the cost functions for cargoes to destination A are formulated. And the cost functions for cargoes to B could be easily adapted based on those results.
3.2.2 Modeling assumptions in two environments

As mentioned previously, the assumptions made in the four scenarios and in the general case are different. This difference mainly occurs in the assumption of the incoming containers/cargo flows.

Difference
- **Assumption of incoming container/cargo flows**
In the four scenarios, the four cargo flows (i.e. 1 to A, 1 to B, 2 to A, 2 to B) are assumed to be loaded separately in the incoming containers. And among them, urgent and non-urgent cargo flows are also assumed as separated. In other words, one incoming container is only allowed to accommodate one of the eight incoming cargo flows. With this assumption, the incoming cargo flows in the four scenarios are identical, and their total costs are hence comparable with each other. If very complicated cargo flows are assumed, then in the scenario where less logistic information is provided, the operator would not be able to make the “weekly plan”. But in the general case, as there is no need for comparison, the mixed incoming cargo flows are assumed.

Common ground
In addition to the difference, there are also some assumptions shared by the four scenarios and the general case.

- **Assumption of container arrival**
In both situations, container arrival is regarded as a Poisson process, which means that the event that a given number of container arrivals occur in a given time interval follows Poisson probability. The assumption is reasonable, because container arrival could be regarded as an independent random event – as normally one arrival will not be influenced by other arrivals and external conditions. In each arrival, there are multiple containers. Therefore, an arrival is called a “batch”. The number of containers in one batch is assumed again as a random variable, which is independent from the arrival.

- **Assumption of barge capacity and barge departure time**
In both situations, the capacity issue of barge is neglected. With this simplification, the departure time of barge will not be influenced by the number of containers to be shipped. However, it should be noted that in practice, small logistic service providers have to consider the capacity issue, as barge operation is usually in command of shipping companies. And if releasing this assumption, the theoretical best barge departure time might not be achieved, because the capacity might already reach its limit before that time. Moreover, as barge usually has a fixed time schedule on a specific shipping route, logistic service providers sometimes might not be able to plan the barge departure time. But in our model, it is also neglected for simplification.

- **Assumption of container/cargo operation time**
In both situations, the only “time” included in the model is the storage time required for container and/or cargo accumulation. Other “times” such as container handling time, container shuttling time and cargo operation time are all ignored. This assumption aims to highlight the
biggest trade-off in cargo consolidation: the more storage and penalty cost but less transportation cost v.s. the less storage and penalty cost but more transportation cost.

- **Assumption of cargo operation procedure**

In both situations, it is assumed that during cargo operation, all the cargoes are taken out from the containers. And after consolidation, they will be reloaded to the outgoing containers. In other words, all the cargoes will be operated. However, in practice, the first-line staffs in the decoupling center might just remove some cargoes from one container and put it into another. Therefore, it will result in a slightly larger cargo operation cost. But as operation cost does not contribute too much to the total cost, this assumption could also be accepted.

- **Assumption of penalty cost**

In both situations, a penalty cost is assigned to the cargoes that will be shipped by barge and the cargoes being consolidated. The reason is that all of these cargoes will undergo a storage either in the stacking area or in the decoupling center, which creates delay at the hinterland. When formulating the penalty cost for a specified storage process, only the deadline of the first container arrival in this storage process is used. This assumption will lead to a larger penalty cost, as the containers that arrive later in this storage process will still be assigned a tight deadline. The consequence of this assumption is putting forward the barge departure time, as only in this way the penalty cost could be counteracted. This phenomenon will be discussed in more details in Appendix E.

### 3.3 Four scenarios and general case in the cost model

In this section, a detailed description of the four scenarios and the general case will be presented first. Subsequently, the action process chain as well as the cost structure in each of them will be discussed.

#### 3.3.1 Introduction to the scenarios

The scenarios and the general case are introduced at the order of the quantity/quality of the logistic information provided to the operator for planning (see Table 1).

<table>
<thead>
<tr>
<th>Table 1 Overview of the logistic information revealed in the four scenarios and the general case</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Information provided</strong></td>
</tr>
<tr>
<td>Scenario 1</td>
</tr>
<tr>
<td>Scenario 2</td>
</tr>
<tr>
<td>Scenario 3</td>
</tr>
<tr>
<td>Scenario 4</td>
</tr>
<tr>
<td>General case</td>
</tr>
</tbody>
</table>

**Scenario 1**

In Scenario 1, as the operator could not expect when and how many containers will arrive at the
port within the coming planning horizon, the only plan he/she could make is to use the most flexible mode – truck – to ship the containers to the hinterland once they come. In order to better understand the plan, a visualization of the total amount of containers at the port is provided in Figure 14. In the graph, Y-axis denotes the number of containers, while X-axis denotes the container arrival time. Note that as container operation is assumed as instantly completed (see 3.2.2 Modeling assumptions in two environments), container arrival time here is the same as container departure time. And the end of planning horizon is denoted as \( t_1 \).

![Figure 14 Consolidation plan in Scenario 1](image)

**Scenario 2**

In Scenario 2, the number of containers in each batch and the container arrival information is revealed to the logistic operator. With the information, the operator could plan a barge which leaves the port at \( t_0 \) (in the middle of the week), so that all the non-urgent containers arriving at the port before \( t_0 \) will be shipped to the hinterland by barge. And the urgent containers arriving during the whole planning horizon as well as the non-urgent containers arriving after \( t_0 \) will be shipped by truck. Again, a visualization of the total amount of containers at the port is provided in Figure 15. It could be observed that there is an accumulation (i.e. storage process) of containers before \( t_0 \), because barge has a relatively fixed time schedule. Compared to barge, truck could be maneuvered at any time as it has a more flexible time schedule. Therefore, accumulation is not required after \( t_0 \).

![Figure 15 Consolidation plan in Scenario 2](image)

**Scenario 3**

In Scenario 3, an extra piece of information – the distribution of container load factors (weight
utilization) – is given to the operator. With this information, the operator could apply cargo consolidation.

Similar to the plan in Scenario 2, the non-urgent containers arriving before \( t_0 \) will be shipped by barge, and the non-urgent containers arriving after \( t_0 \) as well as the urgent containers arriving during the whole planning horizon will still be shipped by truck. However, now some of the non-urgent containers will be opened for cargo consolidation.

In specific, when a batch of containers arrives at the port, all the non-urgent containers will be shuttled to DC, whereas the urgent containers will be shipped to the hinterland instantaneously by truck. Then, the non-urgent containers will be examined the capacity utilization to see whether they need to be consolidated. After examination, a part of containers will be shuttled back to the port for shipment as they already have high capacity utilization, while the rest will be opened for cargo consolidation. Once the consolidation is finished, the consolidated cargoes will be reloaded to the outgoing containers and also shuttled back to the port for shipment. A visualization of the plan is presented in Figure 16.

In the graph, there are two consolidation processes. The first consolidation lasts till \( t_0 \), and the second consolidation lasts from \( t_0 \) to \( t_1 \). The only difference between them is the transportation modes used to ship the cargoes after consolidation. Moreover, note that the second consolidation actually indicates that once the non-urgent containers (arriving after \( t_0 \)) are opened for consolidation, the consolidated cargoes have to be released until \( t_1 \), even if they might already form one or several full truckloads before that time. This is a bit different from the reality, as logistic operators would like to push the containers to the hinterland as soon as possible. However, if considering this issue in the model, it will introduce an extra consolidation policy – quantity policy (i.e. ship until a full truckload is meet), which will largely increase the complexity of the model. Considering this, a discount price is given to the trucks that leave the port at \( t_1 \). This is because if there is always a large trucking demand at the end of each week at the same location, trucking companies might experience less truck reposition cost, which leads to a cheaper unit trucking cost.

![Figure 16 Consolidation plan in Scenario 3](image-url)
Scenario 4
In Scenario 4, the operator is given the more accurate information – the exact load factor of each container instead of a distribution. With this information, the operator will still make the same plan as in Scenario 3. However, the non-urgent containers that will be opened could be determined in advance. Therefore, the capacity utilization check at the decoupling center becomes unnecessary. Consequently, the amount of containers to be shuttled will also decrease.

General case
In the general case, the operator is given the barge turnaround time. With this information, the operator could arrange two barge departures instead of one during a planning horizon. And it is expected that with this extra barge, more containers could be shipped by barge to lower the transportation cost. Again, a visualization of the total amount of containers at the port is presented in Figure 17.

![Figure 17 Consolidation plan in New Scenario](image)

3.3.2 Process chain and cost composition
To formulate the implementation cost of the above “weekly plans”, it is indispensable to understand the process chains in each plan and the corresponding cost structures.

In Scenario 1, as there is no barge transport and no cargo consolidation, once the containers arrive at the port, they will be shipped to the hinterland destination by truck instantaneously. And after the cargo unloading at the hinterland, the empty containers will be shipped back to the sea port by a cheap mode, such as barge. The action process chain is shown in Figure 18. Note that in the figure, “P” stands for the sea port, “D” stands for the destination, black arrow denotes the loaded container flows, and blue arrow denotes the empty container flows.

![Figure 18 Process chain in Scenario 1](image)

In Scenario 2, all the incoming containers will first be unloaded from the vessel. And a part of
them will be immediately handled onto the outgoing trucks, while the rest will be stored at the stacking area in the port/terminal. When the barge is ready, these containers will be handled onto the barge for shipment. For the containers arriving after \( t_0 \), storage is not required. And again, the empty containers will be returned by barge. The process chain is depicted in Figure 19. Note that in the figure, “S” stands for the stacking area.

In Scenario 3, as all the non-urgent containers will undergo capacity check at the decoupling center, there is a demand for container shuttle between the port and the decoupling center. After capacity check, the logistic staffs need to take out the cargoes from the containers, and do the cargo sorting and storage. Finally, the consolidated cargoes will be reloaded to the outgoing containers and shuttled back the port for shipment. The process chain is depicted in Figure 20.

In Scenario 4 and the general case, as the exact load factors of the incoming containers is given, only a part of non-urgent containers will be shuttled to the decoupling center for cargo consolidation. And container capacity check will be eliminated. The process chain is depicted in Figure 21. Note that the black arrow from “P” to “P+s” stands for the stacking process for the non-urgent containers that already have high load factor and will be shipped by barge.

Based on the action chains in the four scenarios and the general case, the cost structure is presented in Table 2. It could be observed from the table that cargo consolidation will greatly increase the handling times. Specifically, when cargo consolidation does not exist, containers will only be unloaded from the vessel and loaded to the outgoing vehicles. After these containers arrive at the hinterland, they will be once again handled from the vehicles. However,
when applying cargo consolidation, containers will need extra handlings onto/off the shuttle. Moreover, in the general case, as mixed cargo flows are allowed, all the containers have to be shuttled to the decoupling center for cargo sorting. Therefore, the stacking cost is excluded.

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>General Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>container unloading from vessel (port)</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>container stacking</td>
<td>✗</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>✗</td>
</tr>
<tr>
<td>container loading to shuttle (port)</td>
<td>✗</td>
<td>✗</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>shuttle to DC</td>
<td>✗</td>
<td>✗</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>container unloading from shuttle (DC)</td>
<td>✗</td>
<td>✗</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>container capacity check</td>
<td>✗</td>
<td>✗</td>
<td>○</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>cargo operation</td>
<td>✗</td>
<td>✗</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>cargo storage</td>
<td>✗</td>
<td>✗</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>container loading to shuttle (DC)</td>
<td>✗</td>
<td>✗</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>shuttle to port</td>
<td>✗</td>
<td>✗</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>container unloading from shuttle (port)</td>
<td>✗</td>
<td>✗</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>container loading to barge/truck (port)</td>
<td>○</td>
<td>✗</td>
<td>○</td>
<td>○</td>
<td>○</td>
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<tr>
<td>shipment by truck</td>
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<td>○</td>
<td>○</td>
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</tr>
<tr>
<td>shipment by barge</td>
<td>✗</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>truck delay</td>
<td>✗</td>
<td>✗</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>barge delay</td>
<td>✗</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>container unloading from barge/truck</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>empty container loading to return barge</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>empty container repositioning</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>empty container unloading from barge</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>

○: the cost item is included  
✗: the cost item is not included
3.4 Cost functions of simplified scenarios

3.4.1 Cost functions of Scenario 1

According to Table 2, the total operational cost in Scenario 1 consists of shipment cost, empty container repositioning cost and handling cost.

**Shipment cost and repositioning cost**

As only truck is used for shipping the containers from the sea port to the hinterland, shipment cost equals to truck cost. To calculate truck cost, it is required to know how many containers are shipped to the hinterland. Note that the number of empty containers returned is always the same as the number of containers going to the hinterland. Therefore, empty container repositioning cost could be formulated similarly as truck cost here. The only difference lies in the unit cost. To formulate the total number of containers going to the hinterland, the following definitions are introduced.

Let \( n_j \) denote the number of containers in the \( j^{th} \) container arrival (i.e. \( j^{th} \) batch). \( n_j \) is an independent random variable, which follows certain probabilistic distribution. Among \( n_j \), the number of containers accommodating Cargo 1 and Cargo 2 that will go to destination A are identified as \( n^A_{j1} \) and \( n^A_{j2} \) respectively. With these definitions, the total number of containers shipped to A could be formulated as a summation of \( (n^A_{j1} + n^A_{j2}) \) for all \( j \) (i.e. for all batches/arrivals). And let \( M \) denote the number of container arrivals during the whole planning horizon \( t_1 \). It is then clear that \( j \in \{1,2,...,M\} \), and the summation could be specified as \( \Sigma_{j=1}^{M} n^A_{j1} + n^A_{j2} \).

Moreover, as container arrival is a stochastic process (i.e. \( M \) is a random variable instead of a constant), it is more reasonable to focus on the expectation of the cost. This is because expectation reflects the average cost performance, which will offer the logistic operator guidance for cost control. Considering this, the total number of containers shipped to A should be formulated as \( E(\Sigma_{j=1}^{M} n^A_{j1} + n^A_{j2}) \). Note that without specific explanation, all the costs mentioned in this model refer to their expectation.

Due to the independence of \( n_j \), the total number of containers shipped to A could be transformed as \( E(n^A_{j1} + n^A_{j2}) \times E(M) \), where \( E(n^A_{j1} + n^A_{j2}) \) stands for the expected number of containers in one batch/arrival and \( E(M) \) stands for the expected number of container arrivals during the whole planning horizon \( t_1 \). As container arrival has Poisson properties (see 3.2.2 Modeling assumptions in two environments), \( E(M) \) is in fact a function of \( t_1 \) and could be denoted as \( m(t_1) \). Therefore, the total number of containers shipped to A is expressed as \( E(n^A_{j1} + n^A_{j2}) \times m(t_1) \). And finally the truck cost is formulated as \( c^A_t \times E(n^A_{j1} + n^A_{j2}) \times m(t_1) \), where \( c^A_t \) denotes the truck cost to destination A per container. And when formulating the empty container repositioning cost, \( c^A_r \) will be replaced by \( c^A_r \), where \( c^A_r \) stands for the unit barge cost for empty containers. The entire function is shown in Equation 1. Note that the coefficient in the equation is written as \( K^A_{T1} \) and \( K^A_{T2} \) for abbreviation.
Container handling cost

As handling cost is formulated as handling times multiplied by unit handling cost \( c_h \), it is required to know how many times are containers handled during the whole planning horizon \( t_1 \). In Scenario 1, containers are first unloaded from the incoming vessels, then loaded to the outgoing trucks, and finally unloaded at the hinterland. Therefore, a container going to the hinterland will experience three handling. And the cost is formulated as \( 3 \times E(\sum_{j=1}^{M} n_{j1}^A + n_{j2}^A) \). On the return way, empty containers are first loaded to the barge at hinterland terminals and then unloaded at the sea port. Therefore, handling cost of empty containers is formulated as \( 2 \times E(\sum_{j=1}^{M} n_{j1}^A + n_{j2}^A) \). The total handling cost is hence a summation of them. The entire function is shown in Equation 2.

