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# Flow consolidation in hinterland container transport: An analysis for perishable and dry cargo

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ABSTRACT

The continuously increasing container throughput has created complex operational problems for port operations and port-hinterland transportation. Increase in negative externalities such as air pollution and road congestion are examples of challenging issues. Consolidation of cargo/container flows may help to alleviate the situation by better utilizing the means of transport and containers. Using analytical models for three scenarios – only-trucking (no-consolidation), container consolidation and combined container/cargo consolidation – we discuss the conditions under which the consolidation of flows can be beneficial. The results imply that shipment distance and type of cargo are important factors that affect the performance of flow consolidation in port-hinterland logistics.

## 1. Introduction

Global container traffic has almost doubled over a decade between 2006 (416 million TEU) and 2016 (710 million TEU) (World Bank, 2017). This increasing trend towards containerization is expected to continue steadily over the next decades as well (Rodrigue and Notteboom, 2015). However, the fast development of container transport has raised some major concerns. The first issue is the road congestion caused by container transport, especially in the regions around the main seaports. The reason for congestion is twofold. First, as many seaports lack organized waterway and railroad transport systems, trucking is mostly the dominant mode for hinterland transport (de Langen et al., 2017). Even for a port such as the Port of Rotterdam with abundant inland waterway resources, 46% of all containers going to/from the port were transported by road in 2015 (Port of Rotterdam, 2015a). The second reason for congestion is that road capacity is relatively low and, accordingly, it can be influenced easily by external conditions such as commuting peak and the Working Time Directive of truck drivers. The growing container trucking sector can cause many negative environmental impacts. It is estimated that 5.6 g $CO_2$/tonne-km is emitted if an export/import container carried by a small containership (444 TEU) and 155 g $CO_2$/tonne-km if it is carried by truck (Liao et al., 2009).

To handle these challenges, one possibility is to reduce the container transport towards the hinterland. This can be achieved in several ways, including an increase in the utilization of containers and transport assets. Most commonly used 40 ft maritime containers can carry a maximum of 22 standard pallets (1.2 m × 1.0 m) (McDonald, 2016). In comparison, a 45 ft container can load 26 pallets, and a 53 ft trailer can stow 30 pallets (Palmer et al., 2018). These numbers demonstrate the potential to increase container and transport assets utilization of hinterland transport by designing the network and handling processes at the cargo level. The cargo

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(and container) flows can be consolidated in a decoupling centre, which is located in or close to the seaport. In this research, incorporating a consolidation process to re-arrange the container flows is called "cargo-driven intermodal transport". The essence of this concept is defining tailored intermodal solutions based on the type of cargo. This concept is expected to provide several benefits in container hinterland transport as depicted in Fig. 1. Firstly [Fig. 1(a)], by consolidation of cargo (to larger containers), the total number of containers towards the hinterland and the demand for container trucking decrease. Reduction in the container trucking leads to less road congestion and lower negative environmental impacts. Moreover, as fewer containers enter the hinterland, a reduction in the empty container movement would be expected. Less movement of empty containers not only contributes to alleviating the road traffic congestion – and the environmental impacts – but also helps to reduce the total operational cost in the transportation chain. As the second benefit [Fig. 1(b)], the cargo consolidation contributes to dissecting the urgent and non-urgent flows and facilitates the modal shift towards barge and train. When urgent and non-urgent cargoes are loaded together in a single container, the container must be regarded as urgent and must be trucked to the destination to avoid any delay. However, if urgent and non-urgent flows are separated in a decoupling centre, it is possible to ship the non-urgent cargoes by a cheaper, cleaner but slower transport mode, such as barge and train, and still to ship the urgent containers by truck. The other benefit of cargo consolidation [Fig. 1(c)] is de-bundling the maritime and continental flows: the consolidation centre can serve as a decoupling point for trans-loading cargoes from seaside containers to continental containers. Consequently, the containers at the maritime side can be released faster to be reused.

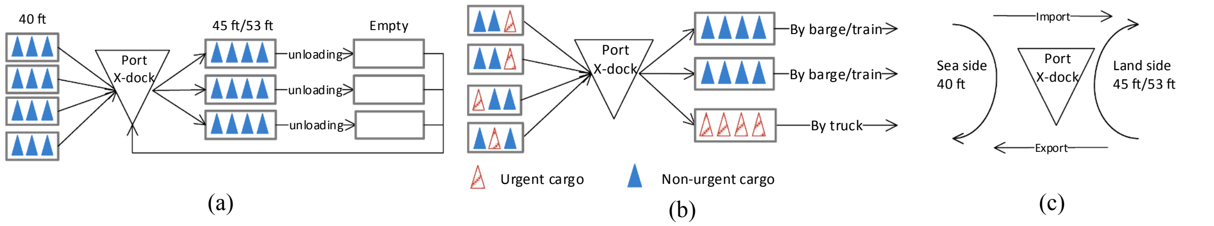



**Fig. 1.** Potential benefits of cargo-driven intermodal transport: fewer containers to the hinterland and less empty movement (a), dissecting urgent/non-urgent flows (b), decoupling maritime/continental flows (c).

Some initiatives of cargo-driven intermodal transport such as Rotterdam Cool Port (Fig. 2) have already started a new freight distribution network by having a decoupling point in the container terminal (Port of Rotterdam, 2015b). A crucial part of Rotterdam Cool Port is building a storage and cross-docking facility for temperature-controlled cargo – such as fruit, vegetables, meat and fish – at the existing ECT City Terminal. Consequently, the reefer containers from deep-sea terminals will be moved to the cross-docking facility, and – after quality check and inspection – the cargo can be consolidated and loaded in a bigger size trailer. Subsequently, the transportation with barge, train or truck is arranged to the hinterland. Meanwhile, as Rotterdam Cool Port is planned in the area with short-sea terminals, reefer containers can be also sent easily to other destinations in Europe. Integration of cross-docking/storage operation in container transhipment and mode planning in the Cool Port project helps to re-shape the logistical process and container/cargo flows. Furthermore, this improves the efficiency of the transport process by preventing empty journeys and improving the utilization of means of transportation and containers.

In this paper, a systemic analysis of cargo-driven intermodal transport is presented and discussed. With this systemic analysis, we aim to study the conditions under which the consolidation of container/cargo flows is beneficial in terms of cost, emission and product quality for perishables. The methodology is to develop an analytical model and to compare the cases with and without flow consolidation. The rest of this paper is organized as follows: Section 2 reviews intermodal freight transport (IFT) and shipment

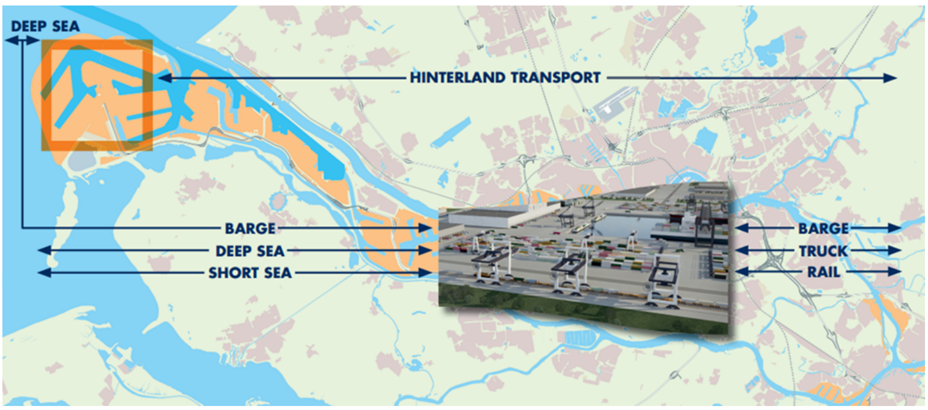



**Fig. 2.** Schematic Rotterdam Cool Port initiative (Port of Rotterdam, 2015b).

consolidation literature. Section 3 describes an analytical cost and emission model for cargo-driven intermodal transport under several scenarios. Sections 4 and 5 apply the model to realistic case studies and present the results of two numerical studies: (1) non-perishable cargoes imported from the Port of Rotterdam; and (2) perishable cargoes including product cooling and product shelf life. Section 6 discusses the findings and provide some managerial insights. Finally, in Section 7, conclusions and future research directions are presented.

## 2. Literature review

In cargo-driven intermodal transport, the mode planning for hinterland container transport is combined with consolidation of incoming cargo flows. Therefore, a review of modelling studies in these two fields is presented in this section.

### 2.1. Mode planning of intermodal freight transport

"Intermodal freight transport" refers to the movement of goods in the same loading unit or vehicle, which uses successively multiple modes of transport (e.g., road, rail and inland waterway) without any handling of goods during transfers between modes (European Commission, 1997). The decisions for IFT planning are usually classified into three main categories: long-term (strategic), medium-term (tactical) and short-term (operational) level (Bontekoning and Priemus, 2004). The planning models at the strategic level are about defining infrastructure network and operating strategies over a relatively long time horizon (Behdani et al., 2016). These models define the transportation network including the location of main facilities and physical transportation resources (SteadieSeifi et al., 2014). Intermodal transport planning at the tactical level aims to efficiently utilize the available resources to define an IFT service (SteadieSeifi et al., 2014). Typical decisions at this level include the determination of routes, choosing the types of services, service schedules, vehicle routing, etc. The operational planning is focused on short-term issues and addresses the detailed balance of demand and supply of resources. The detailed information about vehicles, facilities and activities are mostly available at this level and, accordingly, the operational decisions (e.g., the routing and dispatching of vehicles in the case of disruption occurrence) can be made (Crainic, 2003). A review of the literature on planning models for intermodal transport can be found in Macharis and Bontekoning (2004), Crainic and Kim (2007) and SteadieSeifi et al. (2014).

The flow consolidation on container level – as discussed in this research – is a mode planning problem at the tactical level of intermodal transport. More specifically, the transport mode should be arranged by a service provider who is also responsible for the cargo consolidation. In the existing literature, the mode choice decision is sometimes regarded as the route choice decision for specific trajectories between the starting and ending points (Macharis and Bontekoning, 2004). However, the co-modality can also be part of a mode planning problem; a combination of different transport modes can be defined to obtain an optimal and sustainable utilization of freight transport resources (SteadieSeifi et al., 2014). Accordingly, the mode arrangement involves both slow and less costly transport modes such as barge and train, and the fast and flexible trucking option to execute shipments under time pressure (Zuidwijk and Veenstra, 2014). The co-modality has been a basis for synchromodal freight transport (Behdani et al., 2016; Tavasszy et al., 2015). Co-modality is also important for cargo-driven intermodal transport because the urgent cargoes are mostly not suitable for the consolidation and they need fast hinterland transport to avoid delays, while, in the case of non-urgent cargoes, not only cargo consolidation but also exploitation of cheap transportation modes could be conducted to minimize the total operational cost.

### 2.2. Shipment consolidation

Consolidation of cargoes is studied mainly in two different domains: shipment consolidation and cross-docking. Both domains are about combining several small shipments with the same destination into a single, larger shipment (Boysen and Fliedner, 2010). However, for shipment consolidation, the focus is on making full truckloads to achieve economies of scale in outbound transport, whereas cross-docking is mainly about shipment sorting and minimizing the intermediate/temporal storage by synchronizing the inbound and outbound trucks. The majority of recent studies regarding cross-docking operation have focused primarily on truck scheduling problems, which determine where and when trucks should be processed at dock doors (Ladier and Alpan, 2016). This kind of literature differs from the focus of this paper, i.e., to demonstrate the value of cargo consolidation and its impact on IFT. Therefore, the primary focus of the literature review is on shipment consolidation research. Some of the first systematic studies on shipment consolidation are presented in Beckmann et al. (1953) and Beckmann et al. (1956), which showed that a train could transfer its small loads to another big train heading for the same destination in the railway-switching yard.

Some of the later research in this domain is focused on determining the timing of dispatching the consolidated shipments (Berling and Eng-Larsson, 2016). Jackson (1985) discussed three common consolidation policies in practice: time policy (dispatching in every $T_0$ periods), quantity policy (holding cargoes until the shipment amount reaches $Q_0$) and time-and-quantity policy (dispatching according to the time or quantity policy, depending on which one is satisfied earlier). He discussed that the time policy was the most-frequently-adopted approach in shipment consolidation. To further evaluate these policies, Higginson and Bookbinder (1994) conducted a simulation study to compare the relative costs and delay performance of each policy.

To find the optimal value for dispatching policies, a deterministic analytical model is presented by Blumenfeld et al. (1985), which applied 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 analysing the long-run average performance in a stochastic environment. For example, Higginson (1995) discussed when ESQ is an adequate substitute for a probabilistic analysis of dispatch timing. Stochastic approaches for shipment consolidation have evolved into many different forms. Çetinkaya and Bookbinder (2003), Mutlu et al.

(2010) and Chen et al. (Chen et al., 2017) 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.

To summarize, previous studies have focused on either mode planning on container level or shipment consolidation on cargo level. However, both container and cargo consolidation are important for cargo-driven intermodal transport. This work shows the possibility of combining the co-modality planning and shipment consolidation in the context of container transport. For container consolidation, a time-and-quantity policy is applied. The intermodal service departure time is determined by minimizing total cost or total $CO_2$ emission. For cargo consolidation, a quantity policy (i.e., to release a truck when it is fully loaded) is used. Therefore, this work analyses flow consolidation more comprehensively. Another contribution of this work is that three different concepts are compared to show the benefits of flow consolidation. Total operational cost and $CO_2$ emission are formulated for only-trucking (without consolidation), container consolidation and combined container/cargo consolidation. Based on the model formulation, the differences in cost and environmental impact between the concepts are calculated.

## 3. The mathematical model

In this section, an analytical model is developed to elaborate the impact of flow consolidation in IFT. This model applies the renewal (reward) theory to calculate the total expected operational cost and $CO_2$ emission. The model can be used to determine the optimal schedule and timing of intermodal services.

### 3.1. Problem statement

The scope of modelling (Fig. 3) is set from the container arrival at the port to the container departure at a cross-docking facility in the hinterland, including the mode arrangement for the hinterland transport. This process represents the steps in the Rotterdam Cool Port project. The inbound flows of containers are shuttled firstly to a decoupling centre located in the port area. All the trucking and intermodal services are arranged by a logistics service provider to send containers further to the hinterland. The transportation modes for containers shipment and the assignment of containers to different modes are scheduled. Subsequently, total cost and $CO_2$ emission are formulated for three distinctive scenarios.

- *Scenario 1 (only-trucking):* In the first scenario, trucking is the single option to ship the containers to the hinterland. As the containers arrive at the decoupling centre, they are sent immediately by trucks to the hinterland. Since the container operation is assumed as instantly completed, no container storage is needed.
- *Scenario 2 (container consolidation):* In this scenario, several intermodal services are planned to depart at time $t_0$, $2t_0$, $\cdots, Nt_0$, where $N$ is the frequency of the intermodal service and $N \times t_0$ equals the planning horizon $T$. In mode planning, the urgency factor of containers is considered. Cargo urgency is determined by attributes of the cargo, such as perishability, high-value cargo and the delivery due date requirement of shippers. Usually, mode choice is done by shippers in practice. Therefore, in this scenario, a portion of non-urgent containers is shipped to the hinterland by intermodal services, which is specified by shippers. The rest of the non-urgent containers and the urgent containers are shipped by trucks. In this case, there is an accumulation (i.e., storage) process for the non-urgent containers arriving at the decoupling centre before the departure of intermodal services.
- *Scenario 3 (combined container/cargo consolidation):* Similar to scenario 2, intermodal services are planned to depart at time $t_0$, $2t_0$, $\cdots, Nt_0$. Additionally, cargo consolidation can take place at the decoupling centre; a portion of non-urgent containers that are not shipped by truck is opened and cargoes on pallets are consolidated to tractor trailers to be sent to the hinterland. The other non-urgent containers (i.e., non-opened containers) are sent to the hinterland by intermodal services or trucks. The urgent containers are shipped instantaneously by trucks.

Scenario 2 is the same as scenario 1 if a portion of non-urgent containers is shipped by truck and the portion is 100%. Similarly, scenario 3 is the same as scenario 2 when the portion of opened non-urgent containers is 0%; and scenario 3 is the same as scenario 1 when the portion of opened non-urgent containers is 0% and the portion of non-urgent containers shipped by truck is 100%.

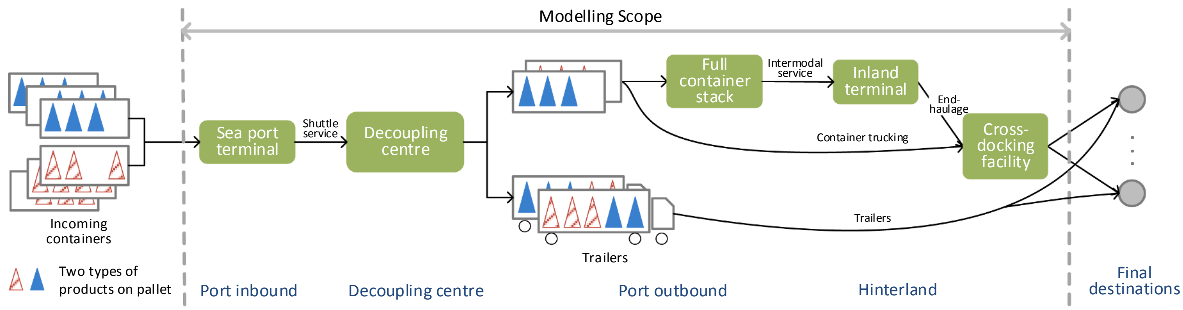



**Fig. 3.** Modelling scope.

### 3.2. Assumptions

In developing the analytical model, the following assumptions are made:

- Container flows arrive in batches, which is a compound Poisson process with batch arrival rate $\lambda$. The number of containers in one batch is assumed as a random variable, which is independent of the batch arrival.
- Trucks and trailers are assumed to be always available at the decoupling centre. The fleet size is also assumed to be unlimited. The schedule of trucks and trailers is thus flexible. When a trailer is not fully loaded, it stays at the decoupling centre (waiting for the next batch of containers).
- In scenario 3 (combined container/cargo consolidation), after cargo consolidation at the port, the trailers travel directly to the final destinations, e.g., supermarkets or retailers' stores. In other words, the cross-docking operation and cargo consolidation are moved from the hinterland to the port area. In order to make scenario 3 comparable with scenario 1 (only-trucking) and scenario 2 (container consolidation), the consolidation at the retailer's cross-docking facility to outbound trailers is also included in the model formulation. In the mathematical model, it is assumed that the shipment cost from the retailer's cross-docking facility to the final destinations is the same for all scenarios. Thus, for scenario 3, the model includes the shipments and operation until the retailer's cross-docking facility instead of the final destinations. This would make all scenarios comparable.
- The cargoes can be shipped together in one container and are operated at one hinterland crossing-docking location. The incoming container flows in all scenarios are also identical, and their total cost and total emission are hence comparable.

### 3.3. Model formulation and analysis

#### 3.3.1. Notations

| | |
|---|---|
| $j$ | container batch (i.e., $j^{th}$ batch) $j \in \{1, 2, \cdots\}$ |
| $n_j$ | number of containers in the $j^{th}$ batch, which is a random variable |
| $\mu$ | representing the expected value of number of containers in a batch |
| $\lambda$ | arrival rate of container batch |
| $T$ | planning horizon (h) |
| $N$ | the frequency of intermodal services |
| $t_0$ | intermodal service departure time (cycle time) (h), $t_0 = \frac{T}{N}$ |
| $U$ | capacity of intermodal service (container) |
| $c_t$ | unit trucking cost (€/container) |
| $c_{IFT}$ | fixed cost of intermodal service for service arrangement (€/cycle) |
| $c_{IFT}^v$ | variable cost of intermodal service (€/container) |
| $c_e$ | unit end-haulage cost (€/container) |
| $c_{tr}$ | unit trailer cost (€/container) |
| $c_h$ | unit container handling cost (€/container) |
| $c_{sh}$ | unit shuttle cost (€/container) |
| $c_{con}$ | unit cargo consolidation cost (€/pallet) |
| $c_s$ | unit container storage cost (€/container /hour) |
| $c_{sp}$ | unit cargo (pallet) storage cost at the decoupling centre or a cross-docking facility (€/pallet/hour) |
| $d_t$ | trucking distance (km) |
| $d_{IFT}$ | distance by intermodal service to inland terminal (km) |
| $d_e$ | end-haulage distance (km) |
| $d_{sh}$ | shuttle distance (km) |
| $v_t$ | fuel usage rate of a truck (litre/km) |
| $v_{IFT}$ | fuel usage rate of an intermodal service (litre/km) |
| $v_{tr}$ | fuel usage rate of a trailer (litre/km) |
| $v_h$ | electricity consumption of container handling (kW/container) |
| $v_{sh}$ | fuel usage rate of shuttle service (litre/km/container) |
| $v_{con}$ | fuel usage rate of cargo consolidation (litre/hour/pallet) |
| $f_d$ | $CO_2$ emission factor per litre fuel (kg/litre) |
| $f_e$ | $CO_2$ emission factor per kW electric (kg/kW) |
| $k_u$ | urgency factor – the share of urgent containers in a batch, $k_u \le 1$, $1 - k_u$ is the share of non-urgent containers |
| $p_t$ | the share of non-urgent container shipped by truck |
| $p_o$ | opening factor – the share of non-urgent containers not shipped by truck that are opened for consolidation, $p_o \le 1$ |
| $l_{c,j}$ | container load factor of the $j^{th}$ batch |
| $L_c$ | representing the expected value of container load factor |
| $pl_{tr}$ | trailer capacity (number of pallets) |
| $pl_c$ | container capacity (number of pallets) |

#### 3.3.2. Model formulation

For each scenario, the formulas for total cost and total $CO_2$ emission are made. In scenario 2 and scenario 3, the cycle time of intermodal service $t_0$ is the decision variable. The expected total cost and total $CO_2$ emission are generalized based on the renewal theory as follows.

- *Scenario 1 (only-trucking)*

In scenario 1, trucking is the only option for hinterland transport. Total cost and total emissions consists of four components: shuttling, container handling, trucking and consolidation (at the hinterland cross-docking facility).

