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Identifying the market areas of port-centric logistics and hinterland intermodal transportation

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Abstract: Many port authorities have developed ambitious strategies to foster hinterland intermodal transportation. In addition, port-centric logistics, that is, the provision of distribution facilities and value-adding activities in the port area, has expanded in multiple ports. Obviously, such port-centric logistics may impact the operations in the hinterland substantially and could potentially reduce opportunities for intermodal transport in the hinterland. We analyze the interaction between port-centric logistics and hinterland intermodal transportation. We take a logistics service provider's perspective and we include some key elements in the model, such as detention fees, extra handling, transport efficiency and empty container repositioning. We develop new analytical results identifying the optimal market areas of truck-only transportation, port-centric logistics and hinterland intermodal transportation. Our results show that tension between port-centric logistics and hinterland intermodal transportation is quite likely to happen in practice. We additionally study the use of continental containers as a way to reconcile port-centric logistics and hinterland intermodal transportation and we derive further results. We illustrate our results via an example and we highlight managerial insights.

Keywords: logistics, hinterland intermodal transportation, port-centric operations, market area theory.

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1 Introduction

Maritime containers have become the backbone of globalization by providing an entirely standardized transportation system to connect nonadjacent economic areas, so that container-based trade now represents more than half of the value of all seaborne trade (UNCTAD, 2015). The vast majority of the distance covered by a maritime container during its journey occurs at sea. However, the costs related to maritime shipping have drastically decreased for three main reasons. First, the ships built in 2012–2015 are on average 2.8 times larger than the ones built 20 years earlier (UNCTAD, 2016). This enables economies of scale and energy efficiency. Second, alliances (see e.g., Slack, Comtois, & McCalla, 2002; Song & Panayides, 2002; Agarwal & Ergun, 2010) and advances in network design (see e.g., Meng, Wang, Andersson, & Thun, 2013; Zheng, Meng, & Sun, 2015; Tran & Haasis, 2015) have increased the efficiency of shipping. Third, bunker costs have been significantly decreased by applying slow-steaming (Finnsgård, Kalantari, Roso, & Woxenius, 2019), but also as a result of lower oil prices during the past few years. Consequently, the costs of inland-related activities often exceed the costs of maritime transportation nowadays. For instance, Notteboom and Rodrigue (2005) state that the proportion of inland costs relative to the total transportation costs of containers ranges from 40% to 80% and with larger vessels the proportion is likely to be even higher now. We focus on the hinterland of a deep-sea port, as this is where much of the competitiveness of global supply chains currently lies.

The main advantage of containerization in the hinterland is the ability for containers to be easily transshipped from one transport mode to another, fostering the development of intermodal transportation. Hinterland intermodal transportation (HIT) reduces congestion and accidents in the surroundings of deep-sea ports and is recognized for its superior environmental performance (Roso, 2007; Dekker, Bloemhof, & Mallidis, 2012; Craig, Blanco, & Sheffi, 2013; Bouchery & Fransoo, 2015). HIT also leads to an increase in competition between ports from the same region (van Klink & van den Berg, 1998; Fan et al., 2015; Vermeiren & Macharis, 2016) as distant locations can be served more efficiently. The main container ports worldwide have developed ambitious strategies to foster high-capacity corridors that enable moving containers from the port to regional load centers and vice versa (van den Berg, 2015). Accordingly, HIT has dramatically affected the development of the hinterland in many regions, so that the rise of inland terminals, dry ports (Roso, Woxenius, & Lumsden, 2009), extended gates (Veenstra, Zuidwijk, & van Asperen, 2012) and intermodal hubs—referred to as the “terminalization” of the hinterland—is considered to be a new phase in port development (Rodrigue & Notteboom, 2009). (See Nguyen and Notteboom, 2019, and Witte, Wiegmans, & Ng, 2019, for recent overviews of the related literature).

Another notable trend in port development relates to the concept of port-centric logistics (PCL). PCL is defined by Mangan, Malwani, and Fynes (2008) as the provision of distribution facilities and value-adding activities in the port area. Two main types of port-centric activities can be distinguished. First, shippers can locate a full-service distribution center in the port surroundings. For instance, Heitz, Dablanc, Olsson, Sánchez-Díaz, and Woxenius (2018) identifies a trend that warehouses are increasingly located either in close proximity to the Port of Gothenburg or in cities about 100 kms from the port, whereas few new warehouses are being built in the area in between. Heitz (2019) finds a similar duality between city-center and peripheral distribution warehouse locations in the Paris metropolitan area. In PCL, the maritime container is generally

transferred from the deep-sea terminal to the distribution center directly by truck due to the short distance. Although some full-service distribution centers can be found in the immediate vicinity of a port, this represents only a small share of port-centric activities nowadays (Monios, Notteboom, Wilmsmeier, & Rodrigue, 2016). There are three main reasons for this limited presence. First, the center of gravity of the demand is often located farther away in the hinterland and locating distribution centers closer to the demand's center of gravity enables the reduction of transportation costs (see e.g. Ambrosino & Scutella, 2005, for a review of the literature on distribution network design). Second, locating distribution centers in the hinterland enables shippers to benefit from port competition and limit the risk of being anchored to a single port (Monios & Wilmsmeier, 2013). Third, shippers usually combine international and local flows in their distribution centers and PCL is not necessarily efficient for local flows if a port is not close to the center of gravity.