Equation 2

\[
E(C_{H_{total}}^{m}) = E(C_{H_{A}}^{A}) + E(C_{H_{m}}^{m})
\]
\[
E(C_{H_{A}}^{A}) = c_h \times 3E(\sum_{j=1}^{M} n_{j1}^A + n_{j2}^A)
\]
\[
= c_h \times 3E(n_{j1}^A + n_{j2}^A) \times E(M)
\]
\[
= K_{H_{1}}^A \times m(t_1)
\]
\[
E(C_{H_{m}}^{m}) = c_h \times 2E(\sum_{j=1}^{M} n_{j1}^A + n_{j2}^A)
\]
\[
= c_h \times 2E(n_{j1}^A + n_{j2}^A) \times E(M)
\]
\[
= K_{H_{2}}^A \times m(t_1)
\]

Total cost and minimum cost

In Scenario 1, as the operator has no logistic information in advance, neither cargo consolidation nor a cheap transportation mode could be exploited. Therefore, there is no opportunity for cost optimization, and the total operational cost equals to the minimum cost. The entire function is shown in Equation 3.
Equation 3

\[ E\left( C_{\text{TOTAL}}^A \right) = E\left( C_{T}^{\text{total}} \right) + E\left( C_{H}^{\text{total}} \right) \]

\[ = C_1 \cdot m(t_1) \]

\[ C_1 = K_{T1}^A + K_{T2}^A + K_{H1}^A + K_{H2}^A \]

\[ E\left( C_{\text{Min}}^A \right) = E\left( C_{\text{TOTAL}}^A \right) \]
3.4.2 Cost functions of Scenario 2

In Scenario 2, the total operational cost consists of shipment cost, empty container repositioning cost, storage cost, handling cost and penalty cost.

**Shipment cost and repositioning cost**

As logistic operator is now able to exploit barge for shipment, shipment cost consists of barge cost and truck cost. To calculate them, it is necessary to know how many containers are shipped by barge and truck to the hinterland respectively during the whole planning horizon \( t_1 \).

According to the process chain described in section 3.3.2 Process chain and cost composition, the barge leaves for the hinterland from the port at \( t_0 \) \( (t_0 < t_1) \), and all the non-urgent containers that arrive at the port before this time will be shipped by barge. Therefore, let \( N \) denote the number of container arrivals by \( t_0 \). As barge departure time \( t_0 \) is independent of planning horizon \( t_1 \), \( M \) and \( N \) are independent as well. There might be a misunderstanding that \( M \) and \( N \) are not independent, as \( M \) is always larger than \( N \). However, the random events that \( M \) and \( N \) describe are actually independent. Specifically, \( M \) describes the event “there are \( M \) container arrivals by \( t_1 \)”, while \( N \) describe the event that “there are \( N \) container arrivals by \( t_0 \)”. It is clear that the occurrence of \( M \) does not indicate the occurrence of \( N \), and vice versa.

By introducing the definition of \( N \), the number of containers that arrive before \( t_0 \) could be formulated as \( E(\sum_{j=1}^{N} n_{j1}^A + n_{j2}^A) \). Among them, the share of non-urgent containers is \( 1 - k_u \), where \( k_u \) is the urgent container factor. With these definitions, barge cost is formulated as \( c_b^A \times (1 - k_u) \times E(\sum_{j=1}^{N} n_{j1}^A + n_{j2}^A) \), where \( c_b^A \) denotes the unit barge cost to destination \( A \) per container. Similar to the calculation in Scenario 1, \( E(\sum_{j=1}^{N} n_{j1}^A + n_{j2}^A) \) could be transformed as \( E(n_{j1}^A + n_{j2}^A) \times E(N) \), where \( E(N) \) means the expected number of container arrivals by \( t_0 \). Like \( E(M) \), \( E(N) \) is also a function of time, and could be expressed as \( m(t_0) \).

The containers shipped by truck now consist of two parts. The first part comes from the urgent containers that arrive at the port before \( t_0 \). The second part comes from the (urgent and non-urgent) containers that arrive later than \( t_0 \), which is expressed as \( E(\sum_{j=N+1}^{M} (n_{j1}^A + n_{j2}^A)) \).

Again, this expression could be transformed as the expected number of containers in one batch/arrival times the expected number of container arrivals between \( t_0 \) and \( t_1 \), i.e. \( E(M - N) \). And due to the independence of \( M \) and \( N \), \( E(M - N) \) could be written as \( E(M) - E(N) \). Therefore, truck cost is calculated as the unit truck cost \( c_t^A \) multiplied by the summation of them.

Again, the empty container repositioning cost will be calculated very easily, due to a conservation in the number of containers. The entire function is shown in Equation 4.
Equation 4

\[
E\left(C_{T}^{\text{total}}\right) = E\left(C_{b}^{A}\right) + E\left(C_{i}^{A}\right) + E\left(C_{T}^{\text{em}}\right)
\]

\[
E\left(C_{b}^{A}\right) = \frac{c_{b}^{A}}{K_{T1}} * \left(1 - k_{u}\right) * E\left(\sum_{j=1}^{N} n_{j1}^{A} + n_{j2}^{A}\right)
\]

\[
= \frac{c_{b}^{A}}{K_{T1}} * \left(1 - k_{u}\right) * E\left(n_{j1}^{A} + n_{j2}^{A}\right) * E\left(N\right)
\]

\[
= K_{T1}^{A} * m(t_{0})
\]

\[
E\left(C_{i}^{A}\right) = \frac{c_{i}^{A}}{K_{T2}} \left[ k_{u} * E\left(\sum_{j=1}^{N} n_{j1}^{A} + n_{j2}^{A}\right) + E\left(\sum_{j=N+1}^{M} n_{j1}^{A} + n_{j2}^{A}\right) \right]
\]

\[
= \frac{c_{i}^{A}}{K_{T2}} \left[ k_{u} * E\left(n_{j1}^{A} + n_{j2}^{A}\right) + E\left(M - (1 - k_{u}) E\left(N\right)\right) \right]
\]

\[
= K_{T2}^{A} * m(t_{i}) - K_{T3}^{A} * m(t_{0})
\]

\[
E\left(C_{T}^{\text{em}}\right) = \frac{c_{b}^{*}}{K_{T4}} \left(\sum_{j=1}^{M} n_{j1}^{A} + n_{j2}^{A}\right)
\]

\[
= \frac{c_{b}^{*}}{K_{T4}} \left(n_{j1}^{A} + n_{j2}^{A}\right) * E\left(M\right)
\]

\[
= K_{T4}^{A} * m(t_{i})
\]

Container storage cost

To calculate container storage cost in Scenario 2, it is necessary to know how many containers will be stored at the stacking area and how long will them be stored. Note that according to the description in section 3.3.1 Introduction to the scenarios, storage cost is only attributed to the non-urgent containers that arrive at the port before \(t_{0}\).

Let \(S_{j}\) denote the arrival time of the \(j^{th}\) batch of containers. And let \(T_{i}\) denote the time interval between the \(i^{th}\) and the \(i - 1^{th}\) container arrival. Therefore, \(S_{j}\) could be expressed, in terms of \(T_{i}\), as \(\sum_{i=1}^{j} T_{i}\). With these denotations, the storage time of the \(j^{th}\) batch of containers is formulated as \(t_{0} - S_{j}\). Consequently, the storage cost of the \(j^{th}\) batch of containers is formulated as the unit storage cost \(c_{b}\) (per container per time), times the number of containers stored \((1 - k_{u}) (n_{j1}^{A} + n_{j2}^{A})\), and times the storage time \(t_{0} - S_{j}\). And to calculate the total cost, it is required to make a summation for all the batches/arrivals before \(t_{0}\). The entire equation is shown in Equation 5.
Due to the independence of $n_j$, the term $E \left( \sum_{i=1}^{N} (n_{j_1} + n_{j_2}) \right)$ in the above equation is transformed as $E(n_{j_1} + n_{j_2}) \cdot E(\sum_{i=1}^{N} t_0 - S_j)$, where $E(\sum_{i=1}^{N} t_0 - S_j)$ stands for the expected (barge-related) storage time of all non-urgent containers that arrive before $t_0$. This expected storage time is further spread out in terms of the inter-arrival time (i.e. $T_1, T_2, ..., T_N$) for calculation. As the inter-arrival time is independent of the number of arrivals, the expected storage time is finally expressed as $E(N) \cdot t_0 / 2$. Note that an approximation is taken during the calculation. In specific, the expected inter-arrival time $E(T_i)$ is replaced by $t_0 / (N + 1)$, so that the cost is expressed in terms of $t_0$ for the later optimization. This approximation will not be validated if $N$ is very small. But normally in practice as there are a lot of container arrivals, it could be accepted.

**Container handling cost**

In Scenario 2, as the number of containers does not change, the handling cost is totally the same as in Scenario 1. The entire equation is shown in Equation 6.
Equation 6

\[
E(C_{H}^{\text{total}}) = E(C_{H}^{\Delta}) + E(C_{H}^{\text{env}})
\]

\[
E(C_{H}^{\Delta}) = c_{h} \times 3E\left(\sum_{j=1}^{M} n_{j_1}^{\Delta} + n_{j_2}^{\Delta}\right)
\]

\[
= c_{h} \times 3E\left(n_{j_1}^{\Delta} + n_{j_2}^{\Delta}\right) \ast E(M)
\]

\[
= K_{H1}^{\Delta} \ast m(t)
\]

\[
E(C_{H}^{\text{env}}) = c_{h} \times 2E\left(\sum_{j=1}^{M} n_{j_1}^{\Delta} + n_{j_2}^{\Delta}\right)
\]

\[
= c_{h} \times 2E\left(n_{j_1}^{\Delta} + n_{j_2}^{\Delta}\right) \ast E(M)
\]

\[
= K_{H2}^{\Delta} \ast m(t)
\]

Penalty cost

In Scenario 2, a penalty cost is assigned to the non-urgent containers shipped by barge, as they all have to wait for the barge, which might create a delay at the hinterland destination A. To formulate penalty cost, it is necessary to know how many containers might be delayed and how long would the delay be. Considering this, the following definitions are introduced.

Let \(\tau_A\) denote the time that the barge arrives at destination A. \(\tau_A\) equals to the barge departure time \(t_0\) plus the barge transition time \(g_b\). Both \(\tau_A\) and \(g_b\) are independent random variables. Besides, let \(D_j^1\) and \(D_j^2\) denote the deadlines of the \(j\)th batch of containers that accommodate Cargo 1 and Cargo 2. Note that the earlier the arrival, the smaller the deadline. With the above definitions, the delay of the \(j\)th batch of containers (accommodating Cargo 1 and Cargo 2) could be expressed as \(\tau_A - D_j^1\) and \(\tau_A - D_j^2\) respectively. Therefore, the penalty cost of the \(j\)th batch of containers is formulated as the unit penalty cost \(c_p^1\) (and \(c_p^2\)), times the number of non-urgent containers \((1 - k_u) \ast n_{j_1}^{\Delta}\) (and \((1 - k_u) \ast n_{j_2}^{\Delta}\)), and times the delay \(\tau_A - D_j^1\) (and \(\tau_A - D_j^2\)). To calculate the total penalty cost, it is required to make a summation for all batches/arrivals that come before \(t_0\). The entire function is shown in Equation 7. Note that \(D_j^1\) and \(D_j^2\) in the equation is replaced by \(D_j^A\) and \(D_j^{\Delta}\) respectively, as mentioned in the model assumption.

Equation 7

\[
E(C_{p}^{A}) = (1 - k_u) \ast E\left(\sum_{j=1}^{N} c_p^1 \times n_{j_1}^{\Delta} \ast (\tau_A - D_j^1) + c_p^2 \times n_{j_2}^{\Delta} \ast (\tau_A - D_j^2)\right)
\]

\[
= (1 - k_u) \ast E\left(\sum_{j=1}^{N} (c_p^1 \times n_{j_1}^{\Delta} + c_p^2 \times n_{j_2}^{\Delta}) \ast (\tau_A - D_j^1) - c_p^1 \times n_{j_1}^{\Delta} \ast D_j^1 - c_p^2 \times n_{j_2}^{\Delta} \ast D_j^2\right)
\]

\[
\leq (1 - k_u) \ast E\left(\sum_{j=1}^{N} (c_p^1 \times n_{j_1}^{\Delta} + c_p^2 \times n_{j_2}^{\Delta}) \ast (\tau_A - D_j^1) - c_p^1 \times n_{j_1}^{\Delta} \ast D_j^1 - c_p^2 \times n_{j_2}^{\Delta} \ast D_j^2\right)
\]

\[
= (1 - k_u) \ast \left\{\left[(c_p^1 \ast E(n_{j_1}^{\Delta}) + c_p^2 \ast E(n_{j_2}^{\Delta})) \ast (\tau_A - D_j^1) - c_p^1 \times D_j^1 \ast E(n_{j_1}^{\Delta}) - c_p^2 \times D_j^2 \ast E(n_{j_2}^{\Delta})\right]\ast E(N)\right\}
\]

\[
= K_{p1}^{A} \ast t_0 \ast E(N) + K_{p2}^{A} \ast E(N)
\]

\[
= K_{p1}^{A} \ast m(t_0) \ast t_0 + K_{p2}^{A} \ast m(t_0)
\]
Total cost and minimum cost

As using barge service will lead to a trade-off between smaller transportation cost and larger storage and penalty cost, an optimal barge departure time $t_0$ might exist to achieve the minimum cost. To find out the analytical expression of the (locally) best $t_0$, a derivative equation is generated. The entire function is shown in Equation 8. In the equation, a $\lambda$ is introduced. The $\lambda$ refers to the arrival rate of the container batches, as the container arrival is assumed as a Poisson process. And by using Renewal Theory, it is very easy to know that $m(t_0) = \lambda t_0$, and $m(t_1) = \lambda t_1$.

Equation 8

$$E(C^A_{\text{TOTAL}}) = E(C^A_T) + E(C^A_S) + E(C^A_H) + E(C^A_P)$$

$$= C_1 * m(t_0) + C_2 * m(t_0) * t_0 + C_3 * m(t_1)$$

$$C_1 = K^A_T - K^A_{T2} + K^A_{P2}$$

$$C_2 = K^A_S + K^A_{P1}$$

$$C_3 = K^A_{T2} + K^A_{T4} + K^A_{H1} + K^A_{n_2}$$

$$\frac{dE(C^A_{\text{TOTAL}})}{dt_0} = C_4 * \frac{dm(t_0)}{dt_0} + C_2 * \left[t_0 * \frac{dm(t_0)}{dt_0} + m(t_0)\right]$$

$$t_0^{\text{opt}} = -\frac{C_1}{2C_2}$$

$$E(C^A_{\text{Min}}) = \lambda t_0 C_3 - \frac{\lambda C^2_1}{4C_2}$$
3.4.3 Cost functions of Scenario 3

In Scenario 3, the total operational cost consists of shipment cost, empty container repositioning cost, shuttle cost, container inspection cost, cargo operation cost, handling cost, storage cost, and penalty cost.

Shipments cost and repositioning cost

Shipments cost in Scenario 3 consists of barge cost and truck cost, which is the same as Scenario 2. But the number of outgoing containers will decrease due to the application of cargo consolidation.