**Proposition 1.** *For the case of only-trucking, the expected total cost and total $CO_2$ emission are defined by:*

$$E(Cost)_{Scenario1} = (5c_h + c_{sh} + c_t + c_{con}pl_cL_c)\mu\lambda T + c_{sp}T\frac{pl_{tr}}{2} \tag{1}$$

$$E(Emission)_{Scenario1} = (5f_e v_h + f_d v_{sh} d_{sh} + f_d v_t d_t + f_d v_{con} pl_c L_c)\mu\lambda T \tag{2}$$

*which include the cost and emission of container terminal handling, shuttling, trucking and consolidation at the cross-docking facility in the hinterland.*

**Proof for Proposition 1.** See Appendix A. □

- Scenario 2 (container consolidation)

In scenario 2, along with trucking, there is intermodal transportation (barge or train) for container shipments.

**Proposition 2.** *In the case of bi-modal hinterland transport where a portion of non-urgent containers can be sent by intermodal services. The expected total cost and total emission are formulated as:*

$$E(Cost)_{Scenario2} = \left[(5c_h + c_{sh} + c_t + c_{con}pl_cL_c)\mu\lambda T + c_{sp}T\frac{pl_{tr}}{2}\right] - (c_t - c_{IFT}^v - c_e)(1-p_t)(1-k_u)\mu\lambda T + \frac{T}{t_0}c_{IFT} + 2c_h(1-p_t)(1-k_u)\mu\lambda T + \frac{c_s}{2}(1-p_t)(1-k_u)\mu T(\lambda t_0 - 1) \tag{3}$$

$$E(Emission)_{Scenario2} = [(5f_e v_h + f_d v_{sh} d_{sh} + f_d v_t d_t + f_d v_{con} pl_c L_c)\mu\lambda T] + 2f_e v_h(1-p_t)(1-k_u)\mu\lambda T - f_d v_t(d_t - d_e)(1-p_t)(1-k_u)\mu\lambda T + \frac{T}{t_0}f_d v_{IFT} d_{IFT} \tag{4}$$

*If the capacity of intermodal service is larger than or equals to the demand, the optimum intermodal service cycle time and frequency to minimize total cost are*:

$$t_{0,Scenario2}^{cost^*} \approx \sqrt{\frac{2c_{IFT}}{c_s(1-p_t)(1-k_u)\mu\lambda}} \quad \text{and} \quad N_{Scenario2}^{cost^*} = \langle T\sqrt{\frac{c_s(1-p_t)(1-k_u)\mu\lambda}{2c_{IFT}}}\rangle$$

*where ⟨⟩ is the function to round up/down to an integer. Whether to round up or round down depends on the shape of the total cost function.*
*The optimum intermodal service cycle time and frequency to minimize total emission are*:

$$t_{0,Scenario2}^{emission^*} = T \quad \text{and} \quad N_{Scenario2}^{emission^*} = 1.$$

*Otherwise, if the capacity of intermodal service is smaller than the demand, the optimum intermodal service cycle time and frequency to minimize total cost and total emission are*:

$$t_{0,Scenario2}^{cost^*} \approx \frac{U}{(1-p_t)(1-k_u)\mu\lambda} \quad \text{and} \quad N_{Scenario2}^{cost^*} = \left\lceil\frac{(1-p_t)(1-k_u)\mu\lambda T}{U}\right\rceil$$

*where ⌈ ⌉ is the function to round up to an integer.*

**Proof for Proposition 2.** See Appendix A. □

The first term in Eq. (3) (within the square brackets) represents the total cost of only-trucking. Therefore, the cost difference scenario 1 and 2 can be presented as:

$$Costdifference_{S2-S1} = 2c_h(1-p_t)(1-k_u)\mu\lambda T - (c_t - c_e - c_{IFT}^v)(1-p_t)(1-k_u)\mu\lambda T + c_{IFT}\frac{T}{t_0^*} + \frac{c_s}{2}(1-p_t)(1-k_u)\mu T(\lambda t_0^* - 1) \tag{5}$$

where $S1$ and $S2$ are scenario 1 and scenario 2, respectively. The first term of Eq. (5) describes the two additional transhipment handling stages of intermodal service that is applied only to non-urgent containers shipped by IFT $(1-p_t)(1-k_u)\mu\lambda T$. The second term is the saving of shipment cost for non-urgent containers shipped by IFT. The unit saving is the difference between the unit trucking cost $c_t$, the variable intermodal cost $c_{IFT}^v$ and the unit end-haulage cost $c_e$. The third term is additional cost of intermodal services, which depends on the frequency of the service $T/t_0$. With the increase of intermodal service frequency – or the decrease of cycle time, $t_0$ – the intermodal service cost will increase. The last term is the additional container storage cost, which also depends on $t_0$. With the increase of intermodal service frequency, the average storage time will decrease, which further reduces the container storage costs. Therefore, there is a trade-off between the shipment cost and container storage cost in this case (see Fig. 4). There is a cutting point representing the lowest total cost (and accordingly, an optimal intermodal service frequency and cycle time). The empirical studies also show that the decision of intermodal service frequency depends usually on transportation cost and storage cost (Rodrigue et al., 2017). Yet, in practice, other factors such as terminal opening hour or availability of workforce are also important in

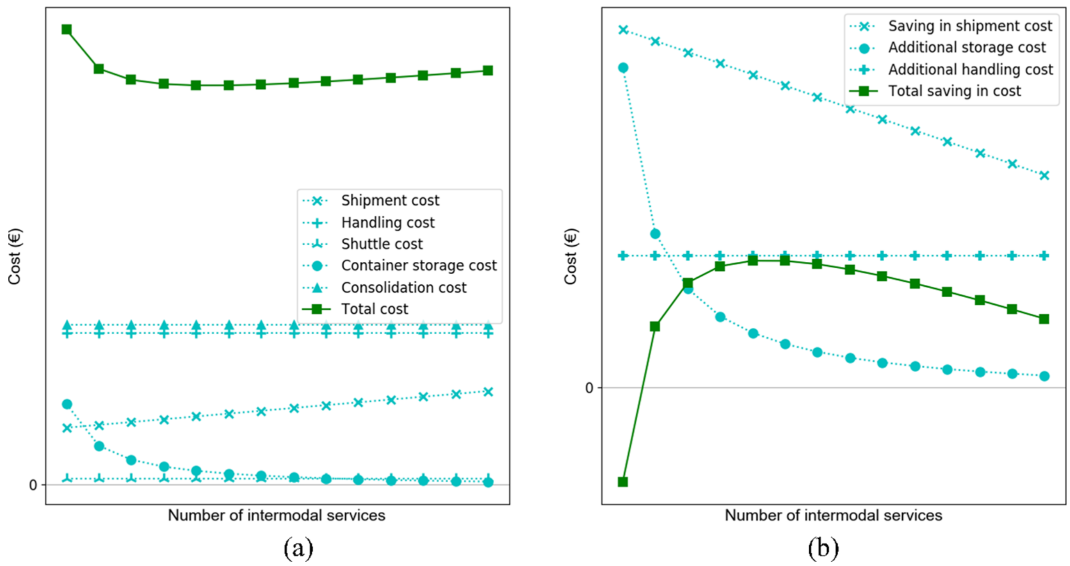



**Fig. 4.** Cost structure of scenario 2 container consolidation (a) and potential saving in cost of scenario 2 compared with scenario 1 only-trucking (b).

defining a detailed service schedule (Behdani et al., 2016).

If the demand in the optimal cycle time $(1-p_t)(1-k_u)\mu\lambda t_0^*$ is lower than the capacity of intermodal service $(U)$, the lowest total cost is feasible. In this case, the optimal cycle time $t_0^*$ is determined by the trade-off between the shipment cost and the container storage cost, which depends on several parameters. It has an increasing relation with the fixed cost of intermodal services $c_{IFT}$. If the cost of operating a cycle of intermodal service increases, the way to minimize total cost is to have fewer intermodal services, which implies that the cycle time $t_0$ should be longer. Besides, $t_0$ also has an increasing relation with the urgency factor $k_u$ and the share of non-urgent containers shipped by truck $p_t$. If there are more containers transported by truck, total trucking cost is higher. Thus, reducing the frequency of intermodal services can reduce total shipment cost, which makes cycle time $t_0$ longer. On the other hand, $t_0$ has a decreasing relation with the container storage cost, number of containers in a batch and arrival rate of container batches. When the storage cost is higher, it is preferred to have less container storage and more frequent intermodal service. Thus, the optimal $t_0$ is decreasing. When the number of containers increases (in that $n_j$ and $\lambda$ increase), with constant $k_u$, $p_t$, the number of non-urgent containers that need to be stored at the full container stacks – and, consequently, the storage cost – are also increasing. Then, it is better to reduce the storage time of containers. Thus, $t_0$ decreases. Otherwise, if the demand is higher than the capacity of intermodal service, the cycle time needs to be reduced according to the capacity (i.e., the intermodal service frequency needs to be increased). Since total cost function is increasing monotonically after the cutting point, the smallest intermodal service frequency that fulfils the demand minimizes total cost.

**Theorem 1.** *If the capacity of intermodal service is enough to carry the demand (i.e.,* $U \geq \sqrt{2c_{IFT}(1-p_t)(1-k_u)\mu\lambda/c_s}$*) and* $c_t > c_{IFT}^v + c_e + 2c_h + \sqrt{2c_{IFT}c_s/[(1-p_t)(1-k_u)\mu\lambda]} - c_s/2\lambda$ *(the unit trucking cost is higher than the total cost to ship a container with intermodal service and in which the fourth and fifth terms are container storage cost), container consolidation is beneficial in terms of cost compared with only-trucking. Furthermore, if the capacity of intermodal service is smaller than the demand (i.e.,* $U < \sqrt{2c_{IFT}(1-p_t)(1-k_u)\mu\lambda/c_s}$*) and* $c_t > c_{IFT}^v + c_{IFT}/U + c_e + 2c_h + c_sU/[2(1-p_t)(1-k_u)\mu\lambda] - c_s/2\lambda$*, container consolidation is beneficial in terms of cost compared with only-trucking.*

**Proof of Theorem 1.** See Appendix A. □

In practice, when the shipment distance is short, unit intermodal service cost $c_{IFT}^v$ is higher than unit trucking cost $c_t$; thus, container consolidation is not beneficial in this case. With the increase of shipment distance, both trucking cost and intermodal service cost increase; furthermore, in general, trucking cost increases faster than intermodal service cost. Other cost terms in the inequality (i.e., end-haulage cost $c_e$, fixed intermodal service cost for service arrangement $c_{IFT}$, container handling cost $c_h$, container storage cost $c_s$) and the demand pattern ($(1-p_t)(1-k_u)\mu\lambda$) do not change with the distance. Thus, when the shipment distance is longer, the chance that trucking cost is larger than intermodal service cost plus a fixed value is higher, which means the chance that container consolidation has saving in total cost is higher. These results are in line with the reality that IFT is suitable within markets over long distance.

Similar to cost, the difference of optimum cases of emission for scenarios 1 and 2 are presented in Eq. (6), which includes the additional emission of handling, the saving in trucking emission and extra intermodal service emission:

$$Emission\ \ difference_{S2-S1} = 2f_e v_h(1-p_t)(1-k_u)\mu\lambda T - f_d v_t(d_t - d_e)(1-p_t)(1-k_u)\mu\lambda T + \frac{T}{t_0^*} f_d v_{IFT} d_{IFT} \tag{6}$$

With constant $\mu$, $\lambda$, $p_t$ and $k_u$, the number of containers transported by truck and intermodal services are fixed, which means the expected emission of trucking and handling are also a constant value. The expectation of total emission depends only on the number of intermodal services. When increasing the intermodal service frequency – decreasing cycle time of intermodal transport ($t_0$) – total emission increases monotonically. Therefore, if the capacity of intermodal service is big enough, the optimum $CO_2$ emission is achieved when there is only one intermodal service departing at the end of the planning horizon $T$. With more intermodal services, there is higher emission for the whole transport system. In practice, one intermodal service might not be able to transport all containers when the container volume is large. The intermodal service cycle time needs to be reduced according to the demand and IFT capacity.

**Theorem 2.** *If the capacity of intermodal service is enough to carry the demand in the planning horizon (i.e., $U \geq (1-p_t)(1-k_u)\mu\lambda$) and $f_d v_t d_t > f_d v_{IFT} d_{IFT}/(1-p_t)(1-k_u)\mu\lambda T + f_d v_t d_e + 2 f_e v_h$ (the unit emission of trucking is larger than that of intermodal service), there is a saving of container consolidation compared with only-trucking in terms of $CO_2$ emission. Furthermore, if the capacity of intermodal service is smaller than the demand in the planning horizon (i.e., $U < (1-p_t)(1-k_u)\mu\lambda T$) and $f_d v_t d_t > f_d v_{IFT} d_{IFT}/U + f_d v_t d_e + 2 f_e v_h$, there is a saving of container consolidation compared with only-trucking in terms of $CO_2$ emission.*

**Proof of Theorem 2.** See Appendix A. □

When the capacity is enough for the demand, if there are fewer containers shipped by truck with lower $p_t$ and $k_u$ (which is equivalent to increasing the utilization of intermodal service), the chance that there is a benefit of container consolidation from emission point of view is higher. In reality, compared with trucking, intermodal service is believed to cause lower emission per container transport (Craig et al., 2013). Therefore, public parties make an effort to stimulate the modal shift to IFT. In practice, the saving in emission also depends on the difference in fuel consumption rate and the difference in shipment distance between trucking and intermodal transportation.

- Scenario 3 (combined container/cargo consolidation)

In scenario 3, part of non-urgent containers shipped by intermodal service – which is defined by $p_o$ – is opened for cargo consolidation at the decoupling centre in the port. $p_o$ is assumed to be fixed/known here; however, in general, $p_o$ can be defined based on a capacity utilization threshold for incoming containers (such as $L_o$), and the non-urgent containers with load factor $l_{c,j}$ smaller than $L_o$ are opened for the consolidation.

**Proposition 3.** *For combined container/cargo consolidation, the expected total cost and total $CO_2$ emission are:*

$$E(Cost)_{Scenario\quad 3} = (5c_h + c_{sh} + c_t + c_{con} p l_c L_c)\mu\lambda T + c_{sp} T p l_{tr} - \left[c_t - (c_e + c_{IFT}^v)(1-p_o) - \frac{c_{tr} p_o p l_c L_c}{p l_{tr}}\right](1-p_t)(1-k_u)\mu\lambda T + c_{IFT}\frac{T}{t_0} - 2c_h (2p_o - 1)(1-p_t)(1-k_u)\mu\lambda T + \frac{c_s}{2}(1-p_o)(1-p_t)(1-k_u)\mu T(\lambda t_0 - 1) \tag{7}$$

$$E(Emission)_{Scenario\quad 3} = (5 f_e v_h + f_d v_{sh} d_{sh} + f_d v_t d_t + f_d v_{con} p l_c L_c)\mu\lambda T - 2 f_e v_h (1-p_t)(1-k_u)(2p_o - 1)\mu\lambda T - f_d\left[v_t d_t - v_t d_e (1-p_o) - v_{tr} d_t p_o \frac{p l_c L_c}{p l_{tr}}\right](1-p_t)(1-k_u)\mu\lambda T + f_d v_{IFT} d_{IFT}\frac{T}{t_0} \tag{8}$$

*If the capacity of intermodal service is higher than the demand, the optimum intermodal service cycle time and frequency to minimize total cost are*:

$$t_{0,Scenario3}^{cost^*} \approx \frac{2c_{IFT}}{c_s(1-p_o)(1-p_t)(1-k_u)\mu\lambda} \quad \text{and} \quad N_{Scenario3}^{cost^*} = \left\langle T\sqrt{\frac{c_s(1-p_o)(1-p_t)(1-k_u)\mu\lambda}{2c_{IFT}}}\right\rangle$$

*The optimum intermodal service cycle time and frequency to minimize total $CO_2$ emission are*:

$$t_{0,Scenario3}^{emission^*} = T \quad \text{and} \quad N_{Scenario3}^{emission^*} = 1$$

*Otherwise, if the capacity of intermodal service is lower than the demand, the optimum intermodal service cycle time and frequency to minimize total cost and total $CO_2$ emission are*:

$$t_{0,Scenario3}^{*} \approx \frac{U}{(1-p_o)(1-p_t)(1-k_u)\mu\lambda} \quad \text{and} \quad N_{Scenario3}^{*} = \left\lceil\frac{(1-p_o)(1-p_t)(1-k_u)\mu\lambda T}{U}\right\rceil$$

**Proof of Proposition 3.** See Appendix A. □

The cost difference of the optimum case compared with scenario 1 is formulated in Eq. (9):

$$Cost\quad difference_{S3-S1} = 2c_h(1-p_t)(1-k_u)(1-2p_o)\mu\lambda T - \left[c_t - (c_e + c_{IFT}^v)(1-p_o) - c_{tr} p_o \frac{p l_c L_c}{p l_{tr}}\right](1-p_t)(1-k_u)\mu\lambda T + c_{IFT}\frac{T}{t_0^*} + \frac{c_s}{2}(1-p_o)(1-p_t)(1-k_u)\mu T(\lambda t_0^* - 1) + c_{sp} T\frac{p l_{tr}}{2} \tag{9}$$

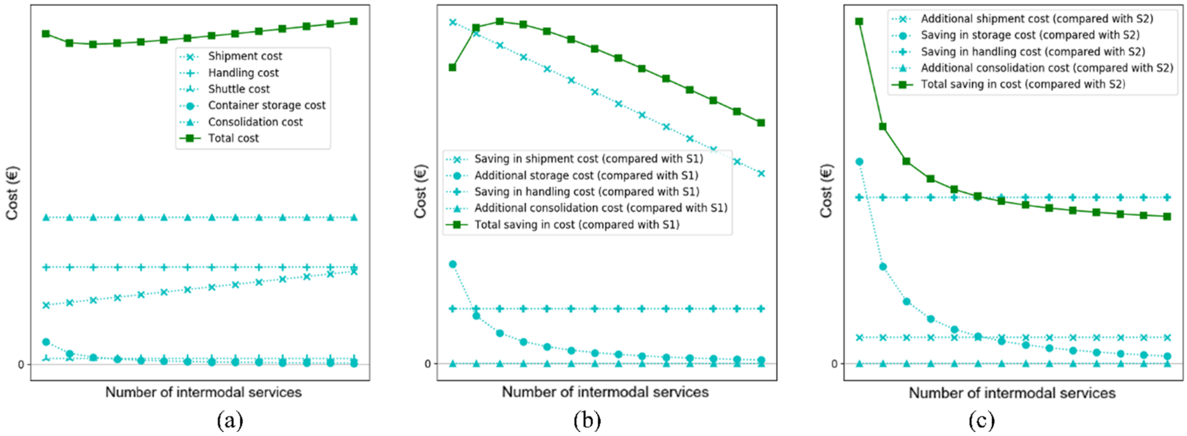



**Fig. 5.** Cost structure of scenario 3 combined container/cargo consolidation (a), saving in cost of scenario 3 compared with scenario 1 only-trucking (b); and saving in cost of scenario 3 compared with scenario 2 container consolidation (c).

The cost difference compared with scenario 2 is formulated in Eq. (10):

$$Cost\quad difference_{S3-S2} = -4c_h p_o(1-p_t)(1-k_u)\mu\lambda T + \left(c_{tr}\frac{pl_c L_c}{pl_{tr}} - c_e - c_{IFT}^{v}\right)p_o(1-p_t)(1-k_u)\mu\lambda T - \frac{c_s}{2}p_o(1-p_t)(1-k_u)\mu T(\lambda t_0 - 1) + c_{sp}T\frac{pl_{tr}}{2} \tag{10}$$

Similar to container consolidation, there is a trade-off between shipment and storage cost (Fig. 5), which determines the optimum operational cost of the transport system. The share of opened container $p_o$ has a positive relation with the optimal cycle time $t_0$. If more containers are opened, more trailers are used for the shipment to the hinterland. The trailer cost increases; then fewer intermodal transport services are organized in order to reduce total cost.

The first term in Eq. (9) is related to container handling cost, which are used to derive proposition 4.

**Proposition 4.** *There is a saving in handling cost of combined container/cargo consolidation compared with only-trucking if more than 50% of the non-urgent containers are opened at the decoupling centre in the port. The saving is* $2c_h(1-p_t)(1-k_u)(1-2p_o)\mu\lambda T$.

**Proof of Proposition 4.** See Appendix A. □

In this model, it is assumed that each pallet is operated once at a cross-docking facility (either in the port or in the hinterland) before sending to final destinations. Thus, the cargo handling costs are the same for all scenarios. About container handling, five handling stages are considered for only-trucking: unloading from the vessel; loading to the shuttle barge; unloading from the shuttle barge; loading to the truck at the terminal; and unloading from the truck at the hinterland cross-docking facility. For containers shipped by intermodal services, two extra transhipment handling stages at the inland terminal are considered. For containers that are consolidated at the port, three container handling stages are considered: unloading from the vessel; loading to the shuttle barge; and unloading from the shuttle barge. It is assumed that, after opening containers at the decoupling centre in the port, no additional container handling is required. Therefore, there is always a saving in handling cost when opening non-urgent containers in the port. With the assumptions of this model, when more than 50% of the non-urgent containers are opened in the port, there will be a saving in handling cost of combined container/cargo consolidation compared with only-trucking.