Hence, in this paper we focus on another type of port-centric activities. This latter includes cargo transloading to semi-trailers or continental containers and vice versa (also referred to as *stuffing and stripping*), palletization, cargo consolidation and sorting as well as light transformation and customization (such as labeling). These activities enable optimizing hinterland transportation without affecting the location of the shippers' distribution centers. This type of port-centric activity has expanded in the surroundings of various ports such as Savannah (Rodrigue, Debie, Fremont, & Gouvernal, 2010), Los Angeles/Long Beach (Rodrigue & Notteboom, 2009), Antwerp (Notteboom, 2016) and Felixstowe (Mangan et al., 2008). These activities in the port induce additional handling and associated costs. However, the advantages of PCL can be significant for the shippers. For instance, Leachman (2008) states that sorting activities in the Los Angeles/Long Beach perimeter induces a net savings to the American economy of about \$1.1 billion per year due to inventory reduction obtained from cargo rebalancing between distribution centers, based on updated information. (See Mangan et al., 2008; Pettit & Beresford, 2009; Monios & Wilmsmeier, 2012; Monios et al., 2016; and Monios, Bergqvist, & Woxenius, 2018, for further details on port-centric activities.) This article discusses only port-centric activities that do not affect the location of the shippers' distribution centers.

PCL and HIT are rarely studied jointly in the literature. Therefore, the assessment of their potential advantages and drawbacks is made in isolation. In this article, we aim at studying the relationship between these two concepts. Indeed, many port authorities worldwide are trying to develop the two concepts in synergy. For instance, the Port of Le Havre opened a new intermodal terminal in 2015 (HAROPA, 2015) while developing in parallel facilities for PCL (Bolloré, 2015). Likewise, the Port of Gothenburg opened a new intermodal terminal in 2017 while also investing considerably in warehouses in the port vicinity (Heitz et al., 2018). Still, there are indications in the academic literature of a possible tension between PCL and HIT. In Europe, for instance, when containers are unloaded in the vicinity of the port, the cargo is often transloaded into semi-trailers. Woxenius and Bergqvist (2011) observe that rail is used to move semi-trailers to a lesser extent than it is used for maritime containers. The same applies to barge transportation. As volume is a key requirement for efficient use of HIT (Bouchery & Fransoo, 2015), Monios et al. (2016) conclude that PCL may reduce the value of HIT, that is, that PCL might induce a reverse modal shift. This is in line with Monios and Wilmsmeier (2012), who state that PCL and HIT are two competing logistics concepts. To the best of our knowledge, the research that studies the relationship between PCL and HIT is mainly conceptual and there is a

need for model-based research on this topic. Such model-based strategic analyses of ocean container shipping systems have become more common over the past few years following the position paper by Fransoo and Lee (2013) but so far have not addressed the consequences of port-centric logistics.

In this article, we apply the market area theory (Erlenkotter, 1989) to identify the demand zones that would be more efficiently served by HIT or PCL. We take a logistics service provider's (LSP) perspective, as Notteboom and Rodrigue (2005) state that the development of the hinterland mainly results from logistics decisions from shippers and their contracted LSPs. Our model includes transport-related costs as well as travel time (through its related value of time) as these two criteria are among the most relevant to model shippers' decisions (Larranaga, Arellana, & Senna, 2017). We additionally study the effects of travel time reliability in Appendix B. We include some key elements in the model, such as detention fees, extra handling, transport efficiency and empty container repositioning. We analytically derive conditions for the use of direct truck (DT) shipment, PCL and HIT and we identify the market areas of these options. Our results show that the tension between PCL and HIT is quite likely to happen in practice. We derive managerial insights from the results obtained, including an analysis of how different stakeholder groups are affected. We additionally study the use of continental containers as a way to reconcile PCL and HIT, and we derive additional results.

The rest of the article is organized as follows. Section 2 highlights the related literature and helps at better positioning our contribution. The model is presented in Section 3 and the main analytical results are derived in Section 4. Section 5 aims at studying the impact of PCL on direct truck shipment and on HIT. Moreover, we analyze the use of continental containers as a way to reconcile PCL and HIT. Section 6 provides an illustrative example that allows us to obtain some additional insights. Finally, Section 7 highlights our main conclusions and some potential future research directions.

2 Literature review

In this section, we first provide a short overview of the empirical literature on shippers' preferences of transport options. Then, we present the main streams of model-based literature related to our work.