According to the process chain in section 3.3.2 Process chain and cost composition, only a part of non-urgent containers will be opened for consolidation after the capacity utilization check. It indicates that cargo consolidation will take place at a certain probability. Considering this, let \( P_{O1}^A \) and \( P_{O2}^A \) denote the probability of non-urgent containers that accommodate Cargo 1 and Cargo 2 being opened for consolidation respectively. Moreover, let \( f_{Li} \) denote the distribution of container load factors, and let \( L_0 \) denote the criterion for utilization check. As non-urgent containers whose load factors are smaller than \( L_0 \) will be opened, \( P_{O1}^A \) and \( P_{O2}^A \) could be expressed in terms of \( f_{Li} \) and \( L_0 \). In specific, \( P_{O1}^A = P(L_{bj1} < L_0) = f_{L1}(L_0) \), \( P_{O2}^A = P(L_{bj2} < L_0) = f_{L2}(L_0) \), where \( L_{bj1} \) and \( L_{bj2} \) are the load factors of the incoming containers that accommodate Cargo 1 and Cargo 2. In addition, let \( L_a \) denote the load factor of the containers after consolidation.

With the above denotations, barge cost could be formulated. The first part of barge cost (denoted as \( C_{b}^{op} \)) is generated by the non-urgent containers that arrive before \( t_0 \) and require consolidation. The number of outgoing containers after consolidation is formulated as the total weight of consolidated cargoes divided by the standard weight of an outgoing container. The total weight of consolidated cargoes is formulated as \( (1 - k_w) \cdot E(\sum_{j=1}^{N} f_{Li}(L_0) \cdot (n_{1j} L_{bj1} + n_{2j} L_{bj2}) \cdot w) \), where \( w \) stands for the maximum weight of a fully loaded container, and \( (n_{1j} L_{bj1} + n_{2j} L_{bj2}) \cdot w \) stands for the total cargo weight of the \( j^{th} \) batch of containers. The standard weight of an outgoing container is \( w \cdot L_a \). Therefore, the total number of outgoing containers after consolidation is expressed as \( (1 - k_w) \cdot E(\sum_{j=1}^{N} f_{Li}(L_0) \cdot (n_{1j} L_{bj1} + n_{2j} L_{bj2})) / L_a \). It is clear that \( L_a \) should be larger than \( L_{bj1} \) and \( L_{bj2} \), as only in this way the number of outgoing containers could be reduced. The second part of barge cost (denoted as \( C_{b}^{un} \)) is generated by the non-urgent containers that arrive before \( t_0 \) and do not require consolidation. The number of these containers is formulated as \( (1 - k_w) \cdot E(\sum_{j=1}^{N} (1 - f_{Li}(L_0)) \cdot (n_{1j} + n_{2j})) \). Finally, barge cost is formulated as the unit barge cost times the total number of containers that use barge service.

In Scenario 3, truck cost consists of three parts. The first part of truck cost (denoted as \( C_{t}^{ur} \)) is generated by the urgent containers arriving in the whole planning horizon. As urgent containers will not be opened for consolidation, the cost is totally the same as that in Scenario 2. The second part of truck cost (denoted as \( C_{t}^{op} \)) is generated by the non-urgent containers that arrive after \( t_0 \) and require consolidation. And the third part of truck cost (denoted as \( C_{t}^{un} \)) is caused by the non-urgent containers that arrive after \( t_0 \) but do not require consolidation. The latter two parts
could be formulated similarly as the above barge cost. The only difference is that as these 
containers all arrive after $t_0$, the summation index $j \in \{N + 1, N + 2, ..., M\}$.

For empty container repositioning cost, it is calculated as the unit repositioning cost $c^e_b$ times 
the number of containers returned to the sea port, which is the same as the number of outgoing 
containers. The entire function is shown in Equation 9.

**Equation 9**

\[
E(C^e_b) = E(C^e_t) + E(C^e_u) + E(C^e_m)
\]

\[
E(C^e_t) = E(C^e_w) + E(C^e_m)
\]

\[
E(C^e_u) = E(C^e_w) + E(C^e_m)
\]

\[
E(C^e_w) = c^e_b \times (1 - k_u) \times E\left( \sum_{j=1}^{N} w \times \left( P_{01} n^a_{j1} L_{n_{j1}} + P_{02} n^a_{j2} L_{n_{j2}} \right) \right)
\]

\[
= c^e_b \times (1 - k_u) \times \frac{f_L(L_u)}{L_u} \times E\left( n^a_{j1} L_{n_{j1}} + n^a_{j2} L_{n_{j2}} \right) \times E(N)
\]

\[
= K^e_{t1} \times m(t_0)
\]

\[
E(C^e_m) = c^e_b \times (1 - k_u) \times E\left( \sum_{j=1}^{N} (1 - P^a_{01}) n^a_{j1} + (1 - P^a_{02}) n^a_{j2} \right)
\]

\[
= c^e_b \times (1 - k_u) \times (1 - f_L(L_u)) \times E\left( n^a_{j1} + n^a_{j2} \right) \times E(N)
\]

\[
= K^e_{t2} \times m(t_0)
\]

\[
E(C^e_i) = c^e_i \times k_u \times E\left( \sum_{j=1}^{M} n^a_{j1} + n^a_{j2} \right)
\]

\[
= c^e_i \times k_u \times E\left( n^a_{j1} + n^a_{j2} \right) \times E(M)
\]

\[
= K^e_{i3} \times m(t_i)
\]

\[
E(C^e_{iu}) = c^e_{iu} \times (1 - k_u) \times E\left( \sum_{j=1}^{N} \frac{P^a_{01} n^a_{j1} L_{n_{j1}} + P^a_{02} n^a_{j2} L_{n_{j2}}}{L_u} \right)
\]

\[
= c^e_{iu} \times (1 - k_u) \times \frac{f_L(L_u)}{L_u} \times E\left( n^a_{j1} L_{n_{j1}} + n^a_{j2} L_{n_{j2}} \right) \times [E(M) - E(N)]
\]

\[
= K^e_{i4} \times [m(t_i) - m(t_0)]
\]

\[
E(C^e_{im}) = c^e_i \times (1 - k_u) \times E\left( \sum_{j=1}^{M} (1 - P^a_{01}) n^a_{j1} + (1 - P^a_{02}) n^a_{j2} \right)
\]

\[
= c^e_i \times (1 - k_u) \times (1 - f_L(L_u)) \times E\left( n^a_{j1} + n^a_{j2} \right) \times [E(M) - E(N)]
\]

\[
= K^e_{i5} \times [m(t_i) - m(t_0)]
\]
\[ E(C_{m}^{o}) = c_{k}^{*} \left[ k_{u} * E\left( \sum_{j=1}^{M} n_{j,1}^{A} + n_{j,2}^{A} \right) + (1-k_{u}) * E\left( \sum_{j=1}^{M} \frac{P_{01}^{A}n_{j,1}^{A}L_{y1} + P_{02}^{A}n_{j,2}^{A}L_{y2}}{L_{u}} + (1-P_{01}^{A})n_{j,1}^{A} + (1-P_{02}^{A})n_{j,2}^{A} \right) \right] \]
\[ = c_{k}^{*} \left[ k_{u} * E(n_{j,1}^{A} + n_{j,2}^{A}) + (1-k_{u}) * E\left[ \left( 1 - f_{L}(L_{o}) + \frac{f_{L}(L_{o})L_{y1}}{L_{u}} \right)n_{j,1}^{A} + \left( 1 - f_{L}(L_{o}) + \frac{f_{L}(L_{o})L_{y2}}{L_{u}} \right)n_{j,2}^{A} \right] \right] * E(M) \]
\[ = K_{m}^{A} * m(t_{i}) \]

**Container shuttle cost**

In Scenario 3, as all the non-urgent containers will undergo capacity utilization check at the decoupling center, a cost will be entailed for container shuttling (by truck) between the port and the decoupling center. To formulate the shuttle cost, it is necessary to find out the number of containers being shuttled.

The containers going to the decoupling center are simply the non-urgent incoming containers that arrive during the whole planning horizon, i.e. \((1-k_{u}) * E(\sum_{j=1}^{M} n_{j,1}^{A} + n_{j,2}^{A})\). Compared to that, the containers going out of decoupling center consist of two parts. The first part is the non-urgent containers that do not require consolidation, i.e. \((1-k_{u}) * (\sum_{j=1}^{M} (1-f_{L}(L_{o})) * (n_{j,1}^{A} + n_{j,2}^{A}))\). The second part is the consolidated non-urgent containers, i.e. \((1-k_{u}) * E(\sum_{j=1}^{M} f_{L}(L_{o}) * (n_{j,1}^{A}L_{b,1} + n_{j,2}^{A}L_{b,2})/L_{a})\). It could be observed that these formulations are similar to those in shipment cost. The only difference is that the summation here is made for all the batches/arrivals coming during the whole planning horizon. The entire function is shown in **Equation 10**.

**Equation 10**

\[ E(C_{sh}^{A}) = E(C_{in}^{A}) + E(C_{out}^{A}) \]

\[ E(C_{in}^{A}) = c_{i}^{*} * (1-k_{u}) * E\left( \sum_{j=1}^{M} n_{j,1}^{A} + n_{j,2}^{A} \right) \]
\[ = c_{i}^{*} * (1-k_{u}) * E(n_{j,1}^{A} + n_{j,2}^{A}) * E(M) \]
\[ = K_{sh,1}^{A} * m(t_{i}) \]

\[ E(C_{out}^{A}) = c_{i}^{*} * (1-k_{u}) * E\left( \sum_{j=1}^{M} \frac{P_{01}^{A}n_{j,1}^{A}L_{y1} + P_{02}^{A}n_{j,2}^{A}L_{y2}}{L_{u}} + (1-P_{01}^{A})n_{j,1}^{A} + (1-P_{02}^{A})n_{j,2}^{A} \right) \]
\[ = c_{i}^{*} * (1-k_{u}) * \left[ \left( 1 - f_{L}(L_{o}) + \frac{f_{L}(L_{o})L_{y1}}{L_{u}} \right)E(n_{j,1}^{A}) + \left( 1 - f_{L}(L_{o}) + \frac{f_{L}(L_{o})L_{y2}}{L_{u}} \right)E(n_{j,2}^{A}) \right] * E(M) \]
\[ = K_{sh,2}^{A} * m(t_{i}) \]

**Container inspection cost**

As all the non-urgent containers come in the whole planning horizon need capacity utilization check, the container inspection cost could be easily formulated as the unit inspection cost \(c_{i}\) times the total number of non-urgent containers \((1-k_{u}) * E(\sum_{j=1}^{M} n_{j,1}^{A} + n_{j,2}^{A})\). The entire equation is shown in **Equation 11**.
Equation 11
\[ E(C^A) = c_s \cdot (1 - k_s) \cdot E \left( \sum_{i=1}^{M} n_i^A + n_j^A \right) \]
\[ = c_s \cdot (1 - k_s) \cdot E \left( n_i^A + n_j^A \right) \cdot E(M) \]
\[ = K^A \cdot m(t) \]

**Cargo operation cost**

When a container is regarded as underutilized after the capacity check, the cargoes inside will be entirely taken out for consolidation. And after consolidation is finished, these cargoes will be reloaded to the outgoing containers. Therefore, the cargo operation cost is formulated as the unit operation cost (per weight) \( c_{co} \) times the total weight of the cargoes being consolidated \((1 - k_u) \cdot E \left( \sum_{j=1}^{N} w_j(L_o \cdot (n_{j1}^A L_{b1} + n_{j2}^A L_{b2})) \right)\). The entire function is shown in Equation 12.

Equation 12
\[ E(C^A_{co}) = c_{co} \cdot (1 - k_u) \cdot E \left( \sum_{j=1}^{M} (P_{j1}^A n_{j1}^A L_{b1} + P_{j2}^A n_{j2}^A L_{b2}) \cdot w \right) \]
\[ = c_{co} \cdot (1 - k_u) \cdot w \cdot f_L(L_o) \cdot E \left( n_{j1}^A L_{b1} + n_{j2}^A L_{b2} \right) \cdot E(M) \]
\[ = K^A_{co} \cdot m(t) \]

**Cargo storage cost**

As cargoes are taken out from the containers, the storage cost will be priced based on cargo weight instead of the number of containers. Therefore, to calculate cargo storage cost, it is necessary to find out how much cargo weight is stored and how long is the storage. And as there are two consolidation processes in Scenario 3 according to the description in section 3.3.2

Process chain and cost composition, the storage cost is calculated twice: storage cost for barge (denoted as \( C_{sb} \)) and storage cost for truck (denoted as \( C_{st} \)).

The storage cost for barge is decomposed as two parts: the storage of cargoes being consolidated (denoted as \( C_{sb}^{AB1} \)) and the storage of containers that do not require cargo consolidation but arrive before \( t_0 \) (denoted as \( C_{sb}^{AB2} \)). Therefore, \( C_{sb}^{AB1} \) is formulated as \( c_{sb}^f \cdot (1 - k_u) \cdot E \left( \sum_{j=1}^{N} w_{j1}(L_o \cdot (n_{j1}^A L_{b1} + n_{j2}^A L_{b2})) (t_0 - S_j) \right) \), where \( c_{sb}^f \) is the unit cargo storage cost per weight. Notice that as the term \( \sum_{j=1}^{N}(t_0 - S_j) \) has already been calculated in the “container storage cost” in Scenario 2, the results could be directly applied here. And \( C_{sb}^{AB2} \) is formulated as \( c_{sb} (1 - k_u) \cdot E \left( \sum_{j=1}^{N} \left( 1 - f_L(L_o) \right) \cdot (n_{j1}^A + n_{j2}^A) \cdot (t_0 - S_j) \right) \).

The storage cost for truck is formulated in a similar way, but the summation index changes: \( c_{st}^f \cdot (1 - k_u) \cdot E \left( \sum_{j=N+1}^{M} w_{j1}(L_o \cdot (n_{j1}^A L_{b1} + n_{j2}^A L_{b2})) (t_1 - S_j) \right) \). And the term \( \sum_{j=N+1}^{M}(t_1 - S_j) \) is once again spread out as in Scenario 2 in order to be expressed in terms of \( t_0 \). Note that as containers that arrive after \( t_0 \) do not need consolidation, and could be immediately shipped
to the hinterland by truck, there is no storage for them. The entire function is shown in Equation 13.