**Theorem 3.** *If the capacity of intermodal service is enough to carry the demand under both scenarios: container consolidation and combined container/cargo consolidation, (i.e.,* $U \geq \sqrt{2c_{IFT}(1-p_t)(1-k_u)\mu\lambda/c_s}$ *) and* $(1-\sqrt{1-p_o})\sqrt{2c_{IFT}c_s(1-p_t)(1-k_u)\mu\lambda} + (c_e + c_{IFT}^{v} + 4c_h - c_s/2\lambda)p_o(1-p_t)(1-k_u)\mu\lambda > c_{tr}pl_r L_c p_o(1-p_t)(1-k_u)\mu\lambda/pl_{tr} + c_{sp}pl_{tr}/2$ *(the intermodal cost for the opened non-urgent containers is higher than the trucking cost by trailer plus cargo consolidation cost), there is a saving in cost of combined container/cargo consolidation compared with bi-modal shipments. If the capacity of intermodal service is smaller than the demand under both scenarios: container consolidation and combined container/cargo consolidation (i.e.,* $U < \sqrt{2c_{IFT}(1-p_o)(1-p_t)(1-k_u)\mu\lambda/c_s}$*) and* $c_{IFT}/U + c_{IFT}^{v} + c_e + 4c_h - c_s/2\lambda > c_{sp}pl_{tr}/[2p_o(1-p_t)(1-k_u)\mu\lambda] + c_{tr}pl_c L_c/pl_{tr}$*, there is a saving in cost of combined container/cargo consolidation compared with bi-modal shipments. Additionally, if the capacity of intermodal service is enough for the demand under scenario combined container/cargo consolidation, but it is smaller than that of container consolidation, (i.e.,* $\sqrt{2c_{IFT}(1-p_o)(1-p_t)(1-k_u)\mu\lambda/c_s} \leq U < \sqrt{2c_{IFT}(1-p_t)(1-k_u)\mu\lambda/c_s}$*) and* $(c_{IFT}/Up_o + c_{IFT}^{v} + c_e + 4c_h - c_s/2\lambda)p_o(1-p_t)(1-k_u)\mu\lambda - \sqrt{2c_{IFT}c_s(1-p_o)(1-p_t)(1-k_u)\mu\lambda} + c_s U/2 > c_{tr}pl_c L_c p_o(1-p_t)(1-k_u)\mu\lambda/pl_{tr} + c_{sp}pl_{tr}/2$*, there is a saving in cost of combined container/cargo consolidation compared with bi-modal shipments.*

**Proof of Theorem 3.** See Appendix A. □

The difference between container consolidation with combined container/cargo consolidation is caused primarily by the number of containers that are opened and transported by trailer. In practice, when the shipment distance is short, the unit cost of intermodal transport is higher than that of trucking. Therefore, when the shipment distance is short, there is a chance that the intermodal cost for the opened non-urgent containers is higher than the trucking cost by trailer plus cargo consolidation cost. Then, combined container/

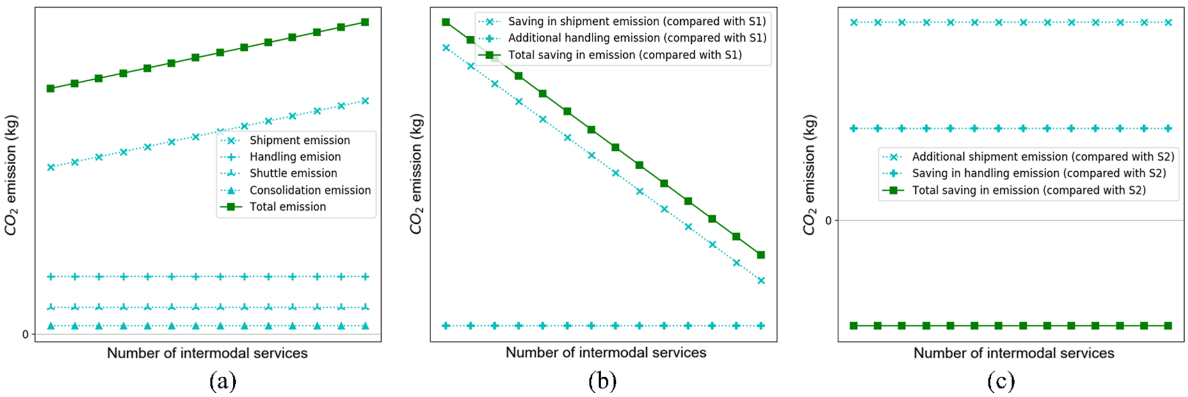



**Fig. 6.** $CO_2$ emission structure of scenario 3 combined container/cargo consolidation (a), saving in $CO_2$ emission of scenario 3 compared with scenario 1 only-trucking (b) and saving in $CO_2$ emission of scenario 3 compared with scenario 2 container consolidation (c).

cargo consolidation is beneficial compared with bi-modal transport. With increasing shipment distance, trucking cost increases faster than intermodal cost, Therefore, with the increase of shipment distance, the advantage of intermodal transport increases.

In terms of $CO_2$ emission, with an increase in intermodal service frequency, total emission will also increase (Fig. 6). Therefore, if the capacity of intermodal service is large enough, the optimum emission level is achieved when there is only one intermodal service. With more intermodal services, the saving in the emission of shipment is decreasing compared with only-trucking. Compared with container consolidation, with the same intermodal service frequencies, the additional shipment emission is constant, since in this case the difference depends only on the number of non-opened non-urgent containers shipped by trailers, which is not influenced by the frequency of intermodal services.

**Theorem 4.** *For both container consolidation and combined container/cargo consolidation, if the capacity of intermodal service is enough to carry the demand (i.e., $U \geq (1-p_t)(1-k_u)\mu\lambda T$), $f_d v_{tr} d_t pl_c L_c/pl_{tr} < f_d v_t d_e + 4 f_e v_h$, $p_o \neq 0$, $p_t \neq 1$, and $k_u \neq 1$, there is a saving in $CO_2$ emission of combined container/cargo consolidation compared with container consolidation. For both container consolidation and combined container/cargo consolidation, if the capacity of intermodal service is not enough to carry the demand (i.e., $U < (1-p_o)(1-p_t)(1-k_u)\mu\lambda T$),$f_d v_{tr} d_t pl_c L_c/pl_{tr} < f_d v_{IFT} d_{IFT}/U + f_d v_t d_e + 4 f_e v_h$ and $p_o \neq 0$, there is a saving in $CO_2$ emission of combined container/cargo consolidation compared with container consolidation. Additionally, if the capacity of intermodal service is enough for the demand of combined container/cargo consolidation; but it is smaller than that of container consolidation (i.e., $(1-p_o)(1-p_t)(1-k_u)\mu\lambda T \leq U < (1-p_t)(1-k_u)\mu\lambda T$), $f_d v_{tr} d_t pl_c L_c/pl_{tr} < f_d v_{IFT} d_{IFT}/Up_o - f_d v_{IFT} d_{IFT}/p_o(1-p_t)(1-k_u)\mu\lambda T + f_d v_t d_e + 4 f_e v_h$ and $p_o \neq 0$, there is a saving in $CO_2$ emission of Combined container/cargo consolidation compared with container consolidation.*

**Proof of Theorem 4.** See Appendix A. □

When the opened non-urgent containers are shipped by trailer instead of intermodal service, there is emission for trailer transport; however, there is a saving in emission of intermodal service including container handling and end-haulage. Thus, when the emission of the trailer shipment is smaller than that of total intermodal emission, there is a saving in the emission of combined container/cargo consolidation compared with container consolidation. When the load factor of containers is lower, the saving of combined container/cargo consolidation is higher, since fewer trailers are needed. Furthermore, the saving depends on the shipment distance and the fuel consumption rate of different modality. In practice, intermodal service distance is longer than trucking distance; however, IFT has less fuel consumption – 20–50% less than trucking (Craig et al., 2013). Accordingly, when the shipment distance of intermodal service is much larger than the distance of trucking, there is a chance that there is a saving in the emission of combined container/cargo consolidation compared with container consolidation.

## 4. Numerical study and discussion of results

To study the analytical model presented in Section 3, case studies are carried out for container hinterland transport from the port of Rotterdam to four inland port cities: Tilburg, Duisburg, Frankfurt, and Basel. We selected four cities since shipment distance is an important factor influencing the performances of intermodal transport. The main-haulage of intermodal transport is carried by barges. A logistics service provider provides a connection from the decoupling centre in the port of Rotterdam to each city. The parameters used in the case studies are in Appendix B.

### 4.1. Model verification

The analytical model is solved with the Monte Carlo method in order to verify the model. The results of the Monte Carlo method and the analytical model are shown in Fig. 7. In general, the results of two methods are very close and the trends of the curves are similar. Furthermore, the optimal barge frequency given by the two methods are also similar. The differences of total cost and $CO_2$ emission between the two methods are less than 1.0% and 1.7%, respectively. The difference is due to the stochastic container batch arrival and the batch size. With the increase of variance of batch inter-arrival time and batch size, the difference of results between Monte Carlo method and the analytical model becomes larger. For cost estimation, the largest difference is from container storage, since it is calculated by the product of batch size and the storage time (depending on batch inter-arrival time). The product of two random variables differs greatly from the product of the mean values. In summary, we can conclude that the analytical model is suitable to support decision-making on intermodal services at the tactical level, and the presented propositions/theorems can be used to estimate the performances of difference scenarios.

### 4.2. Comparison between scenarios

According to Fig. 7, with a relatively short distance (Tilburg), combined container/cargo consolidation has the lowest cost; and container consolidation has even higher cost than only-trucking regardless of the frequency of barge service. Thus, even if the capacity of the barge is smaller than the demand, i.e., the frequency of barge service needs to be increased, combined container/cargo consolidation always has the lowest cost; and container consolidation has the highest cost. From the cost structure (Fig. 8), the main components are the shipment and container handling cost. When the distance is short, although non-urgent containers are shipped by cheaper modality compared with trucking, the increase in container handling cost cannot be cancelled out by the reduction in shipment cost. Thus, container consolidation has a higher cost than the other two scenarios. With the increase of distance (i.e., for the case of Basel), the shipment cost becomes increasingly more important than the container handling cost, which makes container consolidation outperform only-trucking. Furthermore, the cost functions of container consolidation and combined container/cargo consolidation are relatively flat. In the case that barge capacity is smaller than the demand, container consolidation still outperforms combined container/cargo consolidation.

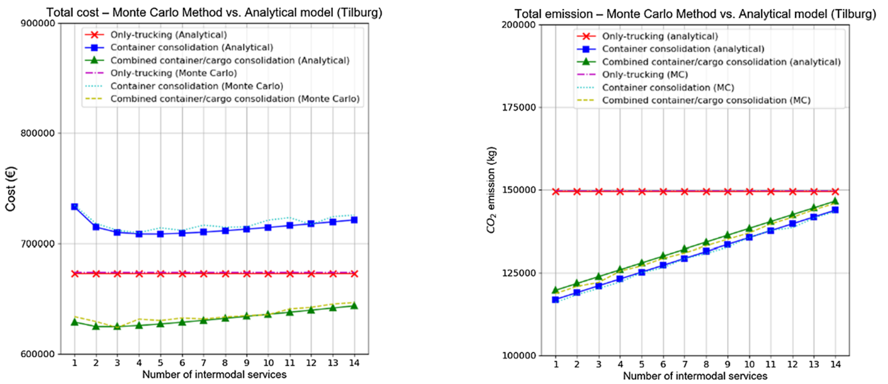
In terms of $CO_2$ emission, when barge capacity is larger than the demand, the minimum emission is achieved when there is one service. Total emission increases by increasing the intermodal service frequency. Additionally, container consolidation has the lowest emission. In the emission structure (Fig. 8), the shipment is the most important element. In container consolidation, there is much less $CO_2$ emission in shipments compared with other scenarios. Although there is an increase in handling emission, it is not comparable with the reduction of shipment emission. However, with a capacity limit, it is possible that combined container/cargo consolidation outperforms container consolidation, and only-trucking outperforms combined container/cargo consolidation. For instance, in the case of Basel, the total cost of combined container/cargo consolidation with two barge services is smaller than that of container consolidation with 12 barge services. The total cost of 13 or more barge services is larger than that of only-trucking. Therefore, the performances of container consolidation and combined container/cargo consolidation depend highly on the capacity and demand patterns.

In summary, in the short-distance case (Tilburg), combined container/cargo consolidation has the lowest cost. There can be a large total cost reduction of combined container/cargo consolidation (around 7.0% compared with only-trucking, and around 12.2% compared with container consolidation) due to shipment and container handling. Total emission for container consolidation and combined container/cargo consolidation in this case are quite similar. Compared with only-trucking, combined container/cargo consolidation can have a maximum reduction of around 20%. Therefore, with the short distance, it is recommended to choose combined container/cargo consolidation. With long shipment distance (Basel), container consolidation outperforms the other two scenarios in both cost and emission when the capacity of intermodal service is larger than the demand. When the capacity is smaller than the demand, there is a chance that combined container/cargo consolidation outperforms container consolidation in terms of $CO_2$ emission. In general, with long shipment distance, it is recommended to choose container consolidation for hinterland transportation.

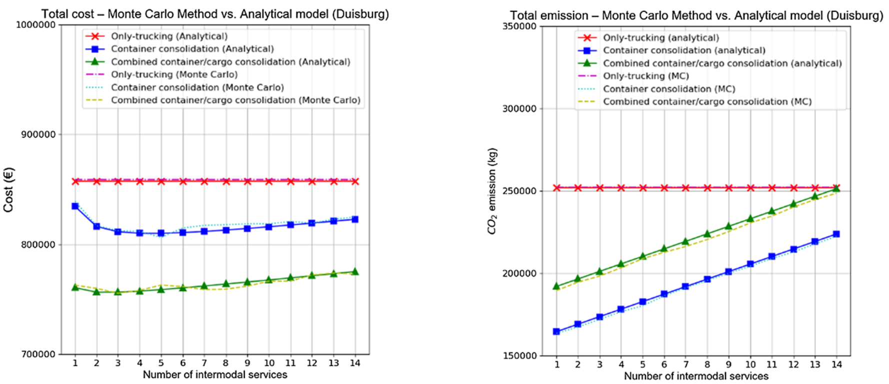
## 5. Model extension and numerical study for perishable products

Over the past twenty years, the demand for the transportation of perishable products has increased (Arduino et al., 2015). Currently, trucking is the dominant mode of reefer hinterland transportation. Traffic delay caused by road congestion can be more problematic for perishable products. Longer transit time increases energy usage for cooling, which is more costly, produces more greenhouse gas emission and might influence product quality (Cheaitou and Cariou, 2012). Additionally, reefers have high investment costs that are more important to achieve high asset utilization (Rodrigue and Notteboom, 2014). However, road congestion increases reefer turnaround time and lowers reefer utilization.

The influence of cargo-driven intermodal transport for perishable products is more difficult to analyse. Firstly, intermodal transportation has lower speed compared with trucking, which increases the transit time – and consequently increases the energy usage for cooling. Therefore, there is a trade-off between the energy consumption of main engines and refrigeration units. Secondly, product quality might be influenced by the additional consolidation and transhipment processes at the decoupling centre and inland terminals. Thus, there are trade-offs between cost, emission and product quality when applying flow consolidation for reefer hinterland transportation. Therefore, the model of the dry container shipment is not sufficient for reefer containers. In this section, the analytical model is extended to the case of intermodal reefer transport.




(a)

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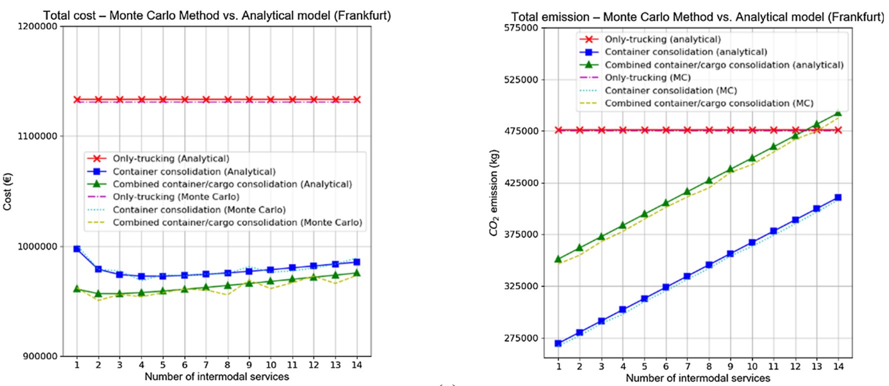


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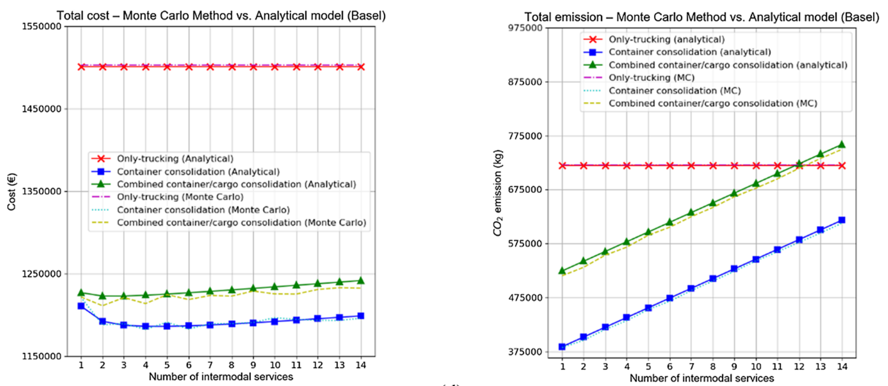


(d)

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**Fig. 7.** Comparison of the results of the Monte Carlo method and the analytical model of dry containers among three scenarios: shipment to Tilburg (a); Duisburg (b); Frankfurt (c); Basel (d).

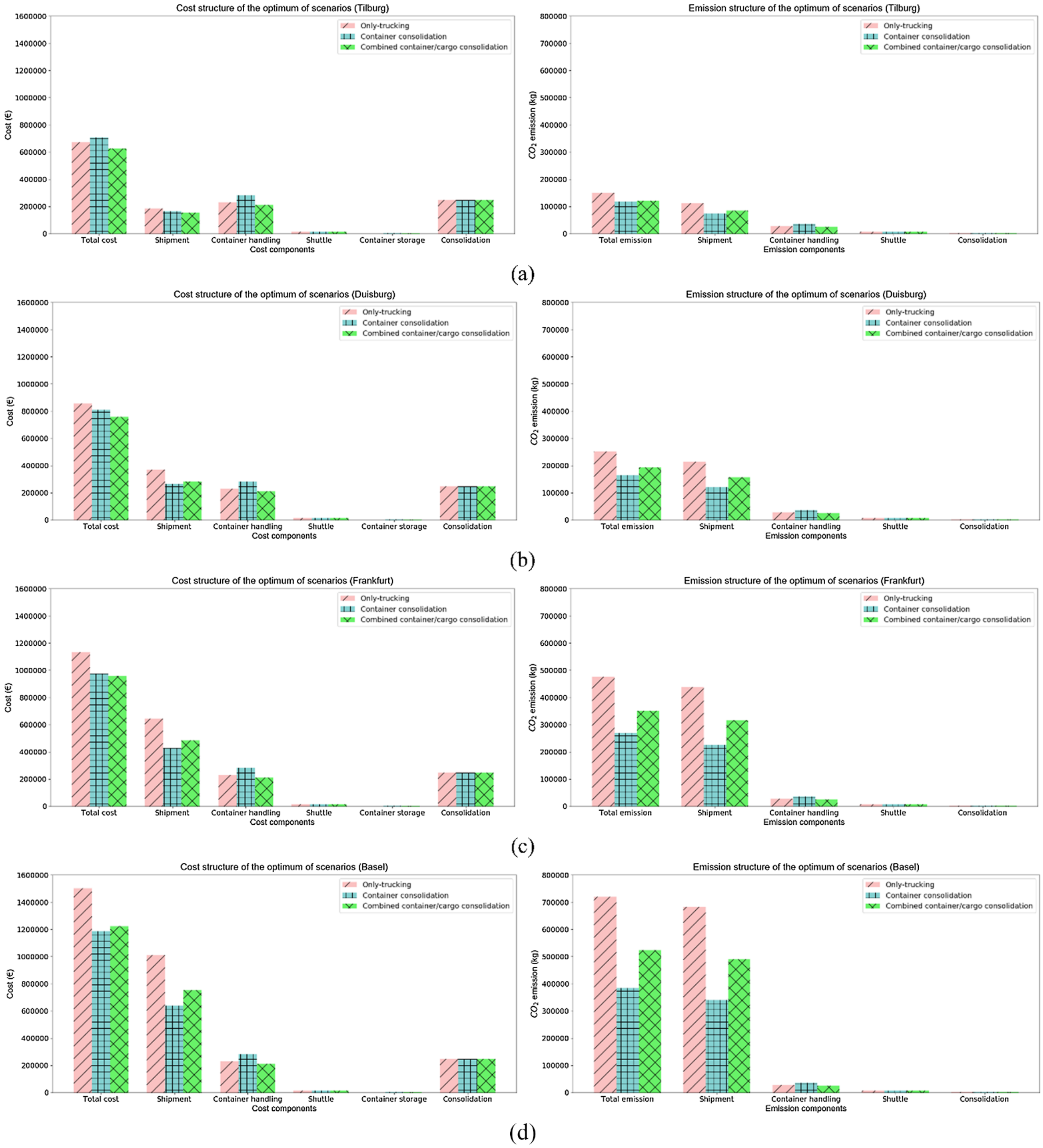



**Fig. 8.** Comparison of cost and emission structure of dry containers among the optimum of three scenarios: shipment to Tilburg (a); Duisburg (b); Frankfurt (c); Basel (d).

### 5.1. Model extension for reefer containers

The scenarios of the reefer model are the same as the dry container model. Additional assumptions are made as follows:

- The container handling time, transit time, shuttle time and cargo consolidation time are assumed to be random variables.
- The non-opened non-urgent reefers arriving just before the departure of an intermodal service – which do not have enough time to be loaded onto the current intermodal service – are stored at the terminal and are transported by the next intermodal service.

Similarly, the non-opened non-urgent reefers (that cannot be loaded onto any intermodal services) arriving at the end of the planning horizon are shipped by trucks to the hinterland. Thus, the container terminal storage time is slightly different from the dry container model.
- The product quality is calculated based on the process time. Since, in all scenarios, each reefer is opened once for consolidation, the cross-docking operation is the same for all scenarios, and the potential quality change due to consolidation is not considered in the model.

Compared with dry container models, total cost includes the additional cooling during the shipment and during container/cargo storage. The cooling cost depends on the cooling time, unit energy consumption for cooling and the unit energy cost. For the shipment, it is assumed that the same fuel is used for cooling by trucks and intermodal services; thus, the difference in cooling cost of difference scenarios depends on the shipment time, which differs for trucking and intermodal services. In addition to the cooling of shipments, electricity is used for reefer storage and cargo storage. The cooling part is included in the unit storage cost (i.e., $c_s$ and $c_{sp}$). Furthermore, a delay penalty is considered for intermodal services, since perishable products are more restricted to delivery time. The delay penalty is calculated according to the number of delayed reefers, delay time and the unit delay penalty. The delay time depends on the process time and the delivery due time. Similar to cost calculation, the emission of cooling is calculated considering the unit $CO_2$ emission of fuel/electricity usage.