**Equation 13**

\[
E(C^A_s) = E(C^{ab}_s) + E(C^{At}_s)
\]

\[
E(C^{ab}_s) = E(C^{ab1}_s) + E(C^{ab2}_s)
\]

\[
E(C^{ab1}_s) = c^f_s * (1 - k_s) * E\left(\sum_{j=1}^{N} (P^0_{01} n^A_{j1} L_{0j1} + P^0_{02} n^A_{j2} L_{0j2}) \ast (t_0 - S_j)\right)
\]

\[
= c^f_s w(1 - k_s) f_L(L_o) \ast E(n^A_{j1} L_{0j1} + n^A_{j2} L_{0j2}) \ast E\left(\sum_{j=1}^{N} t_0 - S_j\right)
\]

\[
\approx \frac{c^f_s}{2} w(1 - k_s) f_L(L_o) \ast E(n^A_{j1} L_{0j1} + n^A_{j2} L_{0j2}) \ast E(N) \ast t_0
\]

\[
= K_{s1}^A \ast m(t_0) \ast t_0
\]

\[
E(C^{ab2}_s) = c_s * (1 - k_s) * E\left(\sum_{j=1}^{N} \left(1 - P^0_{01}\right) n^A_{j1} + \left(1 - P^0_{02}\right) n^A_{j2}\right) \ast (t_0 - S_j)
\]

\[
= c_s * (1 - k_s) \ast \left[1 - f_L(L_o)\right] * E(n^A_{j1} + n^A_{j2}) * E\left(\sum_{j=1}^{N} t_0 - S_j\right)
\]

\[
= K_{s2}^A \ast m(t_0) \ast t_0
\]

\[
E(C^{At}_s) = c^f_s * (1 - k_s) * E\left(\sum_{j=N+1}^{M} (P^0_{01} n^A_{j1} L_{0j1} + P^0_{02} n^A_{j2} L_{0j2}) \ast (t_i - S_j)\right)
\]

\[
= c^f_s w(1 - k_s) f_L(L_o) \ast E(n^A_{j1} L_{0j1} + n^A_{j2} L_{0j2}) \ast E\left(\sum_{j=N+1}^{M} t_i - S_j\right)
\]

\[
= K_{s3}^A \ast E\left[(M - N)t_i - S_{N+1} - \cdots - S_{N}\right]
\]

\[
= K_{s3}^A \ast E\left[(M - N)t_i - (M - N)S_N - (M - N)T_{N+1} - \cdots - T_M\right]
\]

\[
\approx K_{s3}^A \ast E\left[(M - N)t_i - E\left((M - N)N - (M - N) \cdots - 1\right) E(T_i)\right]
\]

\[
\approx K_{s3}^A \ast E\left[(M - N)t_i - \frac{(M - N)(M + N + 1)}{2(N + 1)} t_0\right]
\]

\[
= K_{s3}^A \ast \left\{E(M) - E(N)\right\} t_i - E\left(\frac{(M - N)(M + N + 1)}{2(N + 1)}\right) t_0
\]

\[
= K_{s3}^A \ast \left\{E(M) - E(N)\right\} t_i - E\left(\frac{M^2 + M}{2(N + 1)}\right) t_0 \ast E\left(\frac{N}{2}\right) t_0
\]

\[
= K_{s3}^A \ast \left\{E(M) - E(N)\right\} t_i - E\left(\frac{M^2 + M}{2(N + 1)}\right) t_0 + E\left(\frac{N}{2}\right) t_0
\]

\[
= K_{s3}^A \ast \left\{E(M) - E(N)\right\} t_i - \left[\frac{1}{2(N + 1)}\right] E\left(\frac{1}{2(N + 1)}\right) t_0 + E\left(\frac{N}{2}\right) t_0
\]

\[
= K_{s3}^A \ast \xi(t_i)
\]
Container handling cost

In Scenario 3, there are in total seven handling situations in the container operation, i.e.
container unloading from the vessel, container loading to the shuttle (twice), container unloading
from the shuttle (twice), container loading to the outgoing truck/barge and container unloading
at the hinterland. However, only the non-urgent containers will undergo all these handleings. The
urgent containers will still be handled three times. For the empty containers, there will still be
two handling situations: loading the container onto the return barge, and unloading the empty
containers at the sea port. Note that as the number of incoming and outgoing containers is
different, the cost formulation is realized separately.

The handling cost of incoming containers is formulated as \( c_h \cdot \left[ k_u E \left( \sum_{j=1}^{M} n_{j1}^a + n_{j2}^a \right) + 3(1 - k_u) E \left( \sum_{j=1}^{M} n_{j1}^a + n_{j2}^a \right) \right] \), where \( (1 - k_u) E \left( \sum_{j=1}^{M} n_{j1}^a + n_{j2}^a \right) \) stands for the handling
times of the non-urgent incoming containers. Note that this part will become less due to the
application of cargo consolidation. The entire function is shown in Equation 14.

\[
E \left( C^H \right) = E \left( C^{in}_H \right) + E \left( C^{out}_H \right) + E \left( C^{em}_H \right)
\]

\[
E \left( C^{in}_H \right) = c_s \cdot \left[ \left( k_u E \left( \sum_{j=1}^{M} n_{j1}^a + n_{j2}^a \right) + 3(1 - k_u) E \left( \sum_{j=1}^{M} n_{j1}^a + n_{j2}^a \right) \right) \right] = c_s \cdot \left( 3 - 2k_u \right) \cdot E \left( n_{j1}^a + n_{j2}^a \right) \cdot E \left( M \right)
\]

\[
E \left( C^{out}_H \right) = c_s \cdot \left[ 2k_u E \left( \sum_{j=1}^{M} n_{j1}^a + n_{j2}^a \right) + 4 \left( 1 - k_u \right) \left[ E \left( \sum_{j=1}^{M} P_a n_{j1}^a L_{gj1} + P_a n_{j2}^a L_{gj2} \right) \right] + E \left( \sum_{j=1}^{M} (1 - P_a) n_{j1}^a + (1 - P_a) n_{j2}^a \right) \right]\]

\[
E \left( C^{em}_H \right) = c_s \cdot \left[ 2k_u E \left( \sum_{j=1}^{M} n_{j1}^a + n_{j2}^a \right) + 4 \left( 1 - k_u \right) \left[ 1 - f_L(L_o) + \frac{f_L(L_o) L_{gj1}}{L_o} \right] n_{j1}^a + \left[ 1 - f_L(L_o) + \frac{f_L(L_o) L_{gj2}}{L_o} \right] n_{j2}^a \right] \cdot E \left( M \right)
\]

\[
E \left( C^{em}_H \right) = k_{H1}^A \cdot m(t)
\]

Penalty cost

In Scenario 3, penalty cost is assigned to both barge and truck transportation, as there are two
storage processes. Besides, as the operator knows how much cargo weight would arrive at each
destination, the penalty cost will also be priced based on the cargo weight instead of the number
of containers.

The formulation of barge penalty cost is similar as in Scenario 2. The only difference is that the
number of outgoing containers that might experience delay now decreases to 

\[(1 - k_u)E \left( \sum_{j=1}^N \left( 1 - P^A_{j1} \frac{P^A_{i,j1}}{L_a} \right) n_{j1} + \left( 1 - P^A_{j2} \frac{P^A_{i,j2}}{L_a} \right) n_{j2} \right). \]

And one has to further multiply this quantity by \( L_{b,j1} \cdot w \) (and \( L_{b,j2} \cdot w \)), in order to convert it into the cargo weight.

For truck delay cost, it is formulated as 

\[(1 - k_u)w \cdot E \left( \sum_{j=1}^N \left( c^1_{pc} P^A_{i,j1} L_{b,j1} (D_{j1}^A - \tau_{At}) / L_a + c^2_{pc} P^A_{i,j2} L_{b,j2} (D_{j2}^A - \tau_{At}) / L_a \right) \right), \]

where \( c^1_{pc} \) and \( c^2_{pc} \) is the unit penalty cost per weight per time for Cargo 1 and Cargo 2 respectively, and \( \tau_{At} \) is truck arrival time (at destination A). \( \tau_{At} \) is then expressed in terms of \( t_1 \) and the truck transport time \( g_t \). The entire function is shown in Equation 15.

Equation 15

\[ E(C^A_a) = E(C^A_b) + E(C^A_c) \]

\[ E(C^A_b) = (1 - k_u)w \cdot E \left( \sum_{j=1}^N K^A_{p1} \left( \tau_{ab} - D_{j1}^A \right) + K^A_{p2} \left( \tau_{ab} - D_{j2}^A \right) \right) \]

\[ \leq (1 - k_u)w \cdot E \left( \left( K^A_{p1} + K^A_{p2} \right) \left[ t_0 + E(g_t) \right] - K^A_{p1} D_{j1}^A - K^A_{p2} D_{j2}^A \right) \cdot E(N) \]

\[ = K^A_{p1} \cdot m(t_0) * t_0 + K^A_{p2} \cdot m(t_0) \]

\[ E(C^A_c) = (1 - k_u)w \cdot E \left( \sum_{j=N+1}^M P^A_{i,j1} L_{b,j1} (\tau_{At} - D_{j1}^A) + P^A_{i,j2} L_{b,j2} (\tau_{At} - D_{j2}^A) \right) \]

\[ = (1 - k_u)w \cdot E \left( K^A_{p3} \left( \tau_{At} - D_{j1}^A \right) + K^A_{p4} \left( \tau_{At} - D_{j2}^A \right) \right) \]

\[ \leq (1 - k_u)w \cdot E \left( \left( K^A_{p3} + K^A_{p4} \right) \left[ t_1 + E(g_t) \right] - K^A_{p3} D_{j1}^A - K^A_{p4} D_{j2}^A \right) \cdot E(M) \cdot E(N) \]

\[ = K^A_{p3} \cdot \left[ m(t_1) - m(t_0) \right] \]

**Total cost and minimum cost**

The minimum cost is calculated by using the same way as in Scenario 2. However, as the derivative equation contains the term \( e^{-At_0} \), it becomes difficult to obtain an analytical expression for the best \( t_0 \). For simplification, the term \( e^{-At_0} \) is finally neglected during calculation, as it does not greatly influence the value of best \( t_0 \) (for proof, see Appendix B). The entire function is shown in Equation 16.
Equation 16

\[ E(C_{\text{TOTAL}}^A) = E(C_T^A) + E(C_{3H}^A) + E(C_{CO}^A) + E(C_{n}^A) + E(C_{p}^A) \]

\[ = C_1 \cdot m(t_0) + C_2 \cdot m(t_0) \cdot t_0 + C_3 \cdot \xi(t_0) + C_4 \cdot m(t_1) \]

\[ C_1 = K_{T1}^A + K_{T2}^A - K_{T4}^A + K_{T5}^A + K_{P2}^A - K_{P3}^A \]

\[ C_2 = K_{S1}^A + K_{S2}^A + K_{P1}^A \]

\[ C_3 = K_{S3}^A \]

\[ C_4 = K_{T3}^A + K_{T4}^A + K_{T5}^A + K_{T6}^A + K_{S1}^A + K_{S2}^A + K_{CO}^A + K_{H1}^A + K_{H2}^A + K_{H3}^A + K_{P3}^A \]

\[
\frac{dE(C_{\text{TOTAL}}^A)}{dt_0} = C_1 \cdot \frac{dm(t_0)}{dt_0} + C_2 \cdot \left(t_0 \cdot \frac{dm(t_0)}{dt_0} + m(t_0)\right) + C_3 \cdot \frac{d\xi(t_0)}{dx} \]

\[ = \lambda C_1 + 2\lambda C_2 t_0 + C_3 \left[-\lambda t_1 + \left(\frac{\lambda t_1^2 + 2t_1}{2}\right)\lambda e^{-\lambda t_0} + \lambda t_0\right] \]

\[ t_{0}^{\text{best}} \approx \frac{t_1 C_3 - C_1}{2C_2 + C_3} \]

\[ E(C_{\text{Min}}^A) = \lambda t_1 C_4 + \frac{\lambda t_1 C_3 - 2t_1 C_3}{2} - \frac{(\lambda t_1 C_3 - \lambda C_3)^2}{2\lambda (2C_2 + C_3)} \]
3.4.4 Cost functions of Scenario 4

The cost composition of Scenario 4 is almost the same as Scenario 3, except for the container inspection cost.

Shipments cost and repositioning cost

Shipments cost still consists of barge cost and truck cost. But with more accurate information on the load factors of incoming containers, the containers that will be opened for consolidation could be determined exactly in advance. Considering it, let $\eta_1$ and $\eta_2$ denote the shares of non-urgent containers being opened for cargo consolidation.

The total barge cost is decomposed as the barge cost of non-urgent containers that have high capacity utilization $c^A_b(1 - k_u) \cdot \sum_{j=1}^{M} n^A_{j1} + (1 - \eta_1)n^A_{j1} + (1 - \eta_2)n^A_{j2}$ and the barge cost of non-urgent containers that accommodate consolidated cargoes $c^A_b(1 - k_u) \cdot \sum_{j=1}^{M} \left(\eta_1 n^A_{j1} L_{b1} + \eta_2 n^A_{j2} L_{b2}\right)/L_a$. It could be observed that these formulations resemble the ones in Scenario 3, but now $P_{01}^A$ and $P_{02}^A$ are replaced by $\eta_1$ and $\eta_2$ respectively.

The total truck cost is decomposed as three parts. The first part is the truck cost of urgent containers of the whole planning horizon $c^A_t k_u \cdot \sum_{j=1}^{M} n^A_{j1} + n^A_{j2}$. The second part is the truck cost of non-urgent containers that arrive after $t_0$ and do not require cargo consolidation $c^A_t (1 - k_u) \cdot \sum_{j=M+1}^{N} \left(1 - \eta_1 n^A_{j1} + (1 - \eta_2)n^A_{j2}\right)$. The third part is the truck cost of non-urgent containers that accommodate consolidated cargoes $c^A_t (1 - k_u) \cdot \sum_{j=M+1}^{N} \left(\eta_1 n^A_{j1} L_{b1} + \eta_2 n^A_{j2} L_{b2}\right)/L_a$.

For empty container repositioning cost, it is formulated similarly as in Scenario 3. But again, $P_{01}^A$ and $P_{02}^A$ are replaced by $\eta_1$ and $\eta_2$ respectively. The entire function is shown in Equation 17.
Equation 17

\[
E(C^A) = E(C^p) + E(C^s) + E(C^w)
\]

\[
E(C^b) = E(C^p) + E(C^w)
\]

\[
E(C^r) = E(C^p) + E(C^w)
\]

\[
E(C^v) = c_b^*(1 - k_a) * E\left( \sum_{j=1}^{N} \frac{n_j n_j^tL_{yj} + n_j n_j^sL_{yj}}{L_a} \right)
\]

\[
= c_b^*(1 - k_a) * \left[ \eta_{L_yj}^1 E(n_j^t) + \eta_{L_yj}^2 E(n_j^s) \right] * E(N)
\]

\[
= K_{j1}^* * m(t_0)
\]

\[
E(C^w) = c_b^*(1 - k_a) * E\left( \sum_{j=1}^{N} (1 - \eta_j) n_j^t + (1 - \eta_j) n_j^s \right)
\]

\[
= c_b^*(1 - k_a) * \left[ (1 - \eta_j) E(n_j^t) + (1 - \eta_j) E(n_j^s) \right] * E(N)
\]

\[
= K_{j2}^* * m(t_0)
\]

\[
E(C^m) = c_b^* k_u * E\left( \sum_{j=1}^{N} n_j^s + n_j^s \right)
\]

\[
= c_b^* k_u * E(n_j^t + n_j^s) * E(M)
\]

\[
= K_{j3}^* * m(t_1)
\]

\[
E(C^v) = c_b^* k_u * E\left( \sum_{j=1}^{N} \frac{n_j n_j^tL_{yj} + n_j n_j^sL_{yj}}{L_a} \right)
\]

\[
= c_b^* k_u * \left[ \eta_{L_yj}^1 E(n_j^t) + \eta_{L_yj}^2 E(n_j^s) \right] * [E(M) - E(N)]
\]

\[
= K_{j4}^* * [m(t_0) - m(t_0)]
\]

\[
E(C^m) = c_b^* (1 - k_a) * E\left( \sum_{j=1}^{N} (1 - \eta_j) n_j^t + (1 - \eta_j) n_j^s \right)
\]

\[
= c_b^* (1 - k_a) * \left[ (1 - \eta_j) E(n_j^t) + (1 - \eta_j) E(n_j^s) \right] * [E(M) - E(N)]
\]

\[
= K_{j5}^* * [m(t_0) - m(t_0)]
\]

\[
E(C^m) = c_b^* \left\{ k_u E\left( \sum_{j=1}^{N} n_j^t + n_j^s \right) + (1 - k_a) \left[ \sum_{j=1}^{N} \left( 1 - \eta_j + \frac{\eta_j L_{yj}}{L_a} \right) n_j^t + \left( 1 - \eta_j + \frac{\eta_j L_{yj}}{L_a} \right) n_j^s \right] \right\}
\]

\[
= c_b^* \left\{ k_u E(n_j^t + n_j^s) + (1 - k_a) \left[ \left( 1 - \eta_j + \frac{\eta_j L_{yj}}{L_a} \right) n_j^t + \left( 1 - \eta_j + \frac{\eta_j L_{yj}}{L_a} \right) n_j^s \right] \right\} * E(M)
\]

\[
= K_{j6}^* * m(t_1)
\]

**Container shuttle cost**

In Scenario 4, there are less non-urgent containers shuttled to/from the decoupling center compared to Scenario 3. The shuttle cost to decoupling center is formulated as \(c^p(t - k_u) * \)
\( E(\sum_{j=1}^M \eta_1 n_1^A + \eta_2 n_2^A) \), whereas the shuttle cost to port/terminal is formulated as \( c^0 \cdot (1 - k_u) \cdot E(\sum_{j=1}^M (\eta_1 n_1^A + \eta_2 n_2^A)(L_{j1} + L_{j2})) \). The entire function is shown in Equation 18.

**Equation 18**

\[
E(C_{sh}^A) = E(C_{m}^A) + E(C_{oe}^A)
\]

\[
E(C_{m}^A) = c^0 \cdot (1 - k_u) \cdot E\left( \sum_{j=1}^M \eta_1 n_1^A + \eta_2 n_2^A \right)
\]

\[
= c^0 \cdot (1 - k_u) \cdot E\left( \eta_1 n_1^A + \eta_2 n_2^A \right) \cdot E\left( M \right)
\]

\[
= K_{sh1}^A \cdot m(t_i)
\]

\[
E(C_{oe}^A) = c^0 \cdot (1 - k_u) \cdot E\left( \sum_{j=1}^M \eta_1 n_1^A L_{j1} + \eta_2 n_2^A L_{j2} \right)
\]

\[
= c^0 \cdot (1 - k_u) \cdot \left[ \frac{\eta_1 L_{j1}}{L_u} E\left( n_1^A \right) + \frac{\eta_2 L_{j2}}{L_u} E\left( n_2^A \right) \right] \cdot E\left( M \right)
\]

\[
= K_{sh2}^A \cdot m(t_i)
\]

**Cargo operation cost**

The cargo operation cost in Scenario 4 is formulated similarly as in Scenario 3, but the probability \( P_{D1}^A \) and \( P_{D2}^A \) are once again replaced by the constants \( \eta_1 \) and \( \eta_2 \). The entire function is shown in Equation 19.

**Equation 19**

\[
E(C_{co}^A) = c_{co} \cdot (1 - k_u) \cdot E\left( \sum_{j=1}^M \left( \eta_1 n_1^A L_{j1} + \eta_2 n_2^A L_{j2} \right) \right) \cdot w
\]

\[
= c_{co} \cdot (1 - k_u) \cdot w \cdot E\left( \eta_1 n_1^A L_{j1} + \eta_2 n_2^A L_{j2} \right) \cdot E\left( M \right)
\]

\[
= K_{co}^A \cdot m(t_i)
\]

**Cargo storage cost**

In Scenario 4, there are still two storage processes compared to Scenario 3. Therefore, the storage cost is formulated as the summation of storage cost for barge and the storage cost for truck. The storage cost for barge is decomposed as the storage cost of the consolidated cargoes \( c^A w(1 - k_u) \cdot E(\sum_{j=1}^N (\eta_1 n_1^A L_{j1} + \eta_2 n_2^A L_{j2}))(t_0 - S_j) \) and the storage cost of containers in the stacking area \( c_s (1 - k_u) \cdot E(\sum_{j=1}^N (1 - \eta_1) n_1^A + (1 - \eta_2) n_2^A)(t_0 - S_j) \). Similarly, the storage cost for truck is formulated as \( c^A w(1 - k_u) \cdot E(\sum_{j=N+1}^M (\eta_1 n_1^A L_{j1} + \eta_2 n_2^A L_{j2}))(t_1 - S_j) \). The entire function is shown in Equation 20.
Equation 20

\[ E(C^A_S) = E(C^{AB}_S) + E(C^{Am}_S) \]

\[ E(C^{AB}_S) = E(C^{AB1}_S) + E(C^{AB2}_S) \]

\[ E(C^{AB1}_S) = c_s^f * (1 - k_a) * E\left( \sum_{j=1}^{N} (\eta_j n_{j1}^A L_{j1} + \eta_j n_{j2}^A L_{j2}) * (t_o - S_j) \right) \]

\[ = c_s^f w(1 - k_a) E\left( \eta_j n_{j1}^A L_{j1} + \eta_j n_{j2}^A L_{j2} \right) * E\left( \sum_{j=1}^{N} t_o - S_j \right) \]

\[ \approx \frac{c_s^f}{2} w(1 - k_a) E\left( \eta_j n_{j1}^A L_{j1} + \eta_j n_{j2}^A L_{j2} \right) * E(N) * t_o \]

\[ = K_{S1}^A * m(t_o) * t_o \]

\[ E(C^{AB2}_S) = c_s * (1 - k_a) * E\left( \sum_{j=1}^{N} \left[ (1 - \eta_j) E(n_{j1}^A) + (1 - \eta_j) E(n_{j2}^A) \right] * E\left( \sum_{j=1}^{N} t_o - S_j \right) \right) \]

\[ = K_{S2}^A * m(t_o) * t_o \]

\[ E(C^{Am}_S) = c_s^f * (1 - k_a) * E\left( \sum_{j=N+1}^{M} (\eta_j n_{j1}^A L_{j1} + \eta_j n_{j2}^A L_{j2}) * (t_i - S_j) \right) \]

\[ = c_s^f w(1 - k_a) E\left( \eta_j n_{j1}^A L_{j1} + \eta_j n_{j2}^A L_{j2} \right) * E\left( \sum_{j=N+1}^{M} t_i - S_j \right) \]

\[ \approx K_{S3}^{Am} \left[ E(M) - E(N) \right] t_i - E\left( \frac{(M - N)(M + N + 1)}{2(N + 1)} \right) t_o \]

\[ = K_{S3}^A * \xi(t_i) \]

**Container handling cost**

To formulate the handling cost, we only need to replace \( P_{O1}^0 \) and \( P_{O2}^0 \) in Scenario 3 by \( \eta_1 \) and \( \eta_2 \). The entire function is shown in Equation 21.

Equation 21

\[ E(C^A_m) = E(C_m^m) + E(C^{m'}_m) + E(C^{m''}_m) \]

\[ E(C^{m'}_m) = c_h * \left[ k_n E\left( \sum_{j=1}^{M} n_{j1}^A + n_{j2}^A \right) + 3(1 - k_a) E\left( \sum_{j=1}^{M} n_{j1}^A + n_{j2}^A \right) \right] \]

\[ = c_h * \left( 3 - 2k_a \right) * E(n_{j1}^A + n_{j2}^A) * E(M) \]

\[ = K_{h1}^m * m(t_i) \]
\[ E(C^\text{em}) = c_h \left\{ 2k_a E \left( \sum_{j=1}^{M} n_j^A + n_j^B \right) + 4(1-k_a) \left[ E \left( \sum_{j=1}^{M} \eta_j n_j^A L_{j1} + \eta_j n_j^B L_{j2} \right) + E \left( \sum_{j=1}^{M} (1-\eta_j) n_j^A + (1-\eta_j) n_j^B \right) \right] \right\} \]

\[ = c_h \left\{ 2k_a E (n_j^A + n_j^B) + 4(1-k_a) E \left[ \left( 1-\eta_1 \frac{\eta_1 L_{j1}}{L_a} \right) n_j^A + \left( 1-\eta_2 \frac{\eta_2 L_{j2}}{L_a} \right) n_j^B \right] \right\} * E(M) \]

\[ = K^A_{H2} * m(t_1) \]

\[ E(C^\text{em}) = c_h * 2 * k_a E \left( \sum_{j=1}^{M} n_j^A + n_j^B \right) + (1-k_a) E \left[ \left( 1-\eta_1 \frac{\eta_1 L_{j1}}{L_a} \right) n_j^A + \left( 1-\eta_2 \frac{\eta_2 L_{j2}}{L_a} \right) n_j^B \right] * E(M) \]

\[ = K^A_{H2} * m(t_1) \]

**Penalty cost**

Again, the penalty cost of Scenario 4 could be formulated similarly as in Scenario 3. But the probability \( P_{O1}^A \) and \( P_{O2}^A \) is replaced by the constants \( \eta_1 \) and \( \eta_2 \) respectively. The entire function is shown in Equation 22.

Equation 22

\[ E(C^A_p) = E(C^A_{p1}) + E(C^A_{p2}) \]

\[ E(C^A_{p1}) = (1-k_a) w * E \left( \sum_{j=1}^{N} c_{p1} n_j^A (\tau_{ab} - D_j^A) + c_{p2} n_j^B L_{j2} \left( \tau_{ab} - D_j^A \right) \right) \]

\[ = (1-k_a) w * E \left( \sum_{j=1}^{N} K^A_{p5} (\tau_{ab} - D_j^A) + K^A_{p6} (\tau_{ab} - D_j^A) \right) \]

\[ \approx (1-k_a) w * E \left[ \left( K^A_{p5} + K^A_{p6} \right) (t_0 + g_s) - K^A_{p5} D_{(N+1)}^A - K^A_{p6} D_{(N+1)}^A \right] * E(N) \]

\[ = K^A_{p1} * m(t_0) * t_0 + K^A_{p2} * m(t_0) \]

\[ E(C^A_{p2}) = (1-k_a) w * E \left( \sum_{j=1}^{M} c_{p2} \eta_j L_{j2} \left( \tau_{ab} - D_j^A \right) + c_{p2} \eta_j L_{j2} \left( \tau_{ab} - D_j^A \right) \right) \]

\[ = (1-k_a) w * E \left( \sum_{j=1}^{M} K^A_{p7} (\tau_{ab} - D_j^A) + K^A_{p8} (\tau_{ab} - D_j^A) \right) \]

\[ \approx (1-k_a) w * E \left[ \left( K^A_{p7} + K^A_{p8} \right) (t_0 + g_s) - K^A_{p7} D_{(N+1)}^A - K^A_{p8} D_{(N+1)}^A \right] * E(M) - E(N) \]

\[ = K^A_{p3} * \left[ m(t_1) - m(t_0) \right] \]

**Total cost and minimum cost**

The best \( t_0 \) in Scenario 4 has the same format as in Scenario 3. The difference only occurs in the coefficients. The entire function is shown in Equation 23.
Equation 23

\[
E(C^A_{TOTAL}) = E(C^A_T) + E(C^A_{SH}) + E(C^A_{CO}) + E(C^A_{H}) + E(C^A_P)
\]

\[
= C_1 \cdot m(t_0) + C_2 \cdot m(t_0) \cdot t_0 + C_3 \cdot \xi(t_0) + C_4 \cdot m(t_1)
\]

\[
C_1 = K^A_{T1} + K^A_{T2} - K^A_{T4} + K^A_{T5} - K^A_{P3}
\]

\[
C_2 = K^A_{S1} + K^A_{S2} + K^A_{P1}
\]

\[
C_3 = K^A_{S3}
\]

\[
C_4 = K^A_{T3} + K^A_{T4} + K^A_{T5} + K^A_{T6} + K^A_{SH1} + K^A_{SH2} + K^A_{CO} + K^A_{H1} + K^A_{H2} + K^A_{H3} + K^A_{P3}
\]

\[
\frac{dE(C^A_{TOTAL})}{dt_0} = C_1 \cdot \frac{dm(t_0)}{dt_0} + C_2 \cdot \left( t_0 \cdot \frac{dm(t_0)}{dt_0} + m(t_0) \right) + C_3 \cdot \frac{d\xi(t_0)}{dt_0}
\]

\[
= \lambda C_1 + 2\lambda C_2 t_0 + C_3 \left[ -\lambda t_1 + \left( \frac{\lambda t^2_1 + 2t_1}{2} \right) \lambda e^{-\lambda t_0} + \lambda t_0 \right]
\]

\[
t_0^{best} \approx \frac{t_1 C_3 - C_1}{2C_2 + C_3}
\]

\[
E(C^A_{Min}) = \lambda t_1 C_4 + \frac{\lambda t_1^2 C_3 - 2t_1 C_3}{2} - \frac{(\lambda t_1 C_3 - \lambda C_1)^2}{2\lambda (2C_2 + C_3)}
\]
### 3.5 Cost functions of general case

As mentioned before, in the general case, cargo consolidation will be applied in a more realistic environment, where mixed cargo flows could exist in a single incoming container. With this relaxation, there will be no difference among the container itself, and the number of containers in each batch will be denoted as \( n_j \) instead of \( n_{i,j}^A, n_{i,j}^B, n_{i,j}^P, n_{i,j}^R \). Moreover, as a second barge leaving time \( t_2 \) is introduced in the model, the expected number of container arrivals before \( t_2 \) is then denoted as \( E(V) \). Note that \( E(V) \) and \( E(N) \) are still independent when investigating the random events behind them. And a relationship exists between \( t_2 \) and \( t_0 \) that \( t_2 = t_0 + T \), where \( T \) is the barge turnaround time.

**Shipment cost and repositioning cost**

Shipment cost is decomposed as barge cost and truck cost. Barge cost is calculated as the unit barge cost per container \( c_b^A \), times the total cargo weight accumulated until the second barge leaving time \( E \left( \sum_{j=1}^V a w \left( (1 - k_u)n_j L_{bj} + k_u n_j L_{bj} (1 - f_u) \right) \right) \) divided by the expected weight of an outgoing container \( w \ast L_a \). Note that \( a \) denotes the share of cargoes to destination \( A \) in one batch/arrival, \( k_u \) now denotes the share of containers that contain urgent cargoes, and \( f_u \) denotes the fraction of urgent cargoes in the mixed urgent containers. It could be seen that the equation is slightly different from that in Scenario 4, because now all the containers need to be opened, in order to separate the mixed cargo flows.

Truck cost consists of the truck cost of the urgent (containerized) cargoes in the whole planning horizon \( c_t^A \ast E \left( \sum_{j=1}^M a k_u n_j L_{bj} / L_a \right) \) and truck cost of the non-urgent (containerized) cargoes that arrive after \( t_2 \) \( c_t^A \ast E \left( \sum_{j=v+1}^M a [(1 - k'_u) + k_u (1 - f_u)] n_j L_{bj} / L_a \right) \).

Again, the empty container repositioning cost, is calculated as the unit reposition cost \( c_b^R \) times the number of containers returned. The entire function is shown in Equation 24.
Container shuttle cost

Container shuttle cost consists of the shuttle cost to decoupling center and the shuttle cost back to port/terminal. The former is formulated as $\alpha \ast c_D^A E\left(\sum_{j=1}^{M} n_j L_{a_j}\right)$. The latter is formulated as $\alpha \ast c_D^B E\left(\sum_{j=1}^{M} n_j L_{b_j}/L_{a_j}\right)$. It could be seen that as all the containers will be opened for cargo sorting and consolidation, the number of outgoing containers is only influenced by the factor
\( L_{bj}/L_a \). The entire cost function is shown in Equation 25.

**Equation 25**

\[
E(C_{SH}) = E(C_{SH}^{Air}) + E(C_{SH}^{Airc})
\]

\[
E(C_{SH}^{Air}) = ac_i^D * E\left(\sum_{j=1}^{M} n_j\right)
\]

\[
= ac_i^D * E(n_j) * E(M)
\]

\[
= \rho_{SH1}^A * m(t_i)
\]

\[
E(C_{SH}^{Airc}) = c_i^D * E\left(\sum_{j=1}^{M} \frac{an_j L_{bj}}{L_a}\right)
\]

\[
= \frac{c_i^D}{L_a} * E(n_j) * E(L_{bj}) * E(M)
\]

\[
= \rho_{SH2}^A * m(t_i)
\]

**Cargo operation cost**

As all the cargoes need to be taken out for reorganization and consolidation, the cargo operation cost could be easily formulated as: \( a * c_{co}w * E\left(\sum_{j=1}^{M} n_j L_{bj}\right) \). The entire function is shown in Equation 26.