The impact on product quality is estimated based on total process time subtracted from the shelf life (of cargoes when they arrive at the seaport). For container trucking, the total process time includes container handling, shuttling, trucking and consolidation time. For non-urgent containers transported by intermodal services, the trucking time is replaced by the barge time plus end-haulage time. The container handling time is longer compared with that of trucking, since additional transhipment is carried out in an inland terminal. Furthermore, reefer storage time is included. For opened non-urgent containers shipped by refrigerated trucks, the container handling time is different compared with trucking. The detailed analytical model for reefer is shown in the additional material: Model formulation for perishable cargoes.

### 5.2. Numerical study of perishable products

Numerical studies are carried out for the same cities for the case of perishable products (Fig. 9). In terms of cost, combined reefer/cargo consolidation has the lowest cost regardless of the shipment distance. When the distance is short, reefer consolidation has a higher cost than only-trucking. With the increase of shipment distance, reefer consolidation shows advantage over only-trucking. Based on the cost structure (Fig. 10), the benefit of cheaper transport modality is cancelled out by the longer cooling time during shipment and container storage. Thus, reefer consolidation has higher cost than combined reefer/cargo consolidation even when the distance is long.

In terms of emission, reefer storage uses electricity that is generated by processes that emit $CO_2$; thus, there is a trade-off between the shipment emission and storage emission in this case. With fewer intermodal services – longer storage time – there is an emission reduction in shipment; however, the emission related to reefer storage would increase. For Tilburg and Duisburg, the maximum emission is achieved when there is one service. The results show that, when the distance is short (Tilburg), only-trucking outperforms other scenarios. With increasing distance, combined reefer/cargo consolidation has the lowest emission. In the case of Tilburg and Duisburg, the emission related to reefer consolidation is the highest, since reefer storage is a very important process that is responsible for major emission in addition to the shipment and terminal handling (Fig. 10), which makes $CO_2$ emission in reefer consolidation higher than in other scenarios. With the increase of the shipment distance, the emission related to shipment becomes the dominant factor. The reefer consolidation scenario has similar $CO_2$ emission related to shipment compared with only-trucking; however, the emission is still higher than in a combined reefer/cargo consolidation scenario. Combined reefer/cargo consolidation has a slight increase in emission related to shipment compared with reefer consolidation; however, there is a massive reduction of emission related to reefer storage. Thus, emission related to cooling is an essential factor that needs to be considered for the reefer logistics system.

For shelf life, reefer consolidation has the lowest shelf life because more reefers are shipped by intermodal services with longer transit time with additional terminal storage time. In the worst case (Basel), the decrease of shelf life is around 33% for reefer consolidation compared with only-trucking. Combined reefer/cargo consolidation also shows a reduction of shelf life. However, the reduction is much less compared with a reefer consolidation case. For the Basel scenario, the reduction is around 7%.

In general, combined reefer/cargo consolidation is the best scenario in terms of $CO_2$ emission. It also outperforms only-trucking in terms of cost. Although there is a decrease in shelf life, the reduction is still acceptable compared with reefer consolidation.

### 5.3. Sensitivity analysis

In order to identify the most influential parameters and evaluate the robustness of findings, we performed a sensitivity analysis for perishable cargo shipped to Duisburg. Duisburg is chosen because of high density of cargo flows to and from the Port of Rotterdam. Additionally, it is a well-accepted example of mid-range destinations for the port. Changes in the parameters are standardized as a percentage of $\pm$ 10%. The impact of the changes on total cost, total emission, and shelf life are shown in Tables C1–C3 in Appendix C. In general, most parameters marginally influence the performance measures, and the changes are much less than 10% variation in the parameters. Therefore, the findings of the model are robust to possible deviations or uncertainties in those parameters. An influential factor with a negative impact on the minimum cost and emission of combined reefer/cargo consolidation is the opening factor of non-

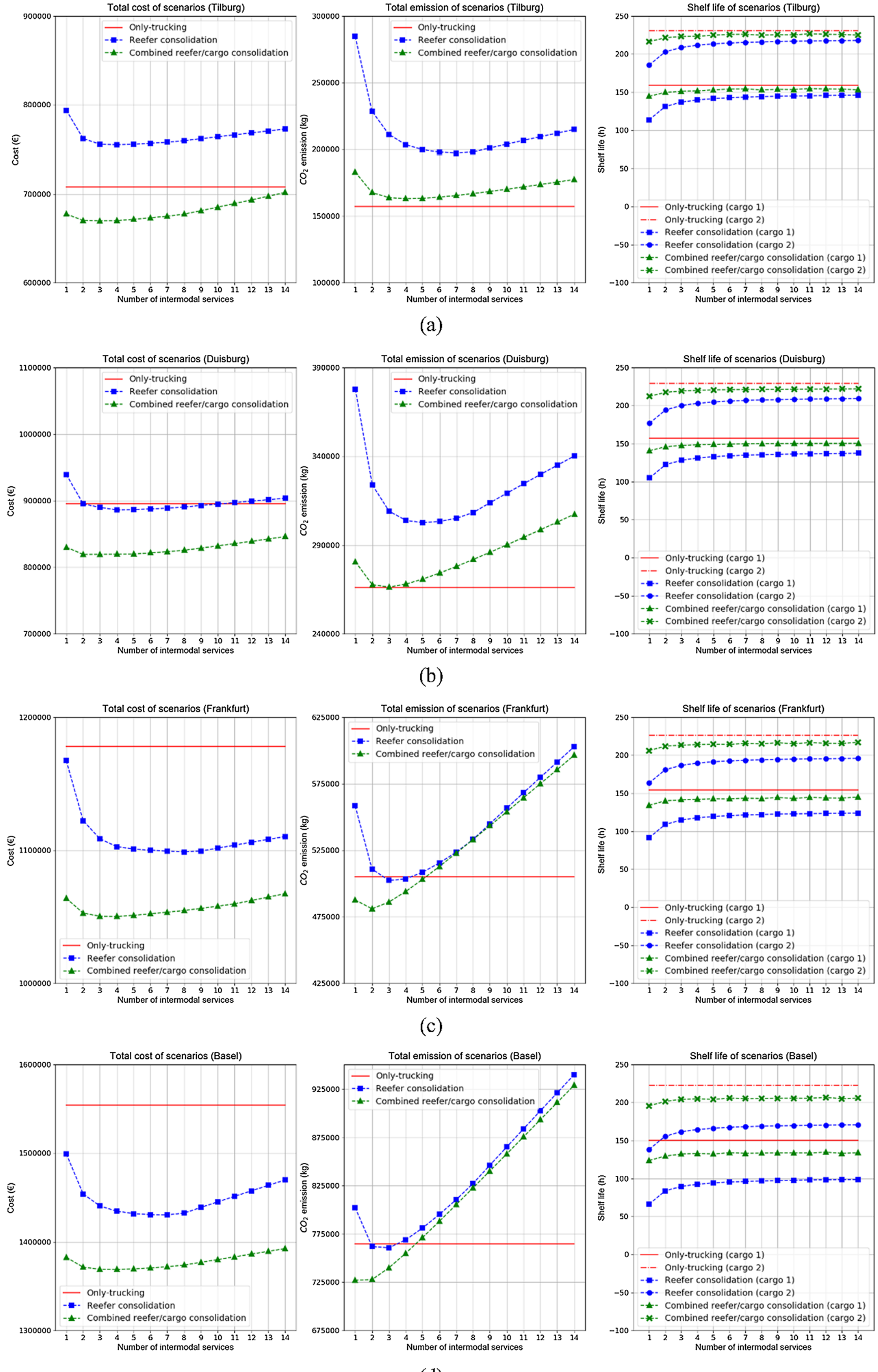



**Fig. 9.** Comparison of cost, emission and shelf life of the reefer models among three scenarios: shipment to Tilburg (a); Duisburg (b); Frankfurt (c); Basel (d).

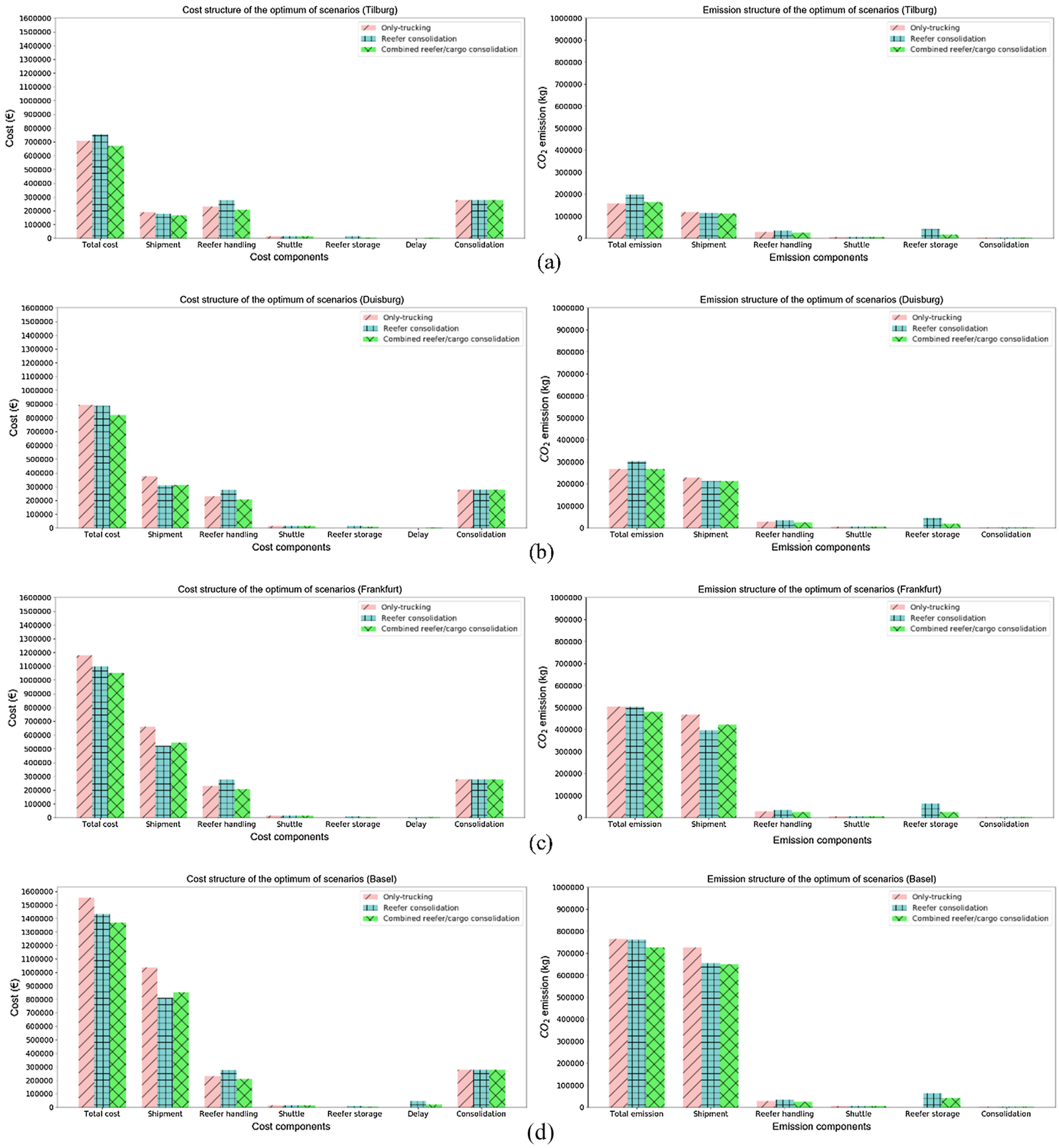
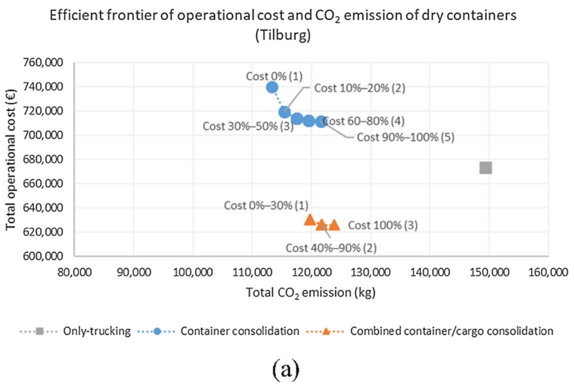



**Fig. 10.** Comparison of cost and emission structure of the reefer models among the optimum of scenarios: shipment to Tilburg (a); Duisburg (b); Frankfurt (c); Basel (d).

urgent reefers. When the opening factor increases, more non-urgent reefers are opened and consolidated in the port, which reduces the number of reefer terminal handling and the number of reefers stored at the terminal. In the case of Duisburg, container terminal handling is an important component of cost and emission structure. Therefore, with increasing opening factor, total cost and emission will decrease. Furthermore, when the number of pallets in refrigerated truck increases, fewer refrigerated trucks are needed. Thus, the number of pallets in a refrigerated truck also has an inverse impact on total cost and emission of combined reefer/cargo consolidation. The remaining parameters have a marginal positive impact on the minimum cost and emission. Among them, however, the unit trucking cost, unit reefer handling cost, unit cargo consolidation cost, trucking distance, number of pallets in reefer and the load factor have relatively high impacts on total cost. Trucking distance and cost have the largest impact on only-trucking, since there are fewer reefers transported by trucks in the other two scenarios. Load factor has the highest impact on combined reefer/cargo consolidation, which influences the number of refrigerated trucks travelling to the hinterland. For emission, the trucking distance, the fuel consumption rate of the truck main engine and the emission factor of fuel consumption have the largest impact; here, trucking



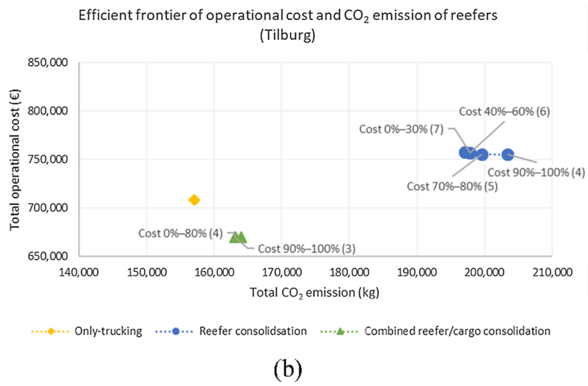




**Fig. 11.** Efficient frontier of Tilburg: efficient frontier of dry containers (a) and efficient frontier of reefers (b). The percentages in the figure show the weights of cost. The numbers in parentheses are intermodal service frequency.

distance and the fuel consumption rate of the truck main engine have a higher impact on only-trucking than in the other two scenarios (8.06% changes in emission). Compared with barge service, when changing the barge shipment distance and the barge fuel consumption rate, the changes in the total emission is much less (0.75%). This indicates the necessity to shift from trucking to intermodal transportation and to use green energy. For shelf life, the parameters have relatively low impact on the shelf life for all scenarios.

### 5.4. Efficient frontiers of dry containers and reefers

The efficient frontiers for dry containers and reefers within the Tilburg scenario are shown in Fig. 11. To generate the efficient frontier, the weighted global criterion method is used in order to optimize the total gap with the optimum cost and the optimum $CO_2$ emission. The objective function combining both cost and $CO_2$ emission is formulated in Eq. (11):

$$\min U = w_1(TotalCost - TotalCost^*) + w_2(TotalEmission - TotalEmission^*) \tag{11}$$

where $w_1$ and $w_2$ are the weights for operational cost and $CO_2$ emission, respectively, such that $w_1 + w_2 = 1$ and $w_1, w_2 > 0$.

From the efficient frontier analysis, it is found that the results are converging. For instance, for the case of container consolidation of dry containers, the optimal results are the same when the weight of cost is 10% and 20%, which is to operate two barge services. For dry containers, switching from one solution to another in order to reduce emission or cost will increase cost or emission to a certain extent. However, for reefers, the slope of the efficient frontiers is close to zero, which implies that there can be a large reduction of $CO_2$ with a slight increase of cost. For instance, in the case of reefer consolidation, comparing seven services with four services, the increase of cost is 0.4%, while the reduction of $CO_2$ is 3.2%. The efficient frontiers of Duisburg, Frankfurt and Basel are similar to that of Tilburg (and are presented in Appendix D). Thus, it is recommended to minimize $CO_2$ emission when making a plan for reefer hinterland transport. For dry containers, decision makers can use the frontiers to compare the cost and emission and to make a decision based on those factors.

## 6. Managerial insights and discussion

The propositions and theorems formulated based on analytical study describe conditions under which different hinterland transportation scenarios are outperforming other scenarios in terms of cost and emission. Numerical study shows the consistency between the findings of the analytical model (which is developed based on renewal theory and the expected cost and emission) and the Monte Carlo simulation (considering the stochasticity in model parameters). Therefore, the propositions and theorems can be used as simple guidelines or rules of thumb in practice to study the viability of different scenarios and estimating the main tactical variables (such as the number of services).

The numerical results show that, in general, combined container/cargo consolidation outperforms only-trucking in terms of cost for dry containers. Container consolidation is beneficial over only-trucking and combined container/cargo when the shipment distance is long. For reefers, combined reefer/cargo consolidation has the lowest cost regardless of distance. In terms of emission, container consolidation is the best option for dry containers. Combined container/cargo consolidation is the best scenario for reefer containers when the shipment distance is long. On the contrary, in the case of short hinterland distance, only-trucking has the lowest emission. Consequently, shipment distance is an important factor that influences the performance of flow consolidation. The influence of distance for dry cargo is characterized especially by the trade-off of shipment and container handling cost. For reefers, however, the cooling cost is also important in this trade-off. In fact, the benefit of cheaper transport modality can be cancelled out by the longer cooling time/cost during shipment and container storage.

Meanwhile, the sensitivity analysis provides some interesting managerial insights for practice. In fact, the cargo/container handling terms (unit reefer handling cost and unit cargo consolidation cost), shipment terms (the unit trucking cost and trucking distance) and the storage pattern of pallets inside the reefer (number of pallets in reefer and the load factor) are among the most influential factors. As a result, these are the areas to improve the flow consolidation and cargo-driven intermodal transport in port-hinterland logistics. It is also interesting to observe that the urgency of reefers – which is a decision made by shippers and communicated to the transport planner – has a marginal influence on the cost/emission performance of consolidation scenarios. However, the opening factor of non-urgent reefers can reduce the cost and emission of combined reefer/cargo consolidation. In fact, as the opening factor increases, more non-urgent reefers are opened and consolidated in the port, which reduces the number of reefer terminal handling stages and the number of reefers stored at the terminal. Also, increasing the pallet capacity of a refrigerated truck has an inverse impact on total cost and emission of combined reefer/cargo consolidation.

Indeed, in order to realize cargo-driven intermodal transport, it is necessary to relocate cross-docking operation upstream in the supply chain – in the port area. This further helps to release maritime containers faster, which increases the asset utilization for container fleets. Furthermore, cargo consolidation makes the port more attractive because of the potential value-added activities provided in the port area. Also, total facility cost can be saved, since different shippers can share the usage of the consolidation facility in the port, which reduces the number of cross-docking facilities in the hinterland. To better serve different shippers, it is necessary to provide value-added services such as labelling, quality control, etc. Indeed, a challenge for implementing the concept can be the availability of land and the required (port) infrastructure.

## 7. Conclusions

In this research, the cargo-driven intermodal transport concept is explored. The central idea of this concept is the consolidation of cargo and container flows before arranging hinterland transport operations. Three scenarios – (1) only-trucking, (2) container consolidation and (3) combined container/cargo consolidation – are modelled and compared in terms of total cost and total $CO_2$ emission for transport of containers to the hinterland. Furthermore, the model is extended to include cooling and product shelf-life estimation for perishable cargoes that are transported in the reefer containers. The analytical models are verified with a Monte Carlo simulation; the conclusion is that the models are suitable to capture the performance on cost, emission and product quality of three scenarios. To support decision-making on transport of containers to the hinterland in finding the optimal intermodal service frequency, several propositions and theorems are also derived from the analytical models.

The model is applied to a case for both non-perishable and perishable cargoes from the Port of Rotterdam to four hinterland destinations. The numerical results of this case show that, from a cost perspective, for dry containers, combined container/cargo consolidation outperforms only-trucking. The container consolidation is beneficial when the shipment distance is long. For reefers, combined reefer/cargo consolidation has the lowest cost regardless of distance. In terms of emission, for dry containers, container consolidation is the best option for hinterland logistics. Combined container/cargo consolidation is the best scenario for reefer containers when the shipment distance is long (in our case for Duisburg), and for short hinterland distance (Tilburg in our case), only-trucking has the lowest emission. As a result, we can conclude that the shipment distance and cargo type are important factors for the performance of flow consolidation in port-hinterland logistics. For future research, the model can be extended to a more complex network with more inland terminals and hinterland cross-docking facilities, including the repositioning of empty containers.

## Acknowledgement

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## Appendix A. Proof of propositions and theorems

**Proof for Proposition 1.** 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. Let $M$ denote the number of container arrivals during the planning horizon $T$. Therefore, the expected total number of containers of the planning horizon is $E(\sum_{j=1}^{M} n_j)$. According to renewal theory, $E(M) = m(T) = \lambda T$, where $\lambda$ is the batch arrival rate. Thus, $E\left(\sum_{j=1}^{M} n_j\right) = \mu\lambda T$. Container handling cost, shuttle cost and trucking cost are $5c_h \cdot \mu\lambda T$, $c_{sh} \cdot \mu\lambda T$, and $c_t \cdot \mu\lambda T$, respectively. Five container handling are counted in the model: unloading from the vessel, loading to and unloading from the shuttle barge, loading to and unloading from the truck. The consolidation cost at the hinterland cross-docking facility includes two parts: the consolidation and the cargo storage. Consolidation cost depends on the number of pallets, The expected consolidation cost is $c_{con} pl_c L_c \mu\lambda T$. Cargo storage cost occurs only when a trailer cannot be fully loaded and must wait for the cargoes in the next batch of containers. Cargo storage cost depends on the number of pallets stored and the time of the storage. The storage time is the same as inter-arrival time of container batches with the mean of $1/\lambda$. The number of pallets stored at the cross-docking facility depends on the number of containers in one batch, container capacity, container load factor and trailer capacity, which is calculated as $n_j pl_c l_{c,j} mod pl_{tr}$. It varies from 1 to $(pl_{tr} - 1)$. In this case, the average $pl_{tr}/2$ is used as an estimation for the expected number of pallets stored at the cross-docking facility. Therefore, the expected cargo storage cost is $c_{sp}(pl_{tr}/2)(1/\lambda)\lambda T = c_{sp} T pl_{tr}/2$. Then, the total cost of scenario 1 is:

$$E(Cost)_{Scenario1} = (5c_h + c_{sh} + c_t + c_{con} pl_c L_c)\mu\lambda T + c_{sp} T \frac{pl_{tr}}{2} \tag{A.1}$$

For total emission, the proof is similar to that of the total cost. Instead of the unit cost, $5f_e v_h$, $f_d v_{sh} d_{sh}$, $f_d v_t d_t$ and $f_d v_{con} pl_c L_c$ are the unit emission of handling, shuttling, trucking and consolidation. The total $CO_2$ emission of scenario 1 is then:

$$E(Emission)_{Scenario1} = (5f_e v_h + f_d v_{sh} d_{sh} + f_d v_t d_t + f_d v_{con} pl_c L_c)\mu\lambda T \tag{A.2}$$

This completes the proof. □

**Proof for Proposition 2.** In scenario 2, the total cost consists of container handling cost, shuttle cost, shipment cost, container storage cost and consolidation cost at the hinterland cross-docking facility. Shuttle cost and consolidation cost are the same as scenario 1, which are $c_{sh}\mu\lambda T$ and $c_{con} pl_c L_c \mu\lambda T + c_{sp} T pl_{tr}/2$ respectively.