**Equation 26**

\[
E(C_{co}^{Air}) = ac_{co}^A * E\left(\sum_{j=1}^{M} W_j\right)
\]

\[
= ac_{co}w * E(n_j) * E(L_{bj}) * E(M)
\]

\[
= \rho_{co}^A * m(t_i)
\]

**Cargo storage cost**

In the general case, all the non-urgent cargoes will need to be stored for consolidation. And as the second barge is introduced, there will be in total three storage processes. Therefore, the storage cost is formulated as: the storage cost for the first barge, the storage for the second barge and the storage cost for the truck. The formulation of these costs is similar as in Scenario 4. Only the coefficients take a change. The entire function is shown in Equation 27.
Equation 27

\[
E(C^A) = E(C^A_{S}) + E(C^A_{S}) \\
E(C^B) = E(C^B_{S}) + E(C^B_{S}) \\
E(C^{A2}) = E(C^{A2}_{S}) + E(C^{A2}_{S})
\]

\[
E(C^{A1}_{S}) = c'_1 a \left[ (1 - k_a') + k_a' (1 - f_a) \right] \ast E \left( \sum_{j=1}^{N} W_j \ast (t_0 - S_j) \right) \\
\approx \frac{c'_1}{2} a \left[ (1 - k_a') + k_a' (1 - f_a) \right] w \ast E(n_j) E(L_{yj}) \ast E(N) \ast t_0 \\
= \rho_{S1} \ast m(t_0) \ast t_0
\]

\[
E(C^{A2}_{S}) = c'_1 a \left[ (1 - k_a') + k_a' (1 - f_a) \right] \ast E \left( \sum_{j=N+1}^{V} W_j \ast (t_2 - S_j) \right) \\
= c'_1 a \left[ (1 - k_a') + k_a' (1 - f_a) \right] w \ast E(n_j) E(L_{yj}) \ast E \left( \sum_{j=N+1}^{V} t_2 - S_j \right) \\
\approx \rho_{S2} \ast \left[ (E(V) - E(N)) (t_0 + T) - \left[ E(V^2) + E(V) \right] E \left( \frac{1}{2(N + 1)} \right) t_0 + E \left( \frac{N}{2} \right) t_0 \right] \\
= \rho_{S2} \ast \psi (t_0, T)
\]

\[
E(C^A_{S}) = c'_1 a \left[ (1 - k_a') + k_a' (1 - f_a) \right] \ast E \left( \sum_{j=1}^{M} W_j \ast (t_1 - S_j) \right) \\
= c'_1 a \left[ (1 - k_a') + k_a' (1 - f_a) \right] w \ast E(n_j) E(L_{yj}) \ast E \left( \sum_{j=1}^{M} t_1 - S_j \right) \\
\approx \rho_{S3} \ast \left[ (E(M) - E(V)) t_1 - \left[ E(M^2) + E(M) \right] E \left( \frac{1}{2(N + 1)} \right) t_0 + \left[ E(V^2) + E(V) \right] E \left( \frac{1}{2(N + 1)} \right) t_0 \right] \\
= \rho_{S3} \ast \phi (t_0, T)
\]

**Container handling cost**

Container handling cost in the general case consists of handling cost of incoming containers, outgoing containers, and empty containers. The number of incoming containers being handled is formulated as \( a \ast E(\sum_{j=1}^{M} n_j) \). And the number of outgoing containers as well as the empty containers being handled is formulated as \( a \ast E(\sum_{j=1}^{M} n_j L_{Bj} / L_{A}) \). The entire function is shown in Equation 28.
Equation 28
\[ E(C^H_H) = E(C^{An}_H) + E(C^{Atl}_H) + E(C^{em}_H) \]

\[ E(C^{An}_H) = 3ac_s * E\left(\sum_{j=1}^{M} n_j\right) \]
\[ = 3ac_s * E(n_j) * E(M) \]
\[ = \rho^{H1}_n * m(t_i) \]

\[ E(C^{Atl}_H) = 4c_h * E\left(\sum_{j=1}^{M} \frac{an_j L_{yj}}{L_u}\right) \]
\[ = \frac{4c_h a}{L_u} * E(n_j) E(L_{yj}) * E(M) \]
\[ = \rho^{H2}_n * m(t_i) \]

\[ E(C^{em}_H) = 2c_h * E\left(\sum_{j=1}^{M} \frac{an_j L_{yj}}{L_u}\right) \]
\[ = \frac{2c_h a}{L_u} * E(n_j) E(L_{yj}) * E(M) \]
\[ = \rho^{H3}_n * m(t_i) \]

Penalty cost
The penalty cost is formulated similarly as in Scenario 4 in the previous section. But as there are three storage processes, the penalty cost also consists of three parts. The whole function is shown in Equation 29.

Equation 29
\[ E(C^A_P) = E(C^{Ab}_P) + E(C^{Ab2}_P) \]

\[ E(C^{Ab}_P) = wa\left[ (1 - k_u) + k_u (1 - f_y) \right] * E(n_j) E(L_{yj}) * E\left(\sum_{j=1}^{N} \beta c_p^i (\tau_{ja} - D_{ja}^i) + (1 - \beta) c_p^j (\tau_{ja} - D_{ja}^j) \right) \]
\[ \leq wa\left[ (1 - k_u) + k_u (1 - f_y) \right] * E(n_j) E(L_{yj}) * \left[ (\beta c_p^i + (1 - \beta) c_p^j) [t_o + E(g_{ja})] - \beta c_p^i D_{ja}^i - (1 - \beta) c_p^j D_{ja}^j \right] * E(N) \]
\[ = \rho^{P1}_n * m(t_o) + \rho^{P2}_n * m(t_i) \]

\[ E(C^{Ab2}_P) = wa\left[ (1 - k_u) + k_u (1 - f_y) \right] * E(n_j) E(L_{yj}) * E\left(\sum_{j=1}^{N} \beta c_p^i (\tau_{ja} - D_{ja}^i) + (1 - \beta) c_p^j (\tau_{ja} - D_{ja}^j) \right) \]
\[ \leq wa\left[ (1 - k_u) + k_u (1 - f_y) \right] * E(n_j) E(L_{yj}) * \left[ (\beta c_p^i + (1 - \beta) c_p^j) [t_o + T + E(g_{ja})] - \beta c_p^i D_{ja}^i - (1 - \beta) c_p^j D_{ja}^j \right] * E(V) \]
\[ = \rho^{P1}_n * m(t_o) + \rho^{P2}_n * m(t_i) \]

\[ E(C^{Vp}_P) = wa\left[ (1 - k_u) + k_u (1 - f_y) \right] * E(n_j) E(L_{yj}) * E\left(\sum_{j=1}^{N} \beta c_p^i (\tau_{ja} - D_{ja}^i) + (1 - \beta) c_p^j (\tau_{ja} - D_{ja}^j) \right) \]
\[ \leq wa\left[ (1 - k_u) + k_u (1 - f_y) \right] * E(n_j) E(L_{yj}) * \left[ (\beta c_p^i + (1 - \beta) c_p^j) [t_i + E(g_{ja})] - c_p^i D_{ja}^i - c_p^j D_{ja}^j \right] * [E(M) - E(V)] \]
\[ = \rho^{P3}_n * [m(t_i) - m(t_o, T)] \]
Total cost and minimum cost

The locally best $t_0$ for the general case is also calculated by taking the derivative. This is because even though another barge leaving time $t_2$ has been introduced, but as $t_2$ could be expressed in terms of $t_0$, the number of decision variables remains the same. The entire function is shown in Equation 30.

Equation 30

$$E(C_{\text{TOTAL}}^A) = E(C_T^A) + E(C_{SH}^A) + E(C_{CO}^A) + E(C_{H}^A) + E(C_{P}^A)$$

$$= C_1 * m(t_0) + C_2 * m(t_0) * t_0 + C_3 * m(t_0, T) + C_4 * m(t_0, T) * t_0$$

$$+ C_5 * \psi(t_0, T) + C_6 * \phi(t_0, T) + C_7 * m(t_0)$$

$$C_1 = \rho_{p2}^A - \rho_{p4}^A$$

$$C_2 = \rho_{s1}^A + \rho_{p1}^A - \rho_{p3}^A$$

$$C_3 = \rho_{p1}^A - \rho_{p4}^A - \rho_{p5}^A$$

$$C_4 = \rho_{p3}^A$$

$$C_5 = \rho_{s2}^A$$

$$C_6 = \rho_{s3}^A$$

$$C_7 = \rho_{p2}^A + \rho_{p3}^A + \rho_{p4}^A + \rho_{p5}^A + \rho_{p6}^A + \rho_{p7}^A + \rho_{p8}^A + \rho_{p9}^A + \rho_{p10}^A + \rho_{p11}^A + \rho_{p12}^A$$

$$\frac{dE(C_{\text{TOTAL}}^A)}{dt_0} = C_1 * \frac{dm(t_0)}{dt_0} + C_2 * \left( t_0 * \frac{dm(t_0)}{dt_0} + m(t_0) \right) + C_3 * \frac{dm(t_0, T)}{dt_0} + C_4 * \left( t_0 * \frac{dm(t_0, T)}{dt_0} + m(t_0, T) \right)$$

$$+ C_5 * \frac{d\psi(t_0, T)}{dt_0} + C_6 * \frac{d\phi(t_0, T)}{dt_0}$$

$$t_0^{\text{best}} = -\frac{\lambda C_1 + \lambda C_3 + \lambda T C_4 - C_5 + C_6 (1 - \lambda t_1 + \lambda T)}{\lambda (2C_2 + 2C_4 + C_6)}$$

$$E(C_{\text{MIN}}) = \left[ \frac{\lambda C_1 + \lambda C_3 + \lambda T C_4 - C_5 + C_6 (1 - \lambda t_1 + \lambda T)}{2\lambda (2C_2 + 2C_4 + C_6)} \right]^2 + \lambda T C_3 + \left( \frac{\lambda T^2}{2} - T \right) C_5$$

$$+ \left( \frac{\lambda T^2}{2} - \lambda t_1 T - t_1 + \frac{\lambda T^2}{2} + T \right) C_6 + \lambda t_1 C_7$$
Chapter 4 Cost Analysis

In chapter 4, a cost analysis is realized based on a fabricated numerical case (see Appendix C). The parameters in the case are calibrated by referring to scientific literature and online resources. The analysis consists of four parts. In the first part, a sensitivity analysis is conducted in order to find which parameters have the largest impact on cargo consolidation. In the second part, a Monte-Carlo simulation is carried out to investigate how the uncertainty in information will influence the operational cost of cargo consolidation. In the third part, a comparison of the minimum cost of the four scenarios will be presented to show in what condition applying cargo consolidation is beneficial for the logistic companies. In the last part, the value of specific logistic information is estimated by comparing the cost items in the four scenarios.

4.1 Sensitivity analysis for parameters

Sensitivity analysis aims to investigate how changes in the model output could be apportioned to different model inputs. In our analysis, changes in the input parameters are first standardized as a percentage of ±10%, ±20% and ±30%. Subsequently, the consequences of these input changes are observed in the model output (i.e. minimum cost). By comparing the output changes, the parameters with the most of impact on the minimum cost could be obtained. The analysis results are shown in Table 3. In the table, some cells are filled with “N/A”, which indicates that either the parameter cannot adopt certain test value, or the parameter is not used in certain scenarios.
### Table 3: Results of sensitivity analysis for parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Orig. value</th>
<th>Test value</th>
<th>General case</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 large cost</td>
<td>34</td>
<td>0.82%</td>
<td>0.82%</td>
<td>N/A</td>
<td>-0.19%</td>
<td>-0.04%</td>
<td>-0.14%</td>
</tr>
<tr>
<td>P2 large cost</td>
<td>0.765</td>
<td>0.765</td>
<td>0.765</td>
<td>0.765</td>
<td>-0.2%</td>
<td>-0.05%</td>
<td>-0.05%</td>
</tr>
<tr>
<td>P3 large cost for empty container</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13%</td>
<td>0.13%</td>
<td>0.13%</td>
</tr>
<tr>
<td>P4 truck cost (including discount)</td>
<td>106.5</td>
<td>106.5</td>
<td>106.5</td>
<td>106.5</td>
<td>106.5%</td>
<td>106.5%</td>
<td>106.5%</td>
</tr>
<tr>
<td>P5 shortage cost</td>
<td>12.75</td>
<td>12.75</td>
<td>12.75</td>
<td>12.75</td>
<td>12.75%</td>
<td>12.75%</td>
<td>12.75%</td>
</tr>
<tr>
<td>P6 container stacking cost</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8%</td>
<td>8%</td>
<td>8%</td>
</tr>
<tr>
<td>P7 container handling cost</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47%</td>
<td>0.47%</td>
<td>0.47%</td>
</tr>
<tr>
<td>P8 cargo storage cost</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02%</td>
<td>0.02%</td>
<td>0.02%</td>
</tr>
<tr>
<td>P9 handling cost</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25%</td>
<td>0.25%</td>
<td>0.25%</td>
</tr>
<tr>
<td>P10 delay cost of 1% per container (per day)</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65%</td>
<td>0.65%</td>
<td>0.65%</td>
</tr>
<tr>
<td>P11 delay cost of 2% per container (per day)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3%</td>
<td>0.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>P12 load factor of incoming containers (mean)</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65%</td>
<td>0.65%</td>
<td>0.65%</td>
</tr>
<tr>
<td>P13 pref lead factor for outgoing container</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8%</td>
<td>0.8%</td>
<td>0.8%</td>
</tr>
<tr>
<td>P14 block check criterion</td>
<td>-0.05</td>
<td>-0.05</td>
<td>-0.05</td>
<td>-0.05</td>
<td>-0.05%</td>
<td>-0.05%</td>
<td>-0.05%</td>
</tr>
<tr>
<td>P15 urgent containers coeff</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>P16 share of mixed/urgent containers</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15%</td>
<td>0.15%</td>
<td>0.15%</td>
</tr>
<tr>
<td>P17 fraction of urgent cargos in a mixed urgent container</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8%</td>
<td>0.8%</td>
<td>0.8%</td>
</tr>
<tr>
<td>P18 share of container 1 &amp; 2 to be opened</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05%</td>
<td>0.05%</td>
<td>0.05%</td>
</tr>
<tr>
<td>P19 share of cargo in one batch</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

The results of the sensitivity analysis for the general case are also presented in Figure 22. It could be seen that P13 (prefixed load factor for outgoing containers), P16 (share of mixed urgent containers), P17 (fraction of urgent cargos in a mixed urgent container) and P19 (share of Cargo 1 in one batch) all have a negative impact on the minimum cost. In other words, when these parameters increase, the minimum cost will decrease. The reasons are as summarized follow. When P13 gets larger, there will be less number of outgoing containers, and therefore the cost spent in container shipment as well as empty container repositioning will reduce. Meanwhile, the handling cost will decrease, due to less container movements. When P16 and P17 become larger, there will be less non-urgent cargoes to be consolidated, which results in a smaller penalty cost. When P19 increases, the overall value of the cargoes will decrease, as Cargo 1 is less valuable than Cargo 2. And consequently the total penalty cost, which depends on the value of cargoes, will decrease.

The rest parameters have a positive impact on the minimum cost. Among them, P12 (load factor of incoming containers) and P3 (unit truck cost) have the largest impact. When P12 increases, cargo consolidation will become less useful, as the reduction in the number of outgoing containers becomes smaller. Consequently, the container shipment cost will increase, leading to a larger minimum cost. When P3 increases, container trucking will become more expensive, which

56/81
largely contributes to the minimum cost.