- ***Shipment cost***

Shipment cost consists of trucking cost and IFT cost, which depends on the number of containers that are shipped by trucks and IFT. The number of containers arriving at the port during $T$ is $\sum_{j=1}^{M} n_j$. Among them, the share of urgent containers is $k_u$. The share of non-urgent containers transported by truck is $p_t(1 - k_u)$. Trucking cost is formulated as $c_t[k_u + p_t(1 - k_u)]\sum_{j=1}^{M} n_j$. The share of non-urgent containers transported by IFT is $(1 - p_t)(1 - k_u)$. These containers are shipped by IFT to an inland terminal. Then they are trucking to the hinterland cross-docking facility. The unit variable IFT cost and the unit end-haulage cost are $c_{IFT}^v$ and $c_e$. Furthermore, operating intermodal service has a fixed cost that depends on the frequency of IFT ($N = T/t_0$). Thus, IFT cost is formulated as $c_{IFT} T/t_0 + (c_{IFT}^v + c_e)(1 - p_t)(1 - k_u)\sum_{j=1}^{M} n_j$, and total shipment cost is formulated as:

$$c_{shipment} = \frac{T}{t_0}c_{IFT} + (c_{IFT}^v + c_e)(1 - p_t)(1 - k_u)\sum_{j=1}^{M} n_j + c_t[k_u + p_t(1 - k_u)]\sum_{j=1}^{M} n_j = \frac{T}{t_0}c_{IFT} + (c_{IFT}^v + c_e)(1 - p_t)(1 - k_u)\mu\lambda T + c_t[k_u + p_t(1 - k_u)]\mu\lambda T \tag{A.3}$$

- ***Container handling cost***

In this scenario, all urgent containers $k_u\sum_{j=1}^{M} n_j$ and a portion of non-urgent containers $p_t(1 - k_u)\sum_{j=1}^{M} n_j$ are transported by trucks with five handling stages (as illustrated in PROOF for PROPOSITION 1), and the rest of the non-urgent containers $(1 - p_t)(1 - k_u)\sum_{j=1}^{M} n_j$ are transported by intermodal services with two extra transhipment handling stages at the inland terminal. Thus, total container handling cost is as follows:

$$c_{container\quad handle} = 5c_h[k_u + p_t(1 - k_u)]\sum_{j=1}^{M} n_j + 7c_h(1 - p_t)(1 - k_u)\sum_{j=1}^{M} n_j = 5c_h[k_u + p_t(1 - k_u)]\mu\lambda T + 7c_h(1 - p_t)(1 - k_u)\mu\lambda T \tag{A.4}$$

- ***Container storage cost***

To calculate the container storage cost, it is necessary to have the number of containers that are stored and the time they are stored. According to the description in Section 3.1, the storage cost is attributed only to the non-urgent containers transported by IFT; and the storage process has cycles based on the intermodal service frequency. Let $ta_j$ denote the arrival time of the $j^{th}$ batch of containers and $it_j$ denote the inter-arrival time between the $(j - 1)^{th}$ batch and the $j^{th}$ batch. The inter-arrival time between two successive batches has a mean of $1/\lambda$. Thus, the expected arrival time of the $j^{th}$ batch is $ta_j = j * 1/\lambda$. The storage time of the container in the $j^{th}$ batch is $t_0 - ta_j = t_0 - \sum_1^j it_j$. The expected storage time of the $j^{th}$ batch is $E(t_0 - ta_j) = t_0 - j/\lambda$. Let $K$ denote the number of container arrivals by time $t_0$ so that $E(K) = \lambda t_0$. Thus, storage cost of one intermodal service is $\sum_{j=1}^{K} c_s(1 - p_t)(1 - k_u)n_j * (t_0 - \sum_1^j it_j)$, where $c_s$ is the unit storage cost of a container. The expected storage cost of one intermodal service can be multiplied by IFT frequency $N$ to get the expected total storage cost, since the expected storage cost is the same for the other $(N - 1)$ cycles. The expected total storage cost is formulated as follows:

$$\begin{aligned} c_{storage} &= N * E\left[\sum_{j=1}^{K} c_s(1 - p_t)(1 - k_u)n_j * \left(t_0 - \sum_1^j it_j\right)\right] = N * c_s(1 - p_t)(1 - k_u)\mu * E\left[\sum_{j=1}^{K}\left(t_0 - \sum_1^j it_j\right)\right] \\ &= N * c_s(1 - p_t)(1 - k_u)\mu * \left[E(K)t_0 - E\left(\sum_{j=1}^{K}\frac{j}{\lambda}\right)\right] = N * c_s(1 - p_t)(1 - k_u)\mu * \left\{E(K)t_0 - \frac{[1 + E(K)]E(K)}{2\lambda}\right\} \\ &= N * c_s(1 - p_t)(1 - k_u)\mu * \left[\lambda t_0 * t_0 - \frac{(1 + \lambda t_0)\lambda t_0}{2\lambda}\right] = \frac{T}{t_0} * c_s(1 - p_t)(1 - k_u)\mu\left(\frac{\lambda t_0^2}{2} - \frac{t_0}{2}\right) \\ &= \frac{c_s}{2}(1 - p_t)(1 - k_u)\mu T(\lambda t_0 - 1) \end{aligned} \tag{A.5}$$

- ***Total cost and minimum cost***

Given all cost terms, the total cost of scenario 2 can be calculated as follows.

$$\begin{aligned}E(C)_{Scenario2} &= c_{shuttle} + c_{container\ \ handle} + c_{shipment} + c_{storage} + c_{consolidation}\\ &= c_{sh}\mu\lambda T + 5c_h[k_u + p_t(1-k_u)]\mu\lambda T + 7c_h(1-p_t)(1-k_u)\mu\lambda T + \frac{T}{t_0}c_{IFT} + (c_{IFT}^v + c_e)(1-p_t)(1-k_u)\mu\lambda T + c_t[k_u\\ &\quad + p_t(1-k_u)]\mu\lambda T + \frac{c_s}{2}(1-p_t)(1-k_u)\mu T(\lambda t_0 - 1) + c_{con}pl_cL_c\mu\lambda T + c_{sp}T\frac{pl_{tr}}{2}\\ &= c_{sh}\mu\lambda T + 5c_h(k_u + p_t - p_tk_u)\mu\lambda T + [5c_h(1-p_t-k_u+p_tk_u)\mu\lambda T + 2c_h(1-p_t)(1-k_u)\mu\lambda T] + \frac{T}{t_0}\\ &\quad c_{IFT} + (c_{IFT}^v + c_e)(1-p_t)(1-k_u)\mu\lambda T + [c_t\mu\lambda T - c_t(1-p_t)(1-k_u)\mu\lambda T] + \frac{c_s}{2}(1-p_t)(1-k_u)\mu T(\lambda t_0 - 1) + c_{con}\\ &\quad pl_cL_c\mu\lambda T + c_{sp}T\frac{pl_{tr}}{2}\\ &= \left[(5c_h + c_{sh} + c_t + c_{con}pl_cL_c)\mu\lambda T + c_{sp}T\frac{pl_{tr}}{2}\right] - (c_t - c_{IFT}^v - c_e)(1-p_t)(1-k_u)\mu\lambda T + \frac{T}{t_0}c_{IFT} + 2c_h\\ &\quad (1-p_t)(1-k_u)\mu\lambda T + \frac{c_s}{2}(1-p_t)(1-k_u)\mu T(\lambda t_0 - 1)\end{aligned} \tag{A.6}$$

The frequency of the intermodal services $N = T/t_0$ is an integer. In this study, this constraint is relaxed in order to make an approximation of the step-wise function with a continuous one. With the approximation, the continuous function is a convex function. The proof of convexity is below. The minimum of the cost function can be found through the derivative.

$$E(C)_{Scenario2}{}' = \frac{c_s(1-p_t)(1-k_u)\mu\lambda T}{2} - \frac{Tc_{IFT}}{t_0^2} = 0 \tag{A.7}$$

$t_0^* \approx \sqrt{2c_{IFT}/c_s(1-p_t)(1-k_u)\mu\lambda}$ and $N^* = \langle T\sqrt{c_s(1-p_t)(1-k_u)\mu\lambda/2c_{IFT}}\rangle$, where $\langle\rangle$ is the function to round up/down to an integer. When $t_0$ is in the interval $(0, \sqrt{2c_{IFT}/c_s(1-p_t)(1-k_u)\mu\lambda})$, $E(C)_{Scenario2}{}' < 0$. The cost function in this interval is decreasing monotonically. When $t_0$ is in the interval $(\sqrt{2c_{IFT}/c_s(1-p_t)(1-k_u)\mu\lambda}, T]$, $E(C)_{Scenario2}{}' > 0$. The cost function in this interval is increasing monotonically. Therefore, $t_{0,Scenario2}^{cost^*} \approx \sqrt{2c_{IFT}/c_s(1-p_t)(1-k_u)\mu\lambda}$ and $N_{Scenario2}^{cost^*} = \langle T\sqrt{c_s(1-p_t)(1-k_u)\mu\lambda/2c_{IFT}}\rangle$ are the optimal values that lead to the minimum total cost, if the IFT capacity is enough to carry the demand in the period $t_{0,Scenario2}^{cost^*}$. The minimum total cost is calculated as below.

$$\begin{aligned}E(C)_{Scenario2}^{min} &\approx \left[(5c_h + c_{sh} + c_t + c_{con}pl_cL_c)\mu\lambda T + c_{sp}T\frac{pl_{tr}}{2}\right] - (c_t - c_{IFT}^v - c_e)(1-p_t)(1-k_u)\mu\lambda T + c_{IFT}\\ &\quad T\sqrt{c_s(1-p_t)(1-k_u)\mu\lambda/2c_{IFT}} + 2c_h(1-p_t)(1-k_u)\mu\lambda T + \frac{c_s}{2}(1-p_t)(1-k_u)\mu T\lambda\sqrt{\frac{2c_{IFT}}{c_s(1-p_t)(1-k_u)\mu\lambda}} - \frac{c_s}{2}\\ &\quad (1-p_t)(1-k_u)\mu T\\ &= \left[(5c_h + c_{sh} + c_t + c_{con}pl_cL_c)\mu\lambda T + c_{sp}T\frac{pl_{tr}}{2}\right] + 2c_h(1-p_t)(1-k_u)\mu\lambda T - (c_t - c_{IFT}^v - c_e)(1-p_t)(1-k_u)\mu\lambda\\ &\quad T + T\sqrt{\frac{c_{IFT}c_s(1-p_t)(1-k_u)\mu\lambda}{2}} + T\sqrt{\frac{c_{IFT}c_s(1-p_t)(1-k_u)\mu\lambda}{2}} - \frac{c_s}{2}(1-p_t)(1-k_u)\mu T\\ &= \left[(5c_h + c_{sh} + c_t + c_{con}pl_cL_c)\mu\lambda T + c_{sp}T\frac{pl_{tr}}{2}\right] + 2c_h(1-p_t)(1-k_u)\mu\lambda T - (c_t - c_e - c_{IFT}^v)(1-p_t)(1-k_u)\mu\lambda\\ &\quad T + T\sqrt{2c_{IFT}c_s(1-p_t)(1-k_u)\mu\lambda} - \frac{c_s}{2}(1-p_t)(1-k_u)\mu T\end{aligned} \tag{A.8}$$

Otherwise, if the demand in the $t_0^* \approx \sqrt{2c_{IFT}/c_s(1-p_t)(1-k_u)\mu\lambda}$ period is larger than the IFT capacity, keeping $t_0^*$ as IFT cycle time violates the capacity constraint. Then, the cycle time of IFT needs to be reduced (i.e., number of IFT needs to be increased) in order to guarantee that the portion $(1-p_t)$ of non-urgent containers can be shipped by IFT. Thus,

$$(1-p_t)(1-k_u)\mu\lambda T \le N \times U \tag{A.9}$$

Then, $N \ge (1-p_t)(1-k_u)\mu\lambda T/U$ and $t_0 \le U/(1-p_t)(1-k_u)\mu\lambda$.

To reduce $t_0$, $t_0$ can only be in the interval $(0, \sqrt{2c_{IFT}/c_s(1-p_t)(1-k_u)\mu\lambda})$. If $t_0 \in (\sqrt{2c_{IFT}/c_s(1-p_t)(1-k_u)\mu\lambda}, T]$, the capacity constraint is violated. In the interval $t_0 \in (0, \sqrt{2c_{IFT}/c_s(1-p_t)(1-k_u)\mu\lambda})$, $E(C)_{Scenario2}{}' < 0$, the total cost function is decreasing monotonically. Thus, it is necessary to reduce $t_0$ as little as possible to keep it close to $\sqrt{2c_{IFT}/c_s(1-p_t)(1-k_u)\mu\lambda}$. Therefore, with capacity limit, the optimal $t_{0,Scenario2}^{cost^*} \approx U/(1-p_t)(1-k_u)\mu\lambda$ and $N_{Scenario2}^{cost^*} = \lceil(1-p_t)(1-k_u)\mu\lambda T/U\rceil$, where $\lceil\ \ \rceil$ is the function to round up to an integer. Accordingly, minimum total cost is formulated as below:

$$E(C)^{min}_{Scenario2} \approx \left[(5c_h + c_{sh} + c_t + c_{con}pl_cL_c)\mu\lambda T + c_{sp}T\frac{pl_{tr}}{2}\right] + 2c_h(1-p_t)(1-k_u)\mu\lambda T - (c_t - c^v_{IFT} - c_e)(1-p_t)(1-k_u)\mu\lambda T + \frac{(1-p_t)(1-k_u)\mu\lambda T}{U}c_{IFT} + \frac{c_s}{2}(1-p_t)(1-k_u)\mu T\left[\lambda\frac{U}{(1-p_t)(1-k_u)\mu\lambda} - 1\right]$$
$$= \left[(5c_h + c_{sh} + c_t + c_{con}pl_cL_c)\mu\lambda T + c_{sp}T\frac{pl_{tr}}{2}\right] + 2c_h(1-p_t)(1-k_u)\mu\lambda T - \left(c_t - c_e - c^v_{IFT} - \frac{c_{IFT}}{U}\right)(1-p_t)(1-k_u)\mu\lambda T + \frac{c_s}{2}TU - \frac{c_s}{2}(1-p_t)(1-k_u)\mu T \quad (A.10)$$

- ***Total emission and minimum emission***

Total emission consists of four components: container handling, shuttle service, land shipment and cargo consolidation. There is no emission during the container and cargo storage. The proof is similar to total cost. Total emission is formulated as follows.

$$E(E)_{Scenario2} = f_dv_td_t[k_u + p_t(1-k_u)]\mu\lambda T + Nf_dv_{IFT}d_{IFT} + f_dv_td_e(1-p_t)(1-k_u)\mu\lambda T + 5f_ev_h[k_u + p_t(1-k_u)]\mu\lambda T + 7f_ev_h(1-p_t)(1-k_u)\mu\lambda T + f_dv_{sh}d_{sh}\mu\lambda T + f_dv_{con}pl_cL_c\mu\lambda T$$
$$= [f_dv_td_t\mu\lambda T - f_dv_td_t(1-p_t)(1-k_u)\mu\lambda T] + Nf_dv_{IFT}d_{IFT} + f_dv_td_e(1-p_t)(1-k_u)\mu\lambda T + 5f_ev_h(k_u + p_t - p_tk_u)\mu\lambda T + [5f_ev_h(1 - p_t - k_u + p_tk_u)\mu\lambda T + 2f_ev_h(1-p_t)(1-k_u)\mu\lambda T] + f_dv_{sh}d_{sh}\mu\lambda T + f_dv_{con}pl_cL_c\mu\lambda T$$
$$= [f_dv_td_t\mu\lambda T - f_dv_td_t(1-p_t)(1-k_u)\mu\lambda T] + Nf_dv_{IFT}d_{IFT} + f_dv_td_e(1-p_t)(1-k_u)\mu\lambda T + 5f_ev_h\mu\lambda T + 2f_ev_h(1-p_t)(1-k_u)\mu\lambda T + f_dv_{sh}d_{sh}\mu\lambda T + f_dv_{con}pl_cL_c\mu\lambda T$$
$$= [(5f_ev_h + f_dv_{sh}d_{sh} + f_dv_td_t + f_dv_{con}pl_cL_c)\mu\lambda T] + 2f_ev_h(1-p_t)(1-k_u)\mu\lambda T - f_dv_t(d_t - d_e)(1-p_t)(1-k_u)\mu\lambda T + \frac{T}{t_0}f_dv_{IFT}d_{IFT} \quad (A.11)$$

Total emission function is a monotonically decreasing function. Total emission increases with the decrease of $t_0$. If the IFT capacity is enough to carry the demand, the optimal $t^{emission^*}_{0,Scenario2}$ is $T$ and the optimal $N^{emission^*}_{Scenario2}$ is 1. The minimum emission is formulated as follows.

$$E(E)^{min}_{Scenario2} = [(5f_ev_h + f_dv_{sh}d_{sh} + f_dv_td_t + f_dv_{con}pl_cL_c)\mu\lambda T] + 2f_ev_h(1-p_t)(1-k_u)\mu\lambda T - f_dv_t(d_t - d_e)(1-p_t)(1-k_u)\mu\lambda T + f_dv_{IFT}d_{IFT} \quad (A.12)$$

Otherwise, if the IFT capacity is smaller than the demand, $t_0$ is reduced similar to the minimum cost calculation. $t^{emission^*}_{0,Scenario2} \approx U/(1-p_t)(1-k_u)\mu\lambda$ and $N^{emission^*}_{Scenario2} = \lceil(1-p_t)(1-k_u)\mu\lambda T/U\rceil$. The minimum emission is formulated as follows.

$$E(E)^{min}_{Scenario2} \approx [(5f_ev_h + f_dv_{sh}d_{sh} + f_dv_td_t + f_dv_{con}pl_cL_c)\mu\lambda T] + 2f_ev_h(1-p_t)(1-k_u)\mu\lambda T - f_d\left(v_td_t - v_td_e - \frac{v_{IFT}d_{IFT}}{U}\right)(1-p_t)(1-k_u)\mu\lambda T \quad (A.13)$$

This completes the proof. □

**Proof for convexity of total cost function of Scenario 2.** A function $f$ is convex if (a) the domain $dom(f)$ is a convex set, and (b) the next inequality holds for all $x, y \in dom(f)$ and $0 \le \beta \le 1$: $f((1-\beta)x + \beta y) \le (1-\beta)f(x) + \beta f(y)$. In this case, the domain of $E(C)_{Scenario2}$ is a set $\ell = (0, T]$. The set is convex, since for each pair $x, y \in \ell$ and for $\beta \in [0, 1]$ the property $(1-\beta)x + \beta y \in \ell$ holds. $E(C)_{Scenario2}$ can be rewritten as:

$$E(C)_{Scenario2} = A + Bt_0 + \frac{C}{t_0} \quad (A.14)$$

in which

$$A = \left[(5c_h + c_{sh} + c_t + c_{con}pl_cL_c)\mu\lambda T + c_{sp}T\frac{pl_{tr}}{2}\right] - (c_t - c^v_{IFT} - c_e)(1-p_t)(1-k_u)\mu\lambda T + 2c_h(1-p_t)(1-k_u)\mu\lambda T - \frac{c_s}{2}(1-p_t)(1-k_u)\mu T$$

$$B = \frac{c_s}{2}(1-p_t)(1-k_u)\mu\lambda T$$

$$C = c_{IFT}T > 0$$

$$
\begin{aligned}
&[(1-\beta)E(C)_{Scenario2}(x)+\beta E(C)_{Scenario2}(y)]-E(C)_{Scenario2}((1-\beta)x+\beta y)\\
&=(1-\beta)\left(A+Bx+\frac{C}{x}\right)+\beta\left(A+By+\frac{C}{y}\right)-\left\{A+B[(1-\beta)x+\beta y]+\frac{C}{(1-\beta)x+\beta y}\right\}\\
&=\frac{C(1-\beta)}{x}+\frac{C\beta}{y}-\frac{C}{(1-\beta)x+\beta y}=\frac{y[(1-\beta)x+\beta y]C(1-\beta)+x[(1-\beta)x+\beta y]C\beta+xyC}{xy[(1-\beta)x+\beta y]}\\
&=\frac{C(1-\beta)^2xy+C\beta(1-\beta)y^2+C\beta(1-\beta)x^2+C\beta^2xy-Cxy}{xy[(1-\beta)x+\beta y]}\\
&=\frac{C(1-\beta)^2xy+C\beta(1-\beta)y^2+C\beta(1-\beta)x^2-C(1-\beta)(1+\beta)xy}{xy[(1-\beta)x+\beta y]}\\
&=\frac{C(1-\beta)((1-\beta)-(1+\beta))xy+C\beta(1-\beta)y^2+C\beta(1-\beta)x^2}{xy[(1-\beta)x+\beta y]}=\frac{C(1-\beta)\beta(x^2+y^2-2xy)}{xy[(1-\beta)x+\beta y]}=\frac{C(1-\beta)\beta(x-y)^2}{xy[(1-\beta)x+\beta y]}\geq 0
\end{aligned}
\tag{A.15}
$$

The total cost function of scenario 2 is a convex function. This completes the proof. □

**Proof of Proposition 3.** In scenario 3, total cost consists of the shuttle cost, container handling cost, shipment cost, container storage cost and consolidation cost. The shuttle cost is the same as scenario 1 and scenario 2, which is $c_{sh}\mu\lambda T$.