The results of sensitivity analysis for the four scenarios are also presented in Appendix D. Similar to the general case, in the presented four scenarios, P3 (unit truck cost) still has the overall largest positive impact on the minimum cost, and P9 (unit handling cost) is much more sensitive than most of other parameters. It is interesting to notice that the impact of P9 is almost the same in the four scenarios. This indicates that even though applying cargo consolidation generates extra costs such as shuttle cost and cargo operation cost, the excessive handling times turns out to be the biggest obstacle for facilitating cargo consolidation. Moreover, note that P14 (utilization check criterion) in Scenario 3 and P18 (share of Container 1 & 2 to be opened) in Scenario 4 both have a positive impact on the minimum cost. This is because more containers being opened for consolidation causes a larger shuttle cost, cargo operation cost and cargo storage cost, which all add to the minimum cost.

4.2 Monte-Carlo simulation: analysis for uncertainty

As the analytical model created in Chapter 3 only uses mean values of parameters and variables for calculation, a Monte-Carlo simulation is presented in this section to see how the uncertainty in logistic information (i.e. the variance of variables) will influence the operational cost of cargo consolidation. The simulation is only carried out for the general case, and the variables selected for simulation are listed in Table 4. The reason for selecting them is because that in reality it is difficult or even impossible to regard them as a constant. For example, truck transportation time is usually influenced by road traffic congestion, arrival rate of container batches is sometimes
influenced by the terminal operation and control in the sea port, and barge turnaround time might be affected by the container operation in the hinterland terminal.

<table>
<thead>
<tr>
<th>Table 4 Input variables for MC simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input variables</strong></td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>arrival rate of container batches</td>
</tr>
<tr>
<td>load factors of incoming containers</td>
</tr>
<tr>
<td>incoming containers in each batch</td>
</tr>
<tr>
<td>barge transportation time</td>
</tr>
<tr>
<td>truck transportation time</td>
</tr>
<tr>
<td>barge turnaround time</td>
</tr>
</tbody>
</table>

$x_1,x_2...x_6$: different sets of random numbers (between 0 and 1) generated in EXCEL for MC simulation

In the above table, some variables use normal distribution for simulation, while others use beta distribution. This difference occurs when a specific upper and/or lower limit of the variables is expected. For example, as normally the barge turnaround time (i.e. $T$) is not likely to exceed 48 hours, beta distribution, which could set an upper limit for the variable, seems more appropriate for describing its behavior.

During the simulation, as it is unknown when the results (i.e. minimum cost in the general case) will converge, a comparison (see Figure 23 and Figure 24) is made here to see the difference of results between a 100-iteration simulation and a 1000-iteration simulation. In both figures, x-axis denotes the iteration times, while y-axis denotes the average minimum cost. In particular, if a point is located at (60, 25000) in the graph, it means that “till the 60th iteration, the average minimum cost of the general case is 250000 euro”.

![Average minimum cost](image)

**Figure 23** Results of 100 iteration MC simulation
According to the above two figures, it could be observed that after 100 iteration, it is still hard to determine whether the results have converged or should the simulation be continued. But after 1000 iteration, it is clear that a convergence has been reached around 288000 euro. Therefore, the 1000-iteration simulation is preferred in this analysis. Moreover, note that the minimum cost from simulation is slightly larger than from the analytical model (i.e. 283700 euro), because the beta distribution used here does not have a symmetrical span around the mean value.

After the simulation under different uncertainty, it is found that the more uncertainty in information, the larger variance in the minimum cost. According to Figure 25, even though both simulations have almost the same average minimum cost, it is very hard for the logistic operator to estimate the operational cost in the next planning horizon under large uncertainty. Therefore, the accuracy of logistic information not only influence the planning behavior (e.g. the extra container inspection in Scenario 3), but also influence the difficulty in cost control.
4.3 Cost comparison and consolidation policy

From the previous two analyses, it is still not clear that in what condition applying cargo consolidation will be a proper action for the logistic companies. Considering this, a visualization of minimum cost among the four scenarios under different logistic information is provided in this section.

According to Table 5, it could be seen that when there is no information concerning container arrival, the only way to deal with the containers that arrive at the sea port (i.e. Port of Rotterdam in the numerical case) is to truck them instantly to the hinterland. Therefore, the minimum cost among the four scenarios equals to the minimum cost in Scenario 1 (see column 2). When the information of container arrival is revealed to the operator, but the load factor of incoming containers is unknown, the operator could choose between container trucking and exploiting a barge during the planning horizon. And the cost performance indicates that exploiting a barge is more economical. Therefore, the minimum cost appears in Scenario 2 (see column 3).

<table>
<thead>
<tr>
<th>Truck cost</th>
<th>No info of arrival</th>
<th>No info of load factor</th>
<th>With info of arrival and load factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0-0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1</td>
<td></td>
</tr>
<tr>
<td>186.5</td>
<td>1</td>
<td>2</td>
<td>3/4 3/4 3/4 2 2 2 2 2 2 2</td>
</tr>
<tr>
<td>200</td>
<td>1</td>
<td>2</td>
<td>3/4 3/4 3/4 3/4 2 2 2 2 2 2</td>
</tr>
<tr>
<td>220</td>
<td>1</td>
<td>2</td>
<td>3/4 3/4 3/4 3/4 2 2 2 2 2 2</td>
</tr>
<tr>
<td>240</td>
<td>1</td>
<td>2</td>
<td>3/4 3/4 3/4 3/4 2 2 2 2 2 2</td>
</tr>
<tr>
<td>260</td>
<td>1</td>
<td>2</td>
<td>3/4 3/4 3/4 3/4 2 2 2 2 2 2</td>
</tr>
<tr>
<td>280</td>
<td>1</td>
<td>2</td>
<td>3/4 3/4 3/4 3/4 2 2 2 2 2 2</td>
</tr>
<tr>
<td>300</td>
<td>1</td>
<td>2</td>
<td>3/4 3/4 3/4 3/4 2 2 2 2 2 2</td>
</tr>
<tr>
<td>320</td>
<td>1</td>
<td>2</td>
<td>3/4 3/4 3/4 3/4 2 2 2 2 2 2</td>
</tr>
<tr>
<td>340</td>
<td>1</td>
<td>2</td>
<td>3/4 3/4 3/4 3/4 2 2 2 2 2 2</td>
</tr>
<tr>
<td>360</td>
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<tr>
<td>380</td>
<td>1</td>
<td>2</td>
<td>3/4 3/4 3/4 3/4 2 2 2 2 2 2</td>
</tr>
<tr>
<td>400</td>
<td>1</td>
<td>2</td>
<td>3/4 3/4 3/4 3/4 2 2 2 2 2 2</td>
</tr>
<tr>
<td>500</td>
<td>1</td>
<td>2</td>
<td>3/4 3/4 3/4 3/4 2 2 2 2 2 2</td>
</tr>
</tbody>
</table>

Table 5 Cargo consolidation decision matrix

When container load factor is accessible, applying cargo consolidation will become an option for the logistic operator. And the decision process will get relatively complicated. When the mean value of the load factor (of incoming containers) is larger than 0.4 (see row 1), exploiting a barge and do not apply cargo consolidation will be better. And therefore the minimum cost occurs in Scenario 2. But when the mean value is lower than 0.4, applying cargo consolidation will result in less operational cost. But whether the minimum cost exists in Scenario 3 or Scenario 4 depends on the accuracy of information. For example, if the exact load factor of each incoming container is given, the capacity inspection at the decoupling center will not take place, which saves the inspection fees. And certainly the minimum cost will exist in Scenario 4. Considering this, “3/4” is used in the table to generally denote that applying cargo consolidation is more advantageous in
Moreover, from the sensitivity analysis for the input parameters, it is found that the load factor of incoming containers and the unit truck cost have the overall largest positive impact on the minimum cost. Consequently, these two factors are further considered for the analysis of Table 5. It could be observed that with a load factor of 0.5, cargo consolidation will be a cheaper solution when unit truck cost is higher than 300 euro per container (see red square). And when unit truck cost reaches 500 euro per container, cargo consolidation will even be beneficial for the incoming containers that have a higher load factor of 0.6.

Furthermore, as the change in unit truck cost indicates the change in travel distance, a service area of cargo consolidation around the sea port could be plotted. Remind that in Chapter 1, Port of Rotterdam has a WCU of about 50% (see Appendix A). And for a unit truck cost of 300 euro, the corresponding travel distance is about 200 kilometers. Combining these two pieces of information, the potential consolidation service area of Port of Rotterdam is determined (see Figure 26). In the graph, city Gent, Brussels, Maastricht, Venlo, Enschede and Swolle are all located about 200 kilometers (route distance) away from Maasvlakte of Port of Rotterdam. Therefore, based on the analysis of this work, for shipping the containers from Port of Rotterdam to those cities, or to the cities/terminals in the deeper hinterland of Europe, applying cargo consolidation will be economically justified.
4.4 Value of logistic information

As different logistic information revealed in the four scenarios entails different planning behaviors, the value of specific information might be estimated by comparing the minimum cost of each scenario.

When comparing Scenario 2 and Scenario 1, it is found that the information on container arrival has added value for shipment planning, as introducing a barge largely reduces the total operational cost. Therefore, in our case, the value of this information is estimated as the difference of the minimum cost in two scenarios, which is about 18000 euro.

Moreover, when comparing Scenario 3 and Scenario 2, it is found that applying cargo consolidation does not contribute to a more economical “weekly plan”. Therefore, for shipping the containers from Port of Rotterdam to Tilburg, information on container load factor has no added value for cutting the operational cost.

Furthermore, compared to Scenario 3, as more precise information (i.e. the exact load factor of incoming containers) is provided to the operator for planning in Scenario 4, the container inspection cost is eliminated. Besides, the shuttle cost also decreases. Consequently, the value of this specific information is estimated as the summation of container inspection cost and the reduction in shuttle cost, which is about 8000 euro.
Chapter 5 Conclusion and Recommendation

Container transport is currently growing fast and will continue to develop in the near future. However, some problems such as the road container congestion, negative environmental impacts due to container trucking, and the low utilization of container capacity are making the container transport less efficient. To deal with these problems, a promising solution is to improve the container weight capacity utilization through cargo consolidation, as it will greatly reduce the semi-loaded containers going to the hinterland from the port.

However, whether cargo consolidation would benefit logistic service providers still needs investigation. And the information required to realize cargo consolidation has not been explored too much as well. Considering these motivations, the main research question of the thesis is formulated as “Under which circumstances can cargoes from different incoming containers arriving at the seaport be consolidated in outgoing containers to the hinterland, in order to reduce the total operational cost of logistics service provider?”

To answer this question, an analytical model is created to investigate the cost performance of cargo consolidation. The cost model consists of four scenarios and one general case. In the four scenarios, simplified assumptions are applied in order to ensure that the cost functions of these scenarios are comparable for the subsequent analysis. In the general case, cargo consolidation is realized in a more realistic environment, where mixed cargo flows are allowed.

In the cost analysis, a fabricated numerical case with calibrated parameters is first presented to run the model. After that, a sensitivity analysis for the parameters used in the general case and the four scenarios is carried out. The results suggest that the load factor of incoming containers and the unit truck cost have the overall largest positive impact on the minimum cost, while the prefixed load factor for the outgoing containers has the largest negative impact on the minimum cost. Subsequently, a Monte-Carlo simulation is provided to test how the minimum cost reacts to the uncertainty in information. It is found that although the average cost performance might be the same, larger uncertainty makes cost control more complicated and less accurate. Then, a matrix is presented to simply determine in what condition applying cargo consolidation is appropriate. From the matrix, cargo consolidation is viable when the load factor of incoming containers is low and/or unit truck cost is high. And for Port of Rotterdam which has an average container utilization rate of 0.5, cargo consolidation is economically justified for shipping the containers to the destinations with a distance of more than 200 kilometers, such as Duisburg and Koln. After that, the value of specific logistic information is estimated by comparing the minimum cost in the four scenarios. It is found that when applying cargo consolidation, the accuracy of information on container load factor has added value for reducing the operational cost. Finally, the impact of penalty cost on barge departure time is analyzed. It is found that a larger penalty cost helps to keep the best barge departure time within the planning horizon, as it counteracts the benefits brought by cargo consolidation and barge shipment.

In this work, although mixed cargo flows are assumed in the general case, it is still unable to observe the benefits of separating these mixed cargoes. Therefore, future work could focus on
this area as an improvement. Moreover, due to the constraints of mathematical skills used, the time spent on container handling, container shuttling and cargo operation is not considered in the model, which proposes another direction for improvement. From an empirical perspective, this improvement might be realized by simulation. Furthermore, as the capacity issue of barge and truck is not considered in the model, more efforts could be devoted to this area as well. Finally, how to reposition the redundant empty containers after consolidation is also not taken into consideration in the model, which might also be realized in a simulation in the future.


PLANCO, & BfG. (2007). Economical and Ecological Comparison of Transport Modes: Road, Railways, Inland Waterways: Federal German Water and Shipping Administration.


Tan, G. (1999). *The impact of demand information sharing on supply chain network*. (PhD), UIUC.


### Appendix

#### A. Weight capacity utilization of Port of Rotterdam (based on 2009 & 2010 statistics)

<table>
<thead>
<tr>
<th>Container size (feet)</th>
<th># of loaded containers (million)</th>
<th>Cargo weight (million ton)</th>
<th>Maximum payload (ton)</th>
<th>WCU (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-29</td>
<td>3.8</td>
<td>58.9</td>
<td>28</td>
<td>55.4</td>
</tr>
<tr>
<td>40-44</td>
<td>5.9</td>
<td>92.9</td>
<td>28</td>
<td>56.2</td>
</tr>
</tbody>
</table>

Method: \[ WCU = \frac{\text{cargo weight}}{\text{# of loaded containers} \times \text{maximum payload}} \]

Source: (PoR, 2009, 2010)
Source: [http://www.mscgva.ch/containers_specifications.html](http://www.mscgva.ch/containers_specifications.html)
B. Accuracy analysis of the analytical result

In the analytical model of Scenario 3, Scenario 4 and the general case, when solving the best barge departure time (i.e. \( t_0 \)), the term \( e^{-\lambda t_0} \) is neglected for simplification (e.g. see Equation 16). The reason is that in practice the arrival rate of containers \( \lambda \) and the shipment release time \( t_0 \) could not be very small. In order to justify this simplification, the Newton-Raphson method is applied to obtain the best \( t_0 \) at the same time, and a comparison is made between the best \( t_0 \) calculated from the two methods. Note that as Newton’s method aims to obtain numerical solutions instead of an analytical expression, \( e^{-\lambda t_0} \) will not be neglected. The results for Scenario 3 (based on the numerical case) are shown in Table 6.

It could be seen that after 32 iterations, the best barge departure time calculated from Newton’s method is around 32.3 hours, while the best barge departure time calculated from the analytical expression is about 32.7 hours. As these two results are quite close, the accuracy of the analytical expression could be validated.