- ***Shipment cost***

Shipment cost of scenario 3 includes trucking cost, IFT cost and trailer cost. All urgent containers and a part of non-urgent containers ($[k_u + p_t(1-k_u)]\sum_{j=1}^{M} n_j$) are transported directly by truck to the hinterland, which results in an expected cost of $c_t[k_u + p_t(1-k_u)]\mu\lambda T$. Some of the rest of the non-urgent containers – those that are transported by tractor trailers – are opened with a factor of $p_o$ that are transported by tractor trailers. The rest of the non-urgent containers are shipped by intermodal transport. Thus, in this scenario, the number of containers transported by intermodal service is $(1-p_o)(1-p_t)(1-k_u)\sum_{j=1}^{M} n_j$. The expected intermodal transport cost is then $c_{IFT}N + (c_e + c_{IFT}^{v})(1-p_o)(1-p_t)(1-k_u)\mu\lambda T$. The number of containers that are opened is $p_o(1-p_t)(1-k_u)\sum_{j=1}^{M} n_j$. It is assumed that these containers in the $j^{th}$ batch have a load factor $l_{c,j}$ (which has expected value of $L_c$), and the capacity of a container and a trailer in terms of the number of pallets is $pl_c$ and $pl_{tr}$, respectively. Thus, in this model, the number of trailers to the hinterland after consolidation is $\lceil p_o(1-p_t)(1-k_u)pl_c\sum_{j=1}^{M} n_j l_{c,j}/pl_{tr}\rceil$. Unit shipment cost of a tractor trailer is $c_{tr}$. With these notations, the shipment cost is formulated as follows.

$$
\begin{aligned}
c_{shipment}&=c_t[k_u+p_t(1-k_u)]\mu\lambda T+c_{IFT}N+(c_{IFT}^{v}+c_e)(1-p_o)(1-p_t)(1-k_u)\mu\lambda T+c_{tr}\left\lceil\frac{p_o(1-p_t)(1-k_u)pl_c\sum_{j=1}^{M}n_jl_{c,j}}{pl_{tr}}\right\rceil\\
&\approx c_t[k_u+p_t(1-k_u)]\mu\lambda T+c_{IFT}N+(c_e+c_{IFT}^{v})(1-p_o)(1-p_t)(1-k_u)\mu\lambda T+c_{tr}p_o(1-p_t)(1-k_u)pl_cL_c\mu\lambda T/pl_{tr}
\end{aligned}
\tag{A.16}
$$

- ***Container handling cost***

The handling cost depends on the number of containers and the number of handling stages required for each container. About trucking and intermodal transport, the calculation is similar to scenario 2. For containers with cargo consolidation at the port area, three handling stages are considered: unloading from the vessel, loading to the shuttle and unloading from the shuttle. After these containers arrive at the cross-docking facility in the port area, they are opened, and the pallets are rearranged to trailers. No additional handling is required for containers. The handling cost is formulated as follows:

$$
\begin{aligned}
c_{handle}&=5c_h[k_u+p_t(1-k_u)]\sum_{j=1}^{M}n_j+7c_h(1-p_o)(1-p_t)(1-k_u)\sum_{j=1}^{M}n_j+3c_hp_o(1-p_t)(1-k_u)\sum_{j=1}^{M}n_j\\
&=5c_h[k_u+p_t(1-k_u)]\mu\lambda T+7c_h(1-p_o)(1-p_t)(1-k_u)\mu\lambda T+3c_hp_o(1-p_t)(1-k_u)\mu\lambda T
\end{aligned}
\tag{A.17}
$$

- ***Container storage cost***

The container storage cost calculation is similar to scenario 2. It is applied only to the containers transported by intermodal services. In this scenario, the number of containers stored at the full container stack in the port is $(1-p_o)(1-p_t)(1-k_u)\sum_{j=1}^{M} n_j$. The container storage cost is formulated as follows:

$$c_{storage} = N * E\left[\sum_{j=1}^{K} c_s(1-p_o)(1-p_t)(1-k_u)n_j * \left(t_0 - \sum_{1}^{j} it_j\right)\right] = N * c_s(1-p_o)(1-p_t)(1-k_u)E(n_j)$$
$$* E\left[\sum_{j=1}^{K}\left(t_0 - \sum_{1}^{j} it_j\right)\right] = N * c_s(1-p_o)(1-p_t)(1-k_u)E(n_j) * \left[E(K)t_0 - E\left(\sum_{j=1}^{K}\frac{j}{\lambda}\right)\right]$$
$$= N * c_s(1-p_o)(1-p_t)(1-k_u)E(n_j) * \left\{E(K)t_0 - \frac{[1+E(K)]E(K)}{2\lambda}\right\}$$
$$= N * c_s(1-p_o)(1-p_t)(1-k_u)E(n_j) * \left[\lambda t_0 * t_0 - \frac{(1+\lambda t_0)\lambda t_0}{2\lambda}\right] = N * c_s(1-p_o)(1-p_t)(1-k_u)E(n_j)\left(\frac{\lambda t_0^2}{2} - \frac{t_0}{2}\right)$$
$$= \frac{c_s}{2}(1-p_o)(1-p_t)(1-k_u)\mu T(\lambda t_0 - 1) \tag{A.18}$$

- ***Consolidation cost***

There are two consolidation locations in this scenario. A part of non-urgent containers are consolidated in the decoupling centre in the port area. The other containers are consolidated in the cross-docking facility in the hinterland. Therefore, the consolidation cost consists of three parts: consolidation cost for all containers; cargo storage cost at the decoupling centre in the port; and cargo storage cost at the cross-docking facility in the hinterland. Consolidation cost depends on the total number of pallets, which is the same as in the other two scenarios: $c_{con}pl_cL_c\mu\lambda T$. The expected cargo storage cost at each location (i.e., port area and hinterland) is $c_{sp}Tpl_{tr}/2$. Then consolidation cost is as follows:

$$c_{consolidation} = c_{con}pl_cL_c\mu\lambda T + c_{sp}T\frac{pl_{tr}}{2} + c_{sp}T\frac{pl_{tr}}{2} = c_{con}pl_cL_c\mu\lambda T + c_{sp}Tpl_{tr} \tag{A.19}$$

- ***Total cost and minimum cost.***

Given all cost terms, the total cost of scenario 3 can be calculated as follows:

$$E(C)_{Scenario3} = c_{sh}\mu\lambda T + 5c_h[k_u + p_t(1-k_u)]\mu\lambda T + 7c_h(1-p_o)(1-p_t)(1-k_u)\mu\lambda T + 3c_hp_o(1-p_t)(1-k_u)\mu\lambda T + c_t$$
$$[k_u + p_t(1-k_u)]\mu\lambda T + c_{IFT}N + (c_e + c_{IFT}^v)(1-p_o)(1-p_t)(1-k_u)\mu\lambda T + \frac{c_{tr}p_o(1-p_t)(1-k_u)pl_cL_c\mu\lambda T}{pl_{tr}} + \frac{c_s}{2}$$
$$(1-p_o)(1-p_t)(1-k_u)\mu T(\lambda t_0 - 1) + c_{con}pl_cL_c\mu\lambda T + c_{sp}Tpl_{tr}$$

$$= c_{sh}\mu\lambda T + 5c_h[k_u + p_t(1-k_u)]\mu\lambda T + [7c_h(1-p_t)(1-k_u)\mu\lambda T - 7c_hp_o(1-p_t)(1-k_u)\mu\lambda T] + 3c_hp_o$$
$$(1-p_t)(1-k_u)\mu\lambda T + [c_t\mu\lambda T - c_t(1-p_t)(1-k_u)\mu\lambda T] + c_{IFT}N + (c_e + c_{IFT}^v)(1-p_o)(1-p_t)(1-k_u)\mu\lambda T + \frac{c_{tr}p_opl_cL_c}{pl_{tr}}$$
$$(1-p_t)(1-k_u)\mu\lambda T + \frac{c_s}{2}(1-p_o)(1-p_t)(1-k_u)\mu T(\lambda t_0 - 1) + c_{con}pl_cL_c\mu\lambda T + c_{sp}Tpl_{tr}$$

$$= c_{sh}\mu\lambda T + 5c_h(k_u + p_t - p_tk_u)\mu\lambda T + [5c_h(1 - p_t - k_u + p_tk_u)\mu\lambda T + 2c_h(1-p_t)(1-k_u)\mu\lambda T] - 4c_hp_o$$
$$(1-p_t)(1-k_u)\mu\lambda T + c_t\mu\lambda T - \left[c_t - (c_e + c_{IFT}^v)(1-p_o) - \frac{c_{tr}p_opl_cL_c}{pl_{tr}}\right](1-p_t)(1-k_u)\mu\lambda T + c_{IFT}$$
$$N + \frac{c_s}{2}(1-p_o)(1-p_t)(1-k_u)\mu T(\lambda t_0 - 1) + c_{con}pl_cL_c\mu\lambda T + c_{sp}Tpl_{tr}$$

$$= c_{sh}\mu\lambda T + 5c_h\mu\lambda T - 2c_h(2p_o - 1)(1-p_t)(1-k_u)\mu\lambda T + c_t\mu\lambda T - \left[c_t - (c_e + c_{IFT}^v)(1-p_o) - \frac{c_{tr}p_opl_cL_c}{pl_{tr}}\right](1-p_t)(1-k_u)\mu$$
$$\lambda T + c_{IFT}N + \frac{c_s}{2}(1-p_o)(1-p_t)(1-k_u)\mu T(\lambda t_0 - 1) + c_{con}pl_cL_c\mu\lambda T + c_{sp}Tpl_{tr}$$

$$= (5c_h + c_{sh} + c_t + c_{con}pl_cL_c)\mu\lambda T + c_{sp}Tpl_{tr} - 2c_h(2p_o - 1)(1-p_t)(1-k_u)\mu\lambda T - \left[c_t - (c_e + c_{IFT}^v)(1-p_o) - \frac{c_{tr}p_opl_cL_c}{pl_{tr}}\right]$$
$$(1-p_t)(1-k_u)\mu\lambda T + c_{IFT}\frac{T}{t_0} + \frac{c_s}{2}(1-p_o)(1-p_t)(1-k_u)\mu T(\lambda t_0 - 1) \tag{A.20}$$

The same as in scenario 2, the integer constraint of IFT frequency is relaxed. With the approximation, the continuous function is a convex function. $E(C)_{Scenario3}$ can be rewritten as:

$$E(C)_{Scenario3} = A + Bt_0 + \frac{C}{t_0} \tag{A.21}$$

in which

$$A = (5c_h + c_{sh} + c_t + c_{con}pl_cL_c)\mu\lambda T + c_{sp}Tpl_{tr} - 2c_h(2p_o - 1)(1 - p_t)(1 - k_u)\mu\lambda T - \left[c_t - (c_e + c_{IFT}^v)(1 - p_o) - \frac{c_{tr}p_opl_cL_c}{pl_{tr}}\right]$$
$$(1 - p_t)(1 - k_u)\mu\lambda T - \frac{c_s}{2}(1 - p_o)(1 - p_t)(1 - k_u)\mu T$$

$$B = \frac{c_s}{2}(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda T$$

$$C = c_{IFT}T > 0$$

The proof of convexity is the same as in the **PROOF for convexity of total cost function of Scenario 2**. Similar to scenario 2, the minimum cost of this cost function can be found through the derivation.

$$E(C)_{Scenario3}' = \frac{c_s(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda T}{2} - \frac{c_{IFT}T}{t_0^2}$$
$$t_0^* \approx \sqrt{2c_{IFT}/c_s(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda},\ N^* = \langle T\sqrt{c_s(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda/2c_{IFT}}\rangle \tag{A.22}$$

Similar to the **PROOF of PROPOSITION 2**, at $t_0^*$, total cost reaches the minimum. If the IFT capacity is enough for the demand in the period $t_0^* \approx \sqrt{2c_{IFT}/c_s(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda}$, the optimum IFT cycle time and frequency are $t_{0,scenario3}^{cost^*} \approx \sqrt{2c_{IFT}/c_s(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda}$, and $N_{scenario3}^{cost^*} = \langle T\sqrt{c_s(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda/2c_{IFT}}\rangle$, respectively. Minimum total cost is formulated as below.

$$E(C)_{Scenario3}^{min}$$
$$= (5c_h + c_{sh} + c_t + c_{con}pl_cL_c)\mu\lambda T + c_{sp}Tpl_{tr} - 2c_h(2p_o - 1)(1 - p_t)(1 - k_u)\mu\lambda T - \left[c_t - (c_e + c_{IFT}^v)(1 - p_o) - \frac{c_{tr}p_opl_cL_c}{pl_{tr}}\right]$$
$$(1 - p_t)(1 - k_u)\mu\lambda T + T\sqrt{2c_{IFT}c_s(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda} - \frac{c_s}{2}(1 - p_o)(1 - p_t)(1 - k_u)\mu T \tag{A.23}$$

Otherwise, if the demand in $t_0^* \approx \sqrt{2c_{IFT}/c_s(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda}$ period is larger than the service capacity, $t_0$ needs to be reduced. Thus,

$$(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda T \leq N \times U \tag{A.24}$$

$N \geq (1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda T/U$ and $t_0 \leq U/(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda$. To reduce $t_0$, $t_0$ can only be in the interval $(0, \sqrt{2c_{IFT}/c_s(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda})$. If $t_0 \in (\sqrt{2c_{IFT}/c_s(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda}, T]$, the capacity constraint is violated. In the interval $t_0 \in (0, \sqrt{2c_{IFT}/c_s(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda})$, $E(C)_{Scenario3}' < 0$. Thus, the total cost function is decreasing monotonically. It is necessary to reduce $t_0$ as little as possible, i.e., to increase intermodal service frequency $N$ as little as possible. Therefore, with capacity limit, the optimal $N_{Scenario3}^{cost^*} = \lceil(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda T/U\rceil$ and $t_{0,Scenario3}^{cost^*} \approx U/(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda$. Accordingly, minimum total cost is formulated as below.

$$E(C)_{Scenario3}^{min}$$
$$= (5c_h + c_{sh} + c_t + c_{con}pl_cL_c)\mu\lambda T + c_{sp}Tpl_{tr} - \left[c_t - \left(c_e + c_{IFT}^v + \frac{c_{IFT}}{U}\right)(1 - p_o) - \frac{c_{tr}p_opl_cL_c}{pl_{tr}}\right](1 - p_t)(1 - k_u)\mu\lambda T - 2c_h$$
$$(2p_o - 1)(1 - p_t)(1 - k_u)\mu\lambda T + \frac{c_s}{2}TU - \frac{c_s}{2}(1 - p_o)(1 - p_t)(1 - k_u)\mu T \tag{A.25}$$

- ***Total emission and minimum emission***

Total emission consists of four components: container handling, shuttle, shipment and consolidation. The proof is similar to total cost. Total emission is formulated as follows.

$$E(E)_{Scenario3}$$
$$= f_d v_t d_t[k_u + p_t(1 - k_u)]\mu\lambda T + f_d v_{IFT} d_{IFT} N + f_d v_t d_e(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda T + f_d v_{tr} d_t p_o(1 - p_t)(1 - k_u)\frac{pl_cL_c}{pl_{tr}}\mu\lambda T + 5f_e$$
$$v_h[k_u + p_t(1 - k_u)]\mu\lambda T + 7f_e v_h(1 - p_o)(1 - p_t)(1 - k_u)\mu\lambda T + 3f_e v_h p_o(1 - p_t)(1 - k_u)\mu\lambda T + f_d v_{sh} d_{sh}\mu\lambda T + f_d v_{con} pl_cL_c\mu\lambda T$$
$$= [(5f_e v_h + f_d v_{sh} d_{sh} + f_d v_t d_t + f_d v_{con} pl_cL_c)\mu\lambda T] - 2f_e v_h(2p_o - 1)(1 - p_t)(1 - k_u)\mu\lambda T - f_d$$
$$\left[v_t d_t - v_t d_e(1 - p_o) - v_{tr} d_t p_o\frac{pl_cL_c}{pl_{tr}}\right](1 - p_t)(1 - k_u)\mu\lambda T + f_d v_{IFT} d_{IFT}\frac{T}{t_0} \tag{A.26}$$

Total emission increases with the decrease of $t_0$. If the IFT capacity is enough for the demand in $T$ period, the optimal $t_{0,Scenario3}^{emission^*}$ is $T$. The optimal service frequency $N_{Scenario3}^{emission^*}$ is 1. Accordingly, minimum total emission is:

$$E(E)^{min}_{Scenario3} = [(5f_e v_h + f_d v_{sh} d_{sh} + f_d v_t d_t + f_d v_{con} pl_c L_c)\mu\lambda T] - 2f_e v_h (1-p_t)(1-k_u)(2p_o-1)\mu\lambda T - f_d \left[v_t d_t - v_t d_e(1-p_o) - v_{tr} d_t p_o \frac{pl_c L_c}{pl_{tr}}\right](1-p_t)(1-k_u)\mu\lambda T + f_d v_{IFT} d_{IFT} \quad (A.27)$$

Otherwise, if service capacity is smaller than the demand in $T$ period, $t_0$ is reduced and $N$ is increased. Then $N^{emission^*}_{Scenario3} = \lceil (1-p_o)(1-p_t)(1-k_u)\mu\lambda T/U \rceil$ and $t^{emission^*}_{0,Scenario3} \approx U/(1-p_o)(1-p_t)(1-k_u)\mu\lambda$. Minimum total emission is:

$$E(E)^{min}_{Scenario3} \approx [(5f_e v_h + f_d v_{sh} d_{sh} + f_d v_t d_t + f_d v_{con} pl_c L_c)\mu\lambda T] - 2f_e v_h (1-p_t)(1-k_u)(2p_o-1)\mu\lambda T - f_d \left[v_t d_t - \left(v_t d_e + \frac{v_{IFT} d_{IFT}}{U}\right)(1-p_o) - v_{tr} d_t p_o \frac{pl_c L_c}{pl_{tr}}\right](1-p_t)(1-k_u)\mu\lambda T \quad (A.28)$$

This completes the proof. □

**Proof of Proposition 4.** The container and cargo handling cost of scenario 1 (only–trucking) is formulated as:

$$c^{s1}_{handle} = 5c_h \mu\lambda T + c_{con} pl_c \mu\lambda T \quad (A.29)$$

The first term in the equation is the container handling cost. The second term is the cargo handling cost at the cross-docking facility in the hinterland.

The container and cargo handling cost of scenario 3 (combined container/cargo consolidation) is formulated as:

$$c^{s3}_{handle} = 5c_h [k_u + p_t(1-k_u)]\mu\lambda T + 7c_h(1-p_o)(1-p_t)(1-k_u)\mu\lambda T + 3c_h p_o(1-p_t)(1-k_u)\mu\lambda T + c_{con} pl_c \mu\lambda T \quad (A.30)$$

The first three terms in the equation are the container handling costs. The last term is the cargo handling cost, which depends on the unit cargo consolidation cost and the total number of pallets. It is assumed that, for each pallet, only one consolidation process is conducted either at the decoupling centre in the port or at the cross-docking facility in the hinterland. After the consolidation, the cargoes are sent to the final destination immediately.

The difference of handling cost between only-trucking and combined container/cargo consolidation is formulated as:

$$\begin{aligned} &Handlingcostdifference_{s3-s1} \\ &= \{5c_h[k_u + p_t(1-k_u)]\mu\lambda T + 7c_h(1-p_o)(1-p_t)(1-k_u)\mu\lambda T + 3c_h p_o(1-p_t)(1-k_u)\mu\lambda T + c_{con} pl_c \mu\lambda T\} \\ &\quad -(5c_h\mu\lambda T + c_{con} pl_c \mu\lambda T) \\ &= 5c_h(k_u + p_t - p_t k_u)\mu\lambda T + 7c_h(1-p_t)(1-k_u)\mu\lambda T - 7c_h p_o(1-p_t)(1-k_u)\mu\lambda T + 3c_h p_o(1-p_t)(1-k_u)\mu\lambda T - 5c_h\mu\lambda T \\ &= 5c_h(k_u + p_t - p_t k_u)\mu\lambda T + [5c_h\mu\lambda T - 5c_h(p_t + k_u - p_t k_u)\mu\lambda T] + 2c_h(1-p_t)(1-k_u)\mu\lambda T - 4c_h p_o \\ &\quad (1-p_t)(1-k_u)\mu\lambda T - 5c_h\mu\lambda T = 2c_h(1-p_t)(1-k_u)\mu\lambda T - 4c_h p_o(1-p_t)(1-k_u)\mu\lambda T = 2(1-2p_o)c_h(1-p_t)(1-k_u)\mu\lambda T \end{aligned} \quad (A.31)$$

There is a saving in handling cost of scenario 3 when the term is a negative number, which is only valid when $1-2p_o<0$, which implies $p_o > 50\%$. Therefore, when more than 50% of the non-urgent containers are opened at the decoupling centre in the port, there is a saving in handling cost of combined container/cargo consolidation compared with only-trucking.

This complete the proof. □

**Proof of Theorem 1.** Comparing scenario 1 and scenario 2, there is a saving of container consolidation in cost only when Eq. (5) is less than zero. Substituting $t_0$ with the optimal $t^{cost^*}_{0,Scenario2}$, Eq. (5) is as below.

If the capacity of IFT is larger than or equals to the demand, then $U \geq (1-p_t)(1-k_u)\mu\lambda t^{cost^*}_{0,sceience}$. Substituting $t^{cost^*}_{0,sceience} \approx \sqrt{2c_{IFT}/c_s(1-p_t)(1-k_u)\mu\lambda}$, we get $\sqrt{2c_{IFT}(1-p_t)(1-k_u)\mu\lambda/c_s} \leq U$. In this case, the cost difference is:

$$\begin{aligned} &Costdifference_{s2-s1} \\ &= 2c_h(1-p_t)(1-k_u)\mu\lambda T - (c_t - c_e - c^v_{IFT})(1-p_t)(1-k_u)\mu\lambda T + T\sqrt{2c_{IFT}c_s(1-p_t)(1-k_u)\mu\lambda} - \frac{c_s}{2}(1-p_t)(1-k_u)\mu T \\ &= \left(2c_h + c_e + c^v_{IFT} - c_t - \frac{c_s}{2\lambda}\right)(1-p_t)(1-k_u)\mu\lambda T + T\sqrt{2c_{IFT}c_s(1-p_t)(1-k_u)\mu\lambda} \\ &= T\sqrt{(1-p_t)(1-k_u)\mu\lambda}\left[\sqrt{2c_{IFT}c_s} - \left(c_t + \frac{c_s}{2\lambda} - 2c_h - c_e - c^v_{IFT}\right)\sqrt{(1-p_t)(1-k_u)\mu\lambda}\right] \end{aligned} \quad (A.32)$$

Since we compared the minimum cost of two scenarios, the condition of $T\sqrt{(1-p_t)(1-k_u)\mu\lambda}\,[\sqrt{2c_{IFT}c_s} - (c_t + c_s/2\lambda - 2c_h - c_e - c^v_{IFT})\sqrt{(1-p_t)(1-k_u)\mu\lambda}] < 0$ guarantees that there is a saving in cost of scenario 2 compared with scenario 1. $T$ is always a positive value. This leads to $\sqrt{2c_{IFT}c_s} - (c_t + c_s/2\lambda - 2c_h - c_e - c^v_{IFT})\sqrt{(1-p_t)(1-k_u)\mu\lambda} < 0$, $1-k_u \neq 0$ and $1-p_t \neq 0$. Furthermore, $\sqrt{2c_{IFT}c_s} - (c_t + c_s/2\lambda - 2c_h - c_e - c^v_{IFT})\sqrt{(1-p_t)(1-k_u)\mu\lambda} < 0$ can be re-written as $c_t > c^v_{IFT} + c_e + 2c_h + \sqrt{2c_{IFT}c_s/(1-p_t)(1-k_u)\mu\lambda} - c_s/2\lambda$, in which $\sqrt{2c_{IFT}c_s/(1-p_t)(1-k_u)\mu\lambda}$ implies that $k_u \neq 1$ and $p_t \neq 1$. Thus, $c_t > c^v_{IFT} + c_e + 2c_h + \sqrt{2c_{IFT}c_s/(1-p_t)(1-k_u)\mu\lambda} - c_s/2\lambda$ would be a necessary condition for the statement that container consolidation has a saving in cost compared with only-trucking when demand of IFT does not exceed the capacity.

If the capacity of IFT is smaller than the demand, then $\sqrt{2c_{IFT}(1-p_t)(1-k_u)\mu\lambda/c_s} > U$. In this case, the cost difference is:

$$\begin{aligned} Costdifference_{s2-s1} &= 2c_h(1-p_t)(1-k_u)\mu\lambda T - \left(c_t - c_e - c_{IFT}^v - \frac{c_{IFT}}{U}\right)(1-p_t)(1-k_u)\mu\lambda T + \frac{c_s}{2}TU - \frac{c_s}{2}(1-p_t)(1-k_u)\mu T \\ &= \left[2c_h + c_e + c_{IFT}^v + \frac{c_{IFT}}{U} - c_t - \frac{c_s}{2\lambda} + \frac{c_s U}{2(1-p_t)(1-k_u)\mu\lambda}\right](1-p_t)(1-k_u)\mu\lambda T \end{aligned} \tag{A.33}$$

$[2c_h + c_e + c_{IFT}^v + c_{IFT}/U - c_t - c_s/2\lambda + c_s U/2(1-p_t)(1-k_u)\mu\lambda](1-p_t)(1-k_u)\mu\lambda T < 0$, which leads to $c_t > c_{IFT}^v + c_{IFT}/U + c_e + 2c_h + c_s U/2(1-p_t)(1-k_u)\mu\lambda - c_s/2\lambda$.

This completes the proof. □

**Proof of Theorem 2.** If Eq. (6) is smaller than zero, there is a saving in emission of scenario 2 compared with scenario 1.

If the capacity of IFT is enough for the demand, $U \geq (1-p_t)(1-k_u)\mu\lambda t_{0,sceience}^{emission^*}$. Substituting $t_{0,sceience}^{emission^*} = T$, we get $(1-p_t)(1-k_u)\mu\lambda T \leq U$. In this case, the difference of emission is:

$$\begin{aligned} Emissiondifference_{s2-s1} &= 2f_e v_h(1-p_t)(1-k_u)\mu\lambda T - f_d v_t(d_t - d_e)(1-p_t)(1-k_u)\mu\lambda T + f_d v_{IFT} d_{IFT} \\ &= f_d v_{IFT} d_{IFT} - [f_d v_t(d_t - d_e) - 2f_e v_h](1-p_t)(1-k_u)\mu\lambda T < 0 \end{aligned} \tag{A.34}$$

Again, when we compare the minimum emission of two scenarios, the condition of $[f_d v_t(d_t - d_e) - 2f_e v_h](1-p_t)(1-k_u)\mu\lambda T > f_d v_{IFT} d_{IFT}$ guarantees that there is a saving in emission of container consolidation compared with only-trucking. The condition can be re-written as $f_d v_t d_t > f_d v_{IFT} d_{IFT}/(1-p_t)(1-k_u)\mu\lambda T + f_d v_t d_e + 2f_e v_h$.

If the IFT capacity is smaller than the demand, $(1-p_t)(1-k_u)\mu\lambda T > U$. In this case, the difference of emission is:

$$\begin{aligned} Emissiondifference_{s2-s1} &= 2f_e v_h(1-p_t)(1-k_u)\mu\lambda T - f_d\left[v_t(d_t - d_e) - \frac{v_{IFT} d_{IFT}}{U}\right](1-p_t)(1-k_u)\mu\lambda T \\ &= \left(\frac{f_d v_{IFT} d_{IFT}}{U} + f_d v_t d_e + 2f_e v_h - f_d v_t d_t\right)(1-p_t)(1-k_u)\mu\lambda T < 0 \end{aligned} \tag{A.35}$$

Since $\mu\lambda T$ is a positive value and $(1-p_t)(1-k_u)\mu\lambda T > U$ guarantees that $p_t \neq 1$ and $k_u \neq 1$, the condition of $f_d v_t d_t > f_d v_{IFT} d_{IFT}/U + f_d v_t d_e + 2f_e v_h$ is necessary such that scenario 2 has a saving in emission compared with scenario 1.

This complete the proof. □

**Proof of Theorem 3.** If the IFT capacity is enough for the demand within both scenario 2 and 3 (i.e., $U \geq \sqrt{2c_{IFT}(1-p_t)(1-k_u)\mu\lambda/c_s}$), which implies that, for both scenario 2 and 3, we can keep the optimum $t_0^*$, the difference between minimum total cost of scenario 3 and scenario 2 is as Eq. (A.36). When it is less than zero, there is a saving within scenario 3.

$$\begin{aligned} &Cost\ \ difference_{s3-s2} \\ &= 2c_h(1-2p_o)(1-p_t)(1-k_u)\mu\lambda T - \left[c_t - (c_e + c_{IFT}^v)(1-p_o) - c_{tr}\frac{p_o pl_c L_c}{pl_{tr}}\right](1-p_t)(1-k_u)\mu\lambda T + T \\ &\sqrt{2c_{IFT}c_s(1-p_o)(1-p_t)(1-k_u)\mu\lambda} - \frac{c_s}{2}(1-p_o)(1-p_t)(1-k_u)\mu T + c_{sp} \\ &T\frac{pl_{tr}}{2} - \left[2c_h(1-p_t)(1-k_u)\mu\lambda T - (c_t - c_e - c_{IFT}^v)(1-p_t)(1-k_u)\mu\lambda T + T\sqrt{2c_{IFT}c_s(1-p_t)(1-k_u)\mu\lambda} - \frac{c_s}{2}\right. \\ &\left.(1-p_t)(1-k_u)\mu T\lambda\right] \\ &= -4c_h p_o(1-p_t)(1-k_u)\mu\lambda T - (c_e + c_{IFT}^v)p_o(1-p_t)(1-k_u)\mu\lambda T + c_{tr}\frac{pl_c L_c}{pl_{tr}}p_o(1-p_t)(1-k_u)\mu\lambda T + \frac{c_s}{2\lambda}p_o \\ &(1-p_t)(1-k_u)\mu\lambda T + T\sqrt{2c_{IFT}c_s(1-p_t)(1-k_u)\mu\lambda}(\sqrt{1-p_o} - 1) + c_{sp}T\frac{pl_{tr}}{2} \\ &= \left(c_{tr}\frac{pl_c L_c}{pl_{tr}} + \frac{c_s}{2\lambda} - c_e - c_{IFT}^v - 4c_h\right)p_o(1-p_t)(1-k_u)\mu\lambda T - T(1-\sqrt{1-p_o})\sqrt{2c_{IFT}c_s(1-p_t)(1-k_u)\mu\lambda} + c_{sp}T\frac{pl_{tr}}{2} < 0 \end{aligned} \tag{A.36}$$

$T$ is always a positive value. Thus, $(c_{tr}pl_c L_c/pl_{tr} + c_s/2\lambda - c_e - c_{IFT}^v - 4c_h)p_o(1-p_t)(1-k_u)\mu\lambda - (1-\sqrt{1-p_o})\sqrt{2c_{IFT}c_s(1-p_t)(1-k_u)\mu\lambda} + c_{sp}pl_{tr}/2 < 0$, which is re-written as:

$$\begin{aligned} &(1-\sqrt{1-p_o})\sqrt{2c_{IFT}c_s(1-p_t)(1-k_u)\mu\lambda} + (c_e + c_{IFT}^v + 4c_h - c_s/2\lambda)p_o(1-p_t)(1-k_u)\mu\lambda > c_{tr}pl_r L_c p_o \\ &\qquad (1-p_t)(1-k_u)\mu\lambda/pl_{tr} + c_{sp}pl_{tr}/2 \end{aligned} \tag{A.37}$$

Furthermore, if the IFT capacity is smaller than the demand within both scenario 2 and 3 (i.e., $U < \sqrt{2c_{IFT}(1-p_o)(1-p_t)(1-k_u)\mu\lambda/c_s}$), which implies that the optimum $t_0^*$ cannot be taken for both scenario 2 and 3 (i.e., $t_0$ needs to be reduced for both scenarios), the difference between minimum total cost of scenario 3 and scenario 2 is as Eq. (A.38).

$$\begin{aligned}
&Cost\ \ difference_{s3-s2}\\
&= 2c_h(1-2p_o)(1-p_t)(1-k_u)\mu\lambda T - \left[c_t - \left(c_e + c_{IFT}^v + \frac{c_{IFT}}{U}\right)(1-p_o) - \frac{c_{tr}p_o pl_c L_c}{pl_{tr}}\right](1-p_t)(1-k_u)\mu\lambda T + \frac{c_s}{2}TU - \frac{c_s}{2}\\
&\quad (1-p_o)(1-p_t)(1-k_u)\mu T + \frac{c_{sp}Tpl_{tr}}{2} - \left[2c_h(1-p_t)(1-k_u)\mu\lambda T - \left(c_t - c_e - c_{IFT}^v - \frac{c_{IFT}}{U}\right)(1-p_t)(1-k_u)\right.\\
&\quad \left.\mu\lambda T + \frac{c_s}{2}TU - \frac{c_s}{2}(1-p_t)(1-k_u)\mu T\right]\\
&= -4c_h p_o(1-p_t)(1-k_u)\mu\lambda T - \left(c_e + c_{IFT}^v + \frac{c_{IFT}}{U}\right)p_o(1-p_t)(1-k_u)\mu\lambda T + c_{tr}\frac{pl_c L_c}{pl_{tr}}p_o(1-p_t)(1-k_u)\mu\lambda T + \frac{c_s}{2\lambda}p_o\\
&\quad (1-p_t)(1-k_u)\mu\lambda T + \frac{c_{sp}Tpl_{tr}}{2} = \left(c_{tr}\frac{pl_c L_c}{pl_{tr}} + \frac{c_s}{2\lambda} - \frac{c_{IFT}}{U} - c_{IFT}^v - c_e - 4c_h\right)p_o(1-p_t)(1-k_u)\mu\lambda T + \frac{c_{sp}Tpl_{tr}}{2}
\end{aligned} \tag{A.38}$$

$T$ is always a positive value. Thus, there is saving in cost of scenario 3 compared with scenario 2, if $(c_{tr}pl_c L_c/pl_{tr} + c_s/2\lambda - c_{IFT}/U - c_{IFT}^v - c_e - 4c_h)p_o(1-p_t)(1-k_u)\mu\lambda + c_{sp}pl_{tr}/2 < 0$, which is re-written as:

$$\frac{c_{IFT}}{U} + c_{IFT}^v + c_e + 4c_h - \frac{c_s}{2\lambda} > \frac{c_{sp}pl_{tr}}{2p_o(1-p_t)(1-k_u)\mu\lambda} + c_{tr}\frac{pl_c L_c}{pl_{tr}} \tag{A.39}$$

Additionally, if the IFT capacity is enough for the demand of scenario 3, but it is smaller than that of scenario 2 (i.e., $\sqrt{2c_{IFT}((1-p_t)(1-k_u)\mu\lambda/c_s} > U \geq \sqrt{2c_{IFT}(1-p_o)(1-p_t)(1-k_u)\mu\lambda/c_s}$), this implies that the optimum $t_0^*$ can be taken for scenario 3; however, $t_0$ of scenario 2 needs to be reduced, and thus the difference between minimum total cost of scenario 3 and scenario 2 is as Eq. (A.40). When Eq. (A.40) is less than zero, there is a saving within scenario 3.

$$\begin{aligned}
&Cost\ \ difference_{s3-s2}\\
&= 2c_h(1-2p_o)(1-p_t)(1-k_u)\mu\lambda T - \left[c_t - (c_e + c_{IFT}^v)(1-p_o) - c_{tr}\frac{p_o pl_c L_c}{pl_{tr}}\right](1-p_t)(1-k_u)\mu\lambda T + T\\
&\quad \sqrt{2c_{IFT}c_s(1-p_o)(1-p_t)(1-k_u)\mu\lambda} - \frac{c_s}{2}(1-p_o)(1-p_t)(1-k_u)\mu T + c_{sp}\\
&\quad T\frac{pl_{tr}}{2} - \left[2c_h(1-p_t)(1-k_u)\mu\lambda T - \left(c_t - c_e - c_{IFT}^v - \frac{c_{IFT}}{U}\right)(1-p_t)(1-k_u)\mu\lambda T + \frac{c_s}{2}TU - \frac{c_s}{2}(1-p_t)(1-k_u)\mu T\right]\\
&= -4c_h p_o(1-p_t)(1-k_u)\mu\lambda T - (c_e + c_{IFT}^v)p_o(1-p_t)(1-k_u)\mu\lambda T + c_{tr}\frac{pl_c L_c}{pl_{tr}}p_o(1-p_t)(1-k_u)\mu\lambda T + T\\
&\quad \sqrt{2c_{IFT}c_s(1-p_o)(1-p_t)(1-k_u)\mu\lambda} - \frac{c_{IFT}}{Up_o}p_o(1-p_t)(1-k_u)\mu\lambda T - \frac{c_s}{2}TU + \frac{c_s}{2\lambda}p_o(1-p_t)(1-k_u)\mu\lambda T + \frac{c_{sp}Tpl_{tr}}{2}\\
&= \left(c_{tr}\frac{pl_c L_c}{pl_{tr}} + \frac{c_s}{2\lambda} - \frac{c_{IFT}}{Up_o} - c_{IFT}^v - c_e - 4c_h\right)p_o(1-p_t)(1-k_u)\mu\lambda T + T\sqrt{2c_{IFT}c_s(1-p_o)(1-p_t)(1-k_u)\mu\lambda} - \frac{c_s}{2}T\\
&\quad U + \frac{c_{sp}Tpl_{tr}}{2} < 0
\end{aligned} \tag{A.40}$$

Since $T > 0$, Eq. (A.40) can be re-written as $(c_{IFT}/Up_o + c_{IFT}^v + c_e + 4c_h - c_s/2\lambda)$ $p_o(1-p_t)(1-k_u)\mu\lambda - \sqrt{2c_{IFT}c_s(1-p_o)(1-p_t)(1-k_u)\mu\lambda} + c_s U/2 > c_{tr}pl_c L_c p_o(1-p_t)(1-k_u)\mu\lambda/pl_{tr} + c_{sp}pl_{tr}/2$.

This completes the proof. □

**Proof of Theorem 4.** If the IFT capacity is enough for the demand within both scenario 2 and 3, (i.e., $U \geq (1-p_t)(1-k_u)\mu\lambda T$), the difference of the minimum $CO_2$ emission between scenario 3 and scenario 2 in terms of emission is formulated as follows.

$$\begin{aligned}
&Emission\ \ difference_{s3-s2}\\
&= 2f_e v_h(1-2p_o)(1-p_t)(1-k_u)\mu\lambda T - f_d\left[v_t d_t - v_t d_e(1-p_o) - v_{tr}d_t p_o\frac{pl_c L_c}{pl_{tr}}\right](1-p_t)(1-k_u)\mu\lambda T + f_d v_{IFT}\\
&\quad d_{IFT} - [2f_e v_h(1-p_t)(1-k_u)\mu\lambda T - f_d v_t(d_t - d_e)(1-p_t)(1-k_u)\mu\lambda T + f_d v_{IFT}d_{IFT}]\\
&= -4f_e v_h p_o(1-p_t)(1-k_u)\mu\lambda T + f_d\left(v_{tr}d_t\frac{pl_c L_c}{pl_{tr}} - v_t d_e\right)p_o(1-p_t)(1-k_u)\mu\lambda T\\
&= \left(f_d v_{tr}d_t\frac{pl_c L_c}{pl_{tr}} - f_d v_t d_e - 4f_e v_h\right)p_o(1-p_t)(1-k_u)\mu\lambda T < 0
\end{aligned} \tag{A.41}$$

$f_d v_{tr}d_t pl_c L_c/pl_{tr} < 4f_e v_h + f_d v_t d_e$, $p_o \neq 0$, $p_t \neq 1$ and $k_u \neq 1$ are the necessary conditions for the statement that combined container/cargo consolidation has lower emission than container consolidation.

Furthermore, if the IFT capacity is smaller than the demand within both scenario 2 and 3 (i.e., $U < (1-p_o)(1-p_t)(1-k_u)\mu\lambda T$), the difference of the minimum $CO_2$ emission between scenario 3 and scenario 2 in terms of emission is formulated as follows.

$$
\begin{aligned}
&\mathit{Emission\ \ difference}_{s3-s2}\\
&= 2f_e v_h(1-2p_o)(1-p_t)(1-k_u)\mu\lambda T - f_d\left[v_t d_t - \left(v_t d_e + \frac{v_{IFT}d_{IFT}}{U}\right)(1-p_o) - v_{tr}d_t p_o\frac{pl_c L_c}{pl_{tr}}\right](1-p_t)(1-k_u)\mu\lambda T - \Bigg[\\
&\quad 2f_e v_h(1-p_t)(1-k_u)\mu\lambda T - f_d\left(v_t d_t - v_t d_e - \frac{v_{IFT}d_{IFT}}{U}\right)(1-p_t)(1-k_u)\mu\lambda T\Bigg]\\
&= -4f_e v_h p_o(1-p_t)(1-k_u)\mu\lambda T + f_d\left(v_{tr}d_t\frac{pl_c L_c}{pl_{tr}} - v_t d_e - \frac{v_{IFT}d_{IFT}}{U}\right)p_o(1-p_t)(1-k_u)\mu\lambda T\\
&= \left(f_d v_{tr}d_t\frac{pl_c L_c}{pl_{tr}} - f_d v_t d_e - \frac{f_d v_{IFT}d_{IFT}}{U} - 4f_e v_h\right)p_o(1-p_t)(1-k_u)\mu\lambda T < 0
\end{aligned}
\tag{A.42}
$$

$U < (1-p_o)(1-p_t)(1-k_u)\mu\lambda T$ guarantees that $p_t \neq 1$ and $k_u \neq 1$. Then the above inequality can be re-written as $f_d v_{tr} d_t pl_c L_c / pl_{tr} < f_d v_{IFT} d_{IFT}/U + f_d v_t d_e + 4f_e v_h$, and $p_o \neq 0$ are the necessary conditions for the statement that combined container/cargo consolidation has lower emission than container consolidation.

Additionally, if the capacity of IFT is smaller than the demand within scenario 2, but it is larger than or is equal to the demand within scenario 3 (i.e., $(1-p_t)(1-k_u)\mu\lambda T > U \geq (1-p_o)(1-p_t)(1-k_u)\mu\lambda T$), the difference of the minimum $CO_2$ emission between scenario 3 and scenario 2 in terms of emission is formulated as follows.

$$
\begin{aligned}
&\mathit{Emission\ \ difference}_{s3-s2}\\
&= 2f_e v_h(1-2p_o)(1-p_t)(1-k_u)\mu\lambda T - f_d\left[v_t d_t - v_t d_e(1-p_o) - v_{tr}d_t p_o\frac{pl_c L_c}{pl_{tr}}\right](1-p_t)(1-k_u)\mu\lambda T + f_d v_{IFT}\\
&\quad d_{IFT} - \left[2f_e v_h(1-p_t)(1-k_u)\mu\lambda T - f_d\left(v_t d_t - v_t d_e - \frac{v_{IFT}d_{IFT}}{U}\right)(1-p_t)(1-k_u)\mu\lambda T\right]\\
&= -4f_e v_h p_o(1-p_t)(1-k_u)\mu\lambda T + f_d\left[v_{tr}d_t\frac{pl_c L_c}{pl_{tr}} - v_t d_e - \frac{v_{IFT}d_{IFT}}{p_o U} + \frac{v_{IFT}d_{IFT}}{p_o(1-p_t)(1-k_u)\mu\lambda T}\right]p_o(1-p_t)(1-k_u)\mu\lambda T\\
&= \left[f_d v_{tr}d_t\frac{pl_c L_c}{pl_{tr}} - f_d v_t d_e - \frac{f_d v_{IFT}d_{IFT}}{Up_o} + \frac{f_d v_{IFT}d_{IFT}}{p_o(1-p_t)(1-k_u)\mu\lambda T} - 4f_e v_h\right]p_o(1-p_t)(1-k_u)\mu\lambda T < 0
\end{aligned}
\tag{A.43}
$$

Since $(1-p_t)(1-k_u)\mu\lambda T > U$ guarantees that $p_t \neq 1$ and $k_u \neq 1, f_d v_{tr} d_t pl_c L_c/pl_{tr} < f_d v_{IFT} d_{IFT}/Up_o - f_d v_{IFT} d_{IFT}/p_o(1-p_t)(1-k_u)\mu\lambda T + f_d v_t d_e + 4f_e v_h$ and $p_o \neq 0$ are the necessary conditions for the statement that combined container/cargo consolidation has lower emission than container consolidation.