<table>
<thead>
<tr>
<th>Iteration</th>
<th>( X_n )</th>
<th>( f(X_n) )</th>
<th>( f'(X_n) )</th>
<th>( X_{n+1} )</th>
<th>Iteration</th>
<th>( X_n )</th>
<th>( f(X_n) )</th>
<th>( f'(X_n) )</th>
<th>( X_{n+1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>3173.484</td>
<td>24.31557</td>
<td>-30.4909</td>
<td>17</td>
<td>31.43242</td>
<td>-41.7405</td>
<td>23.96873</td>
<td>31.7388</td>
</tr>
<tr>
<td>2</td>
<td>-30.4909</td>
<td>56280.8</td>
<td>22.48449</td>
<td>18</td>
<td>33.17388</td>
<td>35.69603</td>
<td>24.05711</td>
<td>31.69007</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>22.48449</td>
<td>-399.569</td>
<td>22.76077</td>
<td>19</td>
<td>31.69007</td>
<td>-30.3725</td>
<td>23.98347</td>
<td>32.95647</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>37.83535</td>
<td>248.0126</td>
<td>-206.782</td>
<td>22</td>
<td>32.79819</td>
<td>18.87853</td>
<td>24.00108</td>
<td>32.68296</td>
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</tr>
<tr>
<td>7</td>
<td>27.58643</td>
<td>-206.382</td>
<td>23.39186</td>
<td>23</td>
<td>32.0129</td>
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<td>24.00108</td>
<td>32.68296</td>
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<td>8</td>
<td>36.31164</td>
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<td>24.13322</td>
<td>26</td>
<td>32.59909</td>
<td>9.989064</td>
<td>24.03072</td>
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<td></td>
</tr>
<tr>
<td>11</td>
<td>29.90161</td>
<td>-108.52</td>
<td>23.86676</td>
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<td>-8.51468</td>
<td>24.01</td>
<td>32.53804</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>34.44854</td>
<td>93.14392</td>
<td>24.10735</td>
<td>28</td>
<td>32.53804</td>
<td>7.266788</td>
<td>24.02777</td>
<td>32.23561</td>
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<td>-78.8874</td>
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<td>29</td>
<td>32.23561</td>
<td>-6.19353</td>
<td>24.01268</td>
<td>32.49361</td>
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<td>61.70434</td>
<td>24.08638</td>
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<td>5.286584</td>
<td>24.02556</td>
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<tr>
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<td>49.1064</td>
<td>24.06986</td>
<td>32</td>
<td>32.46128</td>
<td>3.846076</td>
<td>24.02401</td>
<td>32.30118</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Comparison of \( t_0 \) by using different methods

\( f(X) \): the derivative equation in Equation 15, containing \( e^{-\lambda t_0} \)

\( f'(X) \): the derivative of \( f(X) \), which also contains \( e^{-\lambda t_0} \)
C. Numerical case for cost analysis

The values of parameters used in the cost model are listed in Table 7. In the following content, the calibration process will be discussed.

<table>
<thead>
<tr>
<th>Parameter and variable</th>
<th>Simplified Scenarios</th>
<th>General Case</th>
<th>Symbol</th>
<th>Dimension</th>
<th>value</th>
<th>mean</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td>unit barge cost</td>
<td>○</td>
<td>○</td>
<td>$c^b_0$</td>
<td>euro/container</td>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unit empty container reposition cost</td>
<td>○</td>
<td>○</td>
<td>$c^b_1$</td>
<td>euro/container</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unit truck cost</td>
<td>○</td>
<td>○</td>
<td>$c^t_0$</td>
<td>euro/container</td>
<td>186.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unit truck cost with discount</td>
<td>○</td>
<td>○</td>
<td>$c^t_{1d}$</td>
<td>euro/container</td>
<td>167.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unit shuttle cost</td>
<td>○</td>
<td>○</td>
<td>$c^s_0$</td>
<td>euro/container</td>
<td>0.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unit stacking cost</td>
<td>○</td>
<td>×</td>
<td>$c^s_1$</td>
<td>euro/container/hour</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unit cargo storage cost</td>
<td>○</td>
<td>○</td>
<td>$c^f_0$</td>
<td>euro/ton/hour</td>
<td>2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unit cargo operation cost</td>
<td>○</td>
<td>○</td>
<td>$c_{co}$</td>
<td>euro/ton/hour</td>
<td>10.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unit handling cost</td>
<td>○</td>
<td>×</td>
<td>$c^h_0$</td>
<td>euro/move</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unit delay cost of Con. 1</td>
<td>○</td>
<td>×</td>
<td>$c^p_1$</td>
<td>euro/container/hour</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unit delay cost of Con. 2</td>
<td>○</td>
<td>×</td>
<td>$c^p_2$</td>
<td>euro/container/hour</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>unit delay cost of Cargo 1</td>
<td>○</td>
<td>○</td>
<td>$c^p_{1c}$</td>
<td>euro/ton/hour</td>
<td>0.3</td>
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<tr>
<td>unit delay cost of Cargo 2</td>
<td>○</td>
<td>○</td>
<td>$c^p_{2c}$</td>
<td>euro/ton/hour</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>share of cargoes to A</td>
<td>×</td>
<td>○</td>
<td>$a$</td>
<td>N.A.</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>prefixed load factor for outgoing container</td>
<td>○</td>
<td>○</td>
<td>$L_0$</td>
<td>N.A.</td>
<td>0.85</td>
<td></td>
<td></td>
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<tr>
<td>utilization check criterion</td>
<td>○</td>
<td>×</td>
<td>$L_o$</td>
<td>N.A.</td>
<td>0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>probability of being opened</td>
<td>○</td>
<td>×</td>
<td>$P_{01}^A, P_{02}^A$</td>
<td>N.A.</td>
<td>0.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>urgent container coefficient</td>
<td>○</td>
<td>×</td>
<td>$k_u$</td>
<td>N.A.</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>share of mixed urgent containers</td>
<td>×</td>
<td>○</td>
<td>$k'_{iu}$</td>
<td>N.A.</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fraction of urgent cargoes in a mixed urgent container</td>
<td>×</td>
<td>○</td>
<td>$f_{iu}$</td>
<td>N.A.</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>maximum weight of a loaded container</td>
<td>○</td>
<td>○</td>
<td>$w$</td>
<td>ton</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>share of containers to be opened</td>
<td>○</td>
<td>×</td>
<td>$\eta_1, \eta_2$</td>
<td>N.A.</td>
<td>0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of Con.1 in one batch</td>
<td>○</td>
<td>×</td>
<td>$n^i_1$</td>
<td>container</td>
<td>12</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>number of Con.2 in one batch</td>
<td>○</td>
<td>×</td>
<td>$n^i_2$</td>
<td>container</td>
<td>15</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>number of mixed containers in one batch</td>
<td>×</td>
<td>○</td>
<td>$n_i$</td>
<td>container</td>
<td>60</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>load factor of Con.1</td>
<td>○</td>
<td>×</td>
<td>$L_{b1}$</td>
<td>N.A.</td>
<td>0.65</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>load factor of Con.2</td>
<td>○</td>
<td>×</td>
<td>$L_{b2}$</td>
<td>N.A.</td>
<td>0.65</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>load factor of mixed containers</td>
<td>×</td>
<td>○</td>
<td>$L_{bj}$</td>
<td>N.A.</td>
<td>0.65</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>deadline of Con.1 in the 1st batch</td>
<td>○</td>
<td>○</td>
<td>$D_{1j}$</td>
<td>hour</td>
<td>125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>deadline of Con.2 in the 1st batch</td>
<td>○</td>
<td>○</td>
<td>$D_{2j}$</td>
<td>hour</td>
<td>126</td>
<td></td>
<td></td>
</tr>
<tr>
<td>deadline of Con.1 in the (N+1)st batch</td>
<td>○</td>
<td>○</td>
<td>$D_{(N+1)1}$</td>
<td>hour</td>
<td>207</td>
<td></td>
<td></td>
</tr>
<tr>
<td>deadline of Con.2 in the (N+1)st batch</td>
<td>○</td>
<td>○</td>
<td>$D_{(N+1)2}$</td>
<td>hour</td>
<td>208</td>
<td></td>
<td></td>
</tr>
<tr>
<td>barge transition time</td>
<td>○</td>
<td>○</td>
<td>$g_b$</td>
<td>hour</td>
<td>13.5</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>truck transition time</td>
<td>○</td>
<td>○</td>
<td>$g_t$</td>
<td>hour</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>barge turnaround time</td>
<td>×</td>
<td>○</td>
<td>$T$</td>
<td>hour</td>
<td>36</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>arrival rate of batches</td>
<td>○</td>
<td>○</td>
<td>$\lambda$</td>
<td>batch/hour</td>
<td>0.167</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>
Parameter calibration

As there is no real case that could be applied to operate the model, a numerical case is fabricated here. The parameters and variables in this case are calibrated as much as possible. But as some data are not accessible on the internet, the assumed values are used. The case is created as follow:

The containers arriving at the seaport – Port of Rotterdam (Maasvlakte) – will be shipped to the hinterland terminal – Terminal Tilburg (see Figure 27). The inland waterway and road distance between them are about 120 kilometers.

According to Evers and de Feijter (2004) who made a cost outline of inland container transport tariffs based on the researches from TNO Inro and TRAIL Research School, the inland container transport cost mainly consists of personnel and fuel cost (see Table 8). Personnel cost is priced based on hours whereas fuel cost is priced based on kilometers.
Table 8 Cost outline of inland container transport

<table>
<thead>
<tr>
<th>Time dep personnel other costs</th>
<th>Conven</th>
<th>Shuttle</th>
<th>Coastal Shipping</th>
<th>Rail Transp.</th>
<th>Road Transp.</th>
<th>MTS, manned</th>
<th>MTS, Guided</th>
</tr>
</thead>
<tbody>
<tr>
<td>€/hour</td>
<td>0.45</td>
<td>0.15</td>
<td>0.15</td>
<td>6.40</td>
<td>31.3</td>
<td>31.3</td>
<td>3.1</td>
</tr>
<tr>
<td>€/km</td>
<td>0.33</td>
<td>0.22</td>
<td>0.33</td>
<td>0</td>
<td>16.2</td>
<td>16.2</td>
<td>17.0</td>
</tr>
<tr>
<td>Dist dep fuel other costs</td>
<td>0.014</td>
<td>0.010</td>
<td>0.020</td>
<td>0.06</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>speed km/hour</td>
<td>± 9</td>
<td>± 13</td>
<td>20–25</td>
<td>30–50</td>
<td>60</td>
<td>18–27</td>
<td>18–27</td>
</tr>
</tbody>
</table>

Based on the data in Column 1 (conventional barge service), Column 2 (new barge service) and Column 5 (truck service) in the above table, the unit barge cost and truck cost (euro per container) in the model are calibrated as:

\[
c_b = (0.45 + 0.33) \times \frac{120}{13} + (0.014 + 0.042) \times 120 = 14
\]

\[
c_t = (31.3 + 16.2) \times \frac{120}{60} + (0.26 + 0.22) \times 120 = 153
\]

But as the data in Table 8 are captured 10 years ago, an inflation rate is applied here, which is assumed as 2%. Therefore, the current unit barge and road cost (euro per container) should be:

\[
c_b^d = 14 \times (1 + 0.02)^{10} = 17
\]

\[
c_t^d = 153 \times (1 + 0.02)^{10} = 186.5
\]

For the trucks that departure from the port at \( t_1 \), a 10% discount is considered. Therefore, the discount truck price is 167.85 euro per container. However, based on our experience, it seems that the unit barge cost obtained here is too low. Therefore, another resource is used for calibration. According to Konings (2009), the unit cost of a medium size barge in a round trip from Rotterdam to Duisburg is about 50 euro/TEU (see Figure 28). By introducing a container size factor of 1.5 (i.e. assuming 20ft and 40ft container 1:1), the unit barge cost per container should be 75 euro. And as the waterway distance from Rotterdam to Duisburg is 267 kilometers (PLANCO & BfG, 2007), the unit barge cost per container from Rotterdam to Tilburg will be about 34 euro.

Figure 28 Indicative cost on the route Rotterdam–Duisburg for different number of roundtrips per week and varying transport volumes
Regarding container shuttling (by truck), as a round trip between seaport and decoupling center is assumed as taking up 20 minutes, the unit shuttle cost (euro per container) is calibrated as $c_t^D = 153/(60 \cdot 120/60) \cdot 10 = 12.75$.

According to Riessen (2013), a transfer (which consists of two handlings) in container transport will entail a cost of 23.89 euro. Therefore, the unit handling cost is about 12 euro per move. Moreover, according to Konings (2009), handling cost per move (including gantry/mobile crane cost and labor cost) will decrease with the increase of transshipment volume (see Figure 29). Therefore, for Port of Rotterdam where a lot of container transfers take place, the handling cost will be about 8.5 euro per move. Based on these two sources, the unit handling cost is calibrated as the average of them, i.e $c_h = (12 + 8.5)/2 = 10.25$ euro.

The cost of container stacking is in practice included in Terminal Handling Charges (THC) (EC, 2009). In addition to container stacking, THC covers in total 11 cost items (see Table 9). As some activities such as cost item 2 and 3 are expensive, container stacking only contributes a small portion to THC. Therefore, it is assumed that stacking cost is 10% of THC. After 2008, the average THC charged by Port of Rotterdam is 170 euro per container (EC, 2009). Therefore, stacking cost should be 17 euro per container. And as the dwelling time of a container in stack is usually 1-2 day, the unit stacking cost (euro per container per hour) in the model is calibrated as $c_s = 17/(24 \cdot 1.5) = 0.47$. And as we assume that a fully loaded container is 30 ton, the unit cargo storage cost (euro per weight per hour) is about 0.02.

<table>
<thead>
<tr>
<th>Table 9 Cost elements of Terminal Handling Charges</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Item</strong></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>
The unit penalty cost in the model is dependent on cargo types. Therefore, the value of time (VOT) of cargoes is introduced here. According to De Jong (2000), cargoes that use sea transport (i.e. from origins to Port of Rotterdam) has a VOT of 0.016 euro/ton/hour. And considering the impact of inflation, the current unit cargo penalty cost should be about 0.2 euro/ton/hour. And as there might be some variations in the cost of different types of cargoes, it is assumed that Cargo 1 has the penalty cost of 0.2, while Cargo 2 has the penalty cost of 0.3. And consequently, the unit container penalty cost (euro per container per hour) for Cargo 1 and Cargo 2 are calculated as 6 and 9 respectively.

According to Weisz (2002), the operation cost per pallet in a warehouse is about 3.35 dollar. And as a single container could accommodate 20-30 pallets, the unit cargo operation cost (euro/ton) is calibrated as 2.05. And considering the inflation rate, the unit cargo operation cost is finally calibrated as 2.4 euro/ton.

For the general case, as mixed cargo flows are assumed, we assume that 50% of the cargoes will be shipped to destination A. And the share of Cargo 1 and Cargo 2 is 1:1. Besides, as urgent cargoes are loaded together with non-urgent cargoes, the share of mixed urgent containers is assumed as 0.15, which is slightly higher than the urgent container coefficient in the four scenarios. This is reasonable, as urgent cargoes are diluted in the containers, which increases the share of containers that partially contain urgent cargoes.
D. Visualization of the sensitivity analysis results of the four scenarios

Figure 30 Sensitivity analysis for parameters in Scenario 1

Figure 31 Sensitivity analysis for parameters in Scenario 2
Figure 32 Sensitivity analysis for parameters in Scenario 3

Figure 33 Sensitivity analysis for parameters in Scenario 4
E. Impact of penalty cost on the barge departure time

In the previous chapter, an assumption is made on the penalty cost, that for a specific storage process, only the deadline of the first batch of containers will influence the total penalty cost. The assumption is expected to bring a comparatively larger penalty cost to cargo consolidation. But how this assumption will influence the best barge departure time remains unknown. Considering this, an analysis of the best barge departure time in the general case under different penalty cost is presented. The results are visualized in Figure 34.

The results show that when penalty cost gets smaller, the best barge departure will be postponed, and the minimum cost will decrease, as depicted on the left side of the figure. This is because as penalty cost gets smaller, it is reasonable to let more containers shipped by barge. And therefore the total number of containers shipped by truck will decrease, making the minimum cost smaller. However, when setting the penalty cost as zero, the best barge departure time will be beyond the planning horizon, as denoted by the red square in the figure. This is because, among the existing cost items, penalty cost is one of the strongest factors that will restrict the barge departure time. If penalty cost is not considered, the small storage cost will not be able to counteract the benefits brought by cargo consolidation (i.e. reduction in the outgoing containers) and barge shipment (i.e. cheap transportation fees compared to truck). Therefore, the phenomenon actually indicates that including a penalty cost for cargo consolidation in our case is meaningful.