This complete the proof. □

## Appendix B. Parameter setting for numerical case study

In this case study. The relevant parameters are set in Table B.1.

**Table B.1**
Parameters used in the case study.

| Parameter | | Value | Unit | Reference |
|---|---|---|---|---|
| Arrival rate of container batches | | 0.0685 | per hour | – |
| Number of containers in a batch | | 75 – 85 | container | – |
| Planning horizon | | 168 | hour | – |
| Transit time of truck | Rotterdam – Tilburg | 1.4–1.8 | hour | – |
| | Rotterdam – Duisburg | 2.7–3.5 | | |
| | Rotterdam – Frankfurt | 5.5–7.4 | | |
| | Rotterdam – Basel | 8.5–11.5 | | |
| Transit time of IFT | Rotterdam – Tilburg | 7–9 | hour | Navigate (n.d.) |
| | Rotterdam – Duisburg | 22–26 | | |
| | Rotterdam – Frankfurt | 45–51 | | |
| | Rotterdam – Basel | 90–102 | | |
| Transit time of end-haulage | | 0.8–1.2 | hour | – |
| Container terminal handling time | | 0.05–0.07 | hour/container | Evers and de Feijter (2004) |
| Shuttle time (from deep sea terminal to Cool Port terminal) | | 1.5–2 | hour | Visser et al. (2007) |

(continued on next page)

**Table B.1** (*continued*)

| Parameter | | Value | Unit | Reference |
|---|---|---|---|---|
| Cargo consolidation time (at cross-docking facility in the port or in the hinterland) | | 5.3–5.5 | hour/container | Burdzik et al. (2014) |
| Unit shipment cost by truck | Rotterdam – Tilburg | 200 | €/container | Evers and de Feijter (2004) |
| | Rotterdam – Duisburg | 400 | | |
| | Rotterdam – Frankfurt | 700 | | |
| | Rotterdam – Basel | 1100 | | |
| Fixed barge cost (administration fee of shipment arrangement) | | 2000 | €/cycle | Wiegmans and Konings (2015) |
| Variable barge cost | Rotterdam – Tilburg | 80 | €/container | Van Riessen (2013) |
| | Rotterdam – Duisburg | 120 | | |
| | Rotterdam – Frankfurt | 200 | | |
| | Rotterdam – Basel | 300 | | |
| Unit end-haulage cost | | 60 | €/container | Wiegmans and Konings (2015) |
| Unit container handling cost | | 50 | €/container | Wiegmans and Behdani (2018), Wiegmans and Konings (2015) |
| Unit container storage cost | | 0.94 | €/container/hour | Terminal storage charge (n.d.) |
| Unit pallet storage cost | | 0.1 | €/pallet/hour | Kloosterboer (2016) |
| Unit shuttle cost | | 12.75 | €/container | Adjust based on Konings (2009) |
| Unit cargo consolidation cost | | 16.8 | €/pallet | Kloosterboer (2016) |
| Unit fuel cost | | 1.31 | €/litre | Fuel price in Europe (n.d.) |
| Shipment distance by truck | Rotterdam – Tilburg | 115 | km | – |
| | Rotterdam – Duisburg | 220 | | |
| | Rotterdam – Frankfurt | 450 | | |
| | Rotterdam – Basel | 700 | | |
| Shipment distance by IFT | Rotterdam – Tilburg | 95 | km | Boatbookings Journey Planner (n.d.) |
| | Rotterdam – Duisburg | 210 | | |
| | Rotterdam – Frankfurt | 500 | | |
| | Rotterdam – Basel | 830 | | |
| End-haulage distance | | 40 | km | Wiegmans and Konings (2015) |
| Shuttle distance | | 30 | km | Boatbookings Journey Planner (n.d.) |
| Electricity consumption rate of reefer for cooling | | 7 | kW/hour | Fitzgerald et al. (2011) |
| Fuel consumption rate of refrigerated truck for cooling | | 3 | litre/km | Tassou et al. (2009) |
| Fuel consumption rate of truck main engine | | 0.4 | litre/km | Wiegmans and Konings (2015) |
| Fuel consumption rate of barge main engine | | 8.2 | litre/km | Wiegmans and Konings (2015) |
| Fuel consumption rate of refrigerated truck main engine | | 0.4 | litre/km | – |
| Electricity consumption of container terminal handling | | 12 | kW/hour | Geerlings and van Duin (2011) |
| Fuel consumption rate of shuttle service | | 0.08 | litre/km/container | Wiegmans and Konings (2015) |
| Electricity consumption rate of a pallet during storage | | 0.08 | kW/hour/pallet | Evans (2007) |
| Fuel consumption rate of cargo consolidation | | 0.07 | litre/pallet | Engine powered forklift (n.d.) |
| Emission factor consumption of $CO_2$ emission per litre fuel | | 2.65 | kg/litre | Geerlings and van Duin (2011) |
| Emission factor consumption of $CO_2$ emission per kW electric | | 0.52 | kg/kW | Geerlings and van Duin (2011) |
| Urgency factor | | 30 | % | – |
| Share of non-urgent containers shipped by truck | | 20 | % | – |
| Opening factor of non-urgent container | | 70 | % | – |
| Convert factor from electricity to fuel | | 0.26 | – | – |
| Load factor | Dry containers | 80–100 | % | – |
| | Reefers | 80–100 | % | – |
| Percentage of cargo 1 | | 50 | % | – |
| Number of pallets in a 40 ft container | | 20 | pallet | Container capacity (n.d.) |
| Number of pallets in a trailer/refrigerated truck | | 26 | pallet | Palmer et al. (2018) |

## Appendix C. Sensitivity analysis of perishable cargo

See Tables C.1–C.3.

**Table C.1**
Sensitivity analysis results of total cost for perishable cargo. Red indicates the increase in total cost. Green indicates the decrease in total cost. The cell filled in "NA" indicates that the parameter is not used in certain scenarios.

| Parameter | Original value | Test value | | Total cost | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Scenario 1 | | Scenario 2 | | Scenario 3 | |
| Transit time of truck | 3.14 | 2.826 | 3.454 | −0.08% | 0.08% | −0.04% | 0.04% | −0.08% | 0.08% |
| Transit time of barge | 24 | 21.6 | 26.4 | NA | | −0.29% | 0.34% | −0.11% | 0.14% |
| Transit time of end-haulage | 1 | 0.9 | 1.1 | | | −0.01% | 0.01% | 0.00% | 0.00% |
| Container terminal handling time | 0.0625 | 0.0563 | 0.0688 | 0.00% | 0.00% | −0.12% | 0.12% | −0.09% | 0.09% |
| Shuttle time | 1.75 | 1.575 | 1.925 | 0.00% | 0.00% | 0.00% | 0.00% | −0.01% | 0.01% |
| Cargo consolidation time | 5.4 | 4.86 | 5.94 | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Unit shipment cost by truck | 400 | 360 | 440 | −4.11% | 4.11% | −2.13% | 2.13% | −2.02% | 2.07% |
| Fixed barge cost | 2000 | 1800 | 2200 | NA | | −0.09% | 0.09% | −0.05% | 0.05% |
| Variable barge cost | 120 | 108 | 132 | | | −0.61% | 0.61% | −0.20% | 0.20% |
| Unit end-haulage cost | 60 | 54 | 66 | | | −0.30% | 0.30% | −0.10% | 0.10% |
| Unit shipment cost of refrigerated truck | 400 | 360 | 440 | | | NA | | −1.22% | 1.22% |
| Unit reefer handling cost | 50 | 45 | 55 | −2.57% | 2.57% | −3.10% | 3.10% | −2.53% | 2.53% |
| Unit reefer storage cost | 0.94 | 0.846 | 1.034 | NA | | −0.15% | 0.15% | −0.08% | 0.08% |
| Unit pallet storage cost | 0.1 | 0.09 | 0.11 | 0.00% | 0.00% | 0.00% | 0.00% | −0.01% | 0.01% |
| Unit reefer delay penalty | 2 | 1.8 | 2.2 | NA | | 0.00% | 0.00% | −0.03% | −0.03% |
| Unit shuttle cost | 12.75 | 11.475 | 14.025 | −0.13% | 0.13% | −0.13% | 0.13% | −0.14% | 0.14% |
| Unit cargo consolidation cost | 16.8 | 15.12 | 18.48 | −3.11% | 3.11% | −3.14% | 3.14% | −3.40% | 3.40% |
| Unit fuel cost | 1.31 | 1.179 | 1.441 | −0.08% | 0.08% | −0.34% | 0.34% | −0.17% | 0.17% |
| Shipment distance by truck | 220 | 198 | 242 | −4.11% | 4.11% | −2.13% | 2.13% | −2.02% | 2.07% |
| Shipment distance by barge | 210 | 189 | 231 | NA | | −0.61% | 0.61% | −0.20% | 0.20% |
| End-haulage distance | 40 | 36 | 44 | | | −0.30% | 0.30% | −0.10% | 0.10% |
| Shuttle distance | 30 | 27 | 33 | −0.13% | 0.13% | −0.13% | 0.13% | −0.14% | 0.14% |
| Electricity consumption rate of reefer for cooling | 7 | 6.3 | 7.7 | −0.08% | 0.08% | −0.34% | 0.34% | −0.14% | 0.14% |
| Fuel consumption rate of refrigerated truck for cooling | 3 | 2.7 | 3.3 | NA | | NA | | −0.04% | 0.04% |
| Urgent reefer factor | 0.3 | 0.27 | 0.33 | | | −0.08% | 0.08% | −0.42% | 0.42% |
| Opening factor of non-urgent reefer | 0.7 | 0.63 | 0.77 | | | NA | | 0.90% | −0.97% |
| Number of pallets in a reefer container | 20 | 18 | 22 | −3.11% | 3.11% | −3.14% | 3.14% | −4.65% | 4.65% |
| Number of pallets in a refrigerated truck | 26 | 23.4 | 28.6 | NA | | NA | | 1.63% | −1.29% |
| Convert factor from electricity to fuel | 0.26 | 0.234 | 0.286 | −0.08% | 0.08% | −0.34% | 0.34% | −0.14% | 0.14% |
| Load factor | 0.9 | 0.81 | 0.99 | −3.11% | 3.11% | −3.14% | 3.14% | −4.65% | 4.65% |
| Share of the non-urgent container shipped by truck | 0.2 | 0.18 | 0.22 | NA | | −0.05% | 0.05% | −0.24% | 0.24% |

**Table C.2**
Sensitivity analysis results of total emission for perishable cargo.

| Parameter | Original value | Test value | | Total emission | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Scenario 1 | | Scenario 2 | | Scenario 3 | |
| Transit time of truck | 3.14 | 2.826 | 3.454 | −0.52% | 0.52% | −0.24% | 0.24% | −0.50% | 0.50% |
| Transit time of barge | 24 | 21.6 | 26.4 | NA | | −1.72% | 1.72% | −0.58% | 0.58% |
| Transit time of end-haulage | 1 | 0.9 | 1.1 | | | −0.07% | 0.07% | −0.02% | 0.02% |
| Container terminal handling time | 0.0625 | 0.0563 | 0.0688 | 0.00% | 0.00% | −1.04% | 1.03% | −0.30% | 0.29% |
| Shuttle time | 1.75 | 1.575 | 1.925 | 0.00% | 0.00% | 0.00% | 0.00% | 0.01% | −0.01% |
| Cargo consolidation time | 5.4 | 4.86 | 5.94 | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| Shipment distance by truck | 220 | 198 | 242 | −8.06% | 8.06% | −3.63% | 3.63% | −6.15% | 6.15% |
| Shipment distance by barge | 210 | 189 | 231 | NA | | −0.75% | 0.75% | −0.51% | 0.51% |
| End-haulage distance | 40 | 36 | 44 | | | −0.63% | 0.63% | −0.21% | 0.21% |
| Shuttle distance | 30 | 27 | 33 | −0.22% | 0.22% | −0.19% | 0.19% | −0.22% | 0.22% |
| Electricity consumption rate of reefer for cooling | 7 | 6.3 | 7.7 | −0.52% | 0.52% | −3.55% | 3.55% | −1.55% | 1.55% |
| Fuel consumption rate of refrigerated truck for cooling | 3 | 2.7 | 3.3 | NA | | NA | | −0.26% | 0.26% |
| Fuel consumption rate of truck main engine | 0.4 | 0.36 | 0.44 | −8.06% | 8.06% | −4.26% | 4.26% | −3.93% | 3.93% |
| Fuel consumption rate of barge main engine | 8.2 | 7.38 | 9.02 | NA | | −0.75% | 0.75% | −0.51% | 0.51% |
| Fuel consumption rate of refrigerated truck main engine | 0.4 | 0.36 | 0.44 | | | NA | | −2.43% | 2.43% |
| Electricity consumption of reefer terminal handling | 12 | 10.8 | 13.2 | −1.08% | 1.08% | −1.13% | 1.13% | −0.97% | 0.97% |
| Fuel consumption of shuttle service | 0.08 | 0.072 | 0.088 | −0.22% | 0.22% | −0.19% | 0.19% | −0.22% | 0.22% |
| Electricity consumption rate of a pallet during storage | 0.08 | 0.072 | 0.088 | 0.00% | 0.00% | 0.00% | 0.00% | −0.01% | 0.01% |
| Fuel consumption rate of cargo consolidation | 0.07 | 0.063 | 0.077 | −0.12% | 0.12% | −0.10% | 0.10% | −0.12% | 0.12% |
| Emission factor consumption of $CO_2$ emission per liter fuel | 2.65 | 2.385 | 2.915 | −8.92% | 8.92% | −7.33% | 7.33% | −8.32% | 8.32% |
| Emission factor consumption of $CO_2$ emission per kW electric | 0.52 | 0.468 | 0.572 | −1.08% | 1.08% | −2.67% | 2.67% | −1.68% | 1.68% |
| Urgent reefer factor | 0.3 | 0.27 | 0.33 | NA | | 0.19% | −0.19% | −0.22% | 0.22% |
| Opening factor of non-urgent reefer | 0.7 | 0.63 | 0.77 | | | NA | | 1.61% | −1.64% |
| Number of pallets in a reefer container | 20 | 18 | 22 | −0.12% | 0.12% | −0.10% | 0.10% | −2.80% | 2.80% |
| Number of pallets in a refrigerated truck | 26 | 23.4 | 28.6 | NA | | NA | | 3.50% | −2.77% |
| Convert factor from electricity to fuel | 0.26 | 0.234 | 0.286 | −0.52% | 0.52% | −2.02% | 2.02% | −0.85% | 0.85% |
| Load factor | 0.9 | 0.81 | 0.99 | −0.12% | 0.12% | −0.10% | 0.10% | −0.12% | 0.12% |
| Share of the non-urgent container shipped by truck | 0.2 | 0.18 | 0.22 | NA | | 0.11% | −0.11% | −0.13% | 0.13% |

**Table C.3**
Sensitivity analysis results of product shelf life for perishable cargo.

| Parameter | Original value | Test value | | Shelf life product 1 | | | | | | Shelf life product 2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Scenario 1 | | Scenario 2 | | Scenario 3 | | Scenario 1 | | Scenario 2 | | Scenario 3 | |
| Transit time of truck | 3.14 | 2.826 | 3.454 | 0.20% | –0.20% | 0.12% | –0.12% | 0.18% | –0.18% | 0.14% | –0.14% | 0.08% | –0.08% | 0.12% | –0.12% |
| Transit time of barge | 24 | 21.6 | 26.4 | NA | | 0.85% | –0.85% | 0.23% | –0.23% | NA | | 0.56% | –0.56% | 0.16% | –0.16% |
| Transit time of end-haulage | 1 | 0.9 | 1.1 | | | 0.04% | –0.04% | 0.01% | –0.01% | | | 0.02% | –0.02% | 0.01% | –0.01% |
| Container terminal handling time | 0.0625 | 0.0563 | 0.0688 | 0.02% | –0.02% | 0.61% | –0.60% | 0.18% | –0.18% | 0.01% | –0.01% | 0.40% | –0.40% | 0.12% | –0.12% |
| Shuttle time | 1.75 | 1.575 | 1.925 | 0.11% | –0.11% | 0.12% | –0.12% | 0.11% | –0.11% | 0.08% | –0.08% | 0.08% | –0.08% | 0.08% | –0.08% |
| Cargo consolidation time | 5.4 | 4.86 | 5.94 | 0.34% | –0.34% | 0.39% | –0.39% | 0.36% | –0.36% | 0.24% | –0.24% | 0.26% | –0.26% | 0.24% | –0.24% |
| Urgent reefer factor | 0.3 | 0.27 | 0.33 | NA | | –0.63% | 0.63% | –0.17% | 0.17% | NA | | –0.41% | 0.41% | –0.12% | 0.12% |
| Opening factor of non-urgent reefer | 0.7 | 0.63 | 0.77 | | | NA | | –0.94% | 0.94% | | | NA | | –0.63% | 0.63% |
| Share of the non-urgent container shipped by truck | 0.2 | 0.18 | 0.22 | | | –0.37% | 0.37% | –0.10% | 0.10% | | | –0.24% | 0.24% | –0.07% | 0.07% |

## Appendix D. Efficient frontier

See Figs. D.1–D.3.

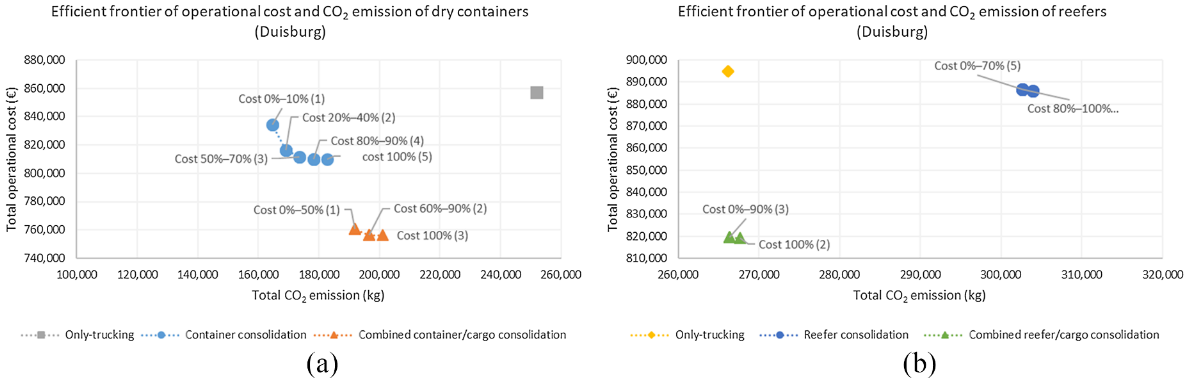



**Fig. D1.** Efficient frontier of Duisburg: efficient frontier of dry containers (a) and reefers (b).

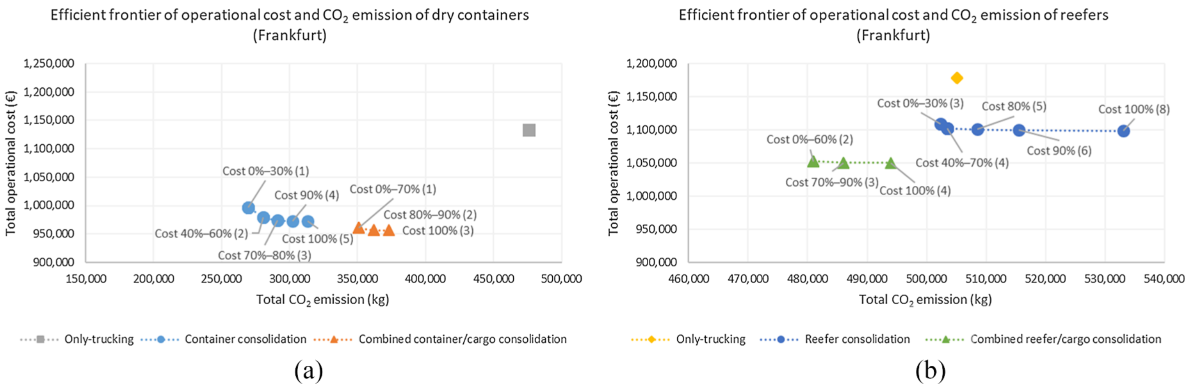
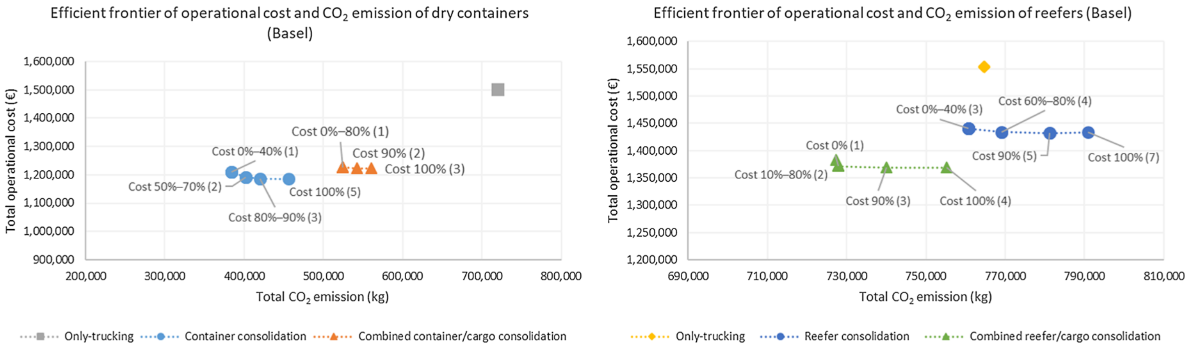



**Fig. D2.** Efficient frontier of Frankfurt: efficient frontier of dry containers (a) and reefers (b).




(a) (b)

**Fig. D3.** Efficient frontier of Basel: efficient frontier of dry containers (a) and reefers (b).

## Appendix E. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tre.2019.08.011.

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