Several recent contributions aim at analyzing shippers' preferences of transport modes. We focus here on comparisons made for inland transportation where the main modes available are trucks, trains and barges. As trains and barges rarely enable reaching the shipper's location, this requires extra trucking for perhaps both pre- and post-haulage. Therefore, train and barge are generally operated as part of an intermodal solution. Most research comparing direct shipment by truck with intermodal transportation generally selects a number of relevant criteria and then conducts stated-choice experiments through surveys. Recent contributions (Nugroho, Whiteing, & de Jong, 2016; Larranaga et al., 2017; Duan, Tavasszy, & Rezaei, 2019) highlight that the key decision variables affecting modal choice are transport costs, travel time and reliability of travel time. These results are confirmed by other studies comparing inland transport options with short-sea shipping (see Brooks, Puckett, Hensher, & Sammons, 2012; López-Navarro, 2014; Chang & Thai, 2017). Among these three criteria, transport cost and travel time are well defined, while the reliability of travel time is more difficult to apprehend. Therefore, our model accounts for both transport costs and travel time. We additionally

study the effect of the reliability of travel time as an extension in Appendix B. Note that Shams, Asgari, and Jin (2017) specifically focus on this latter topic and help us better understand the value of reliability.

There are three main streams of model-based literature related to our work. First, the modal choice decision is studied from a shipper's perspective by jointly considering inventory decisions and transport mode selection. This stream of literature can be traced back to Baumol and Vinod (1970), who included transportation features in the economic order quantity model. The model they propose was then extended and refined (see e.g., Liberatore, 1979; McGinninis, 1979; Sheffi, Eskandari, & Koutsopoulos, 1988; McGinnis, 1989; Tyworth, 1991; Tyworth & Zeng, 1998). (See Meixell & Norbis, 2008 for a detailed review.) In those models, the lead time and lead-time variability that differ from one transportation option to another play a key role by affecting the inventory levels of the shippers. More recently, Dullaert and Zamparini (2013) assess the impact of lead-time variability on the traffic mode selection using simulation. They show that the consequences of lead-time variability reduction depend heavily on the demand distribution structure and on the targeted service level. This first stream of literature is very relevant and enables getting a good knowledge of the dynamics between different transportation options from a shipper's perspective. However, the models do not take the location of the shippers directly into account and, therefore, the possible tension between PCL and HIT is not easy to analyze using these models.

Second, modal choice is a key issue in the transportation literature. Modal choice is usually considered as a tactical decision in transportation models. (See SteadieSeifi, Dullaert, Nuijten, Van Woensel, & Raoufi, 2014, for a review of the operations research literature on intermodal transportation planning.) According to SteadieSeifi et al. (2014), the decisions on intermodal transportation at the tactical level relate to service network design (i.e., the planning of intermodal services, including traffic mode selection) and network flow planning (i.e., the routing of the flow in the network, and consequently the selection of the intermodal services used). (See Ypsilantis & Zuidwijk, 2013; Bouchery, Fazi, & Fransoo, 2015; Demir et al., 2016; van Riessen, Negenborn, & Dekker, 2016; Wang & Meng, 2017, and references therein for recent developments in this field.) Note that service network design and network flow planning are also studied for the maritime leg of container transportation. (For this, see Fan, Wilson, & Dahl, 2015; Rothenbächer, Drexler, & Irnich, 2016; Balakrishnan & Karsten, 2017). Network flow and service network design models generally include discrete demand, where the objective is to serve a set of consignees considered as sinks in the network. The models enable the selection of the best intermodal option for each consignee, but, as for inventory-theoretic models for traffic mode selection, the tension between PCL and HIT is generally not analyzed. Note that some models approximate the demand as continuous over a demand zone. This modeling technique can be traced back to Newell (1973) and Daganzo (1991), who strongly contributed to a widespread application. (See Langevin, Mbaraga, & Campbell, 1996, for a review of the early development in continuous demand approximation models, and Dasci & Verter, 2001, and Tsao, Mangotra, Lu, & Dong, 2012, for some more recent applications.) Note that continuous demand approximation is generally handled at the network design level, since hub location decisions are considered. In our work, we focus on tactical decisions by assuming that the terminals are already located and we aim at identifying the areas that are more efficiently served by several transportation options, including PCL and HIT. This is a much more common decision

situation than locating new terminals since intermodal terminals are significant, long-lived investments and transport demand reflects rather stable economic geography patterns. We are not aware of any article that focuses on tactical decisions for HIT with continuous demand approximation.

The third stream of literature consists of applications of the market area theory (also called spatial theory). The aim of this technique is to identify the size and topological feature of the demand zone that is optimally served by a facility. To the best of our knowledge, Erlenkotter (1989) was the first author to connect the continuous demand approximation models cited above to the market area theory. Erlenkotter (1989) also offers a review of the early work on market area theory and proposes a typology to characterize general optimal market area models. The key elements of this typology include the shape of the market, the distance norm, the facility cost function and the transport cost function. Whereas the market area theory has become standard in the facility location and hub-and-spoke network design literature (see e.g., Carlsson & Jia, 2013; Averbakh, Berman, Kalcsics, & Krass, 2015; Sedghi, Shavandi, & Abouee-Mehrizi, 2017), applications to intermodal transportation are less common. From our knowledge, Nierat (1997) presented the first application, identifying the shape and size of the market area for an intermodal terminal. Nierat (1997) showed that under the Euclidean distance norm and for strictly positive origin haulage distances (and therefore costs), the market area of an intermodal terminal is part of the family of Descartes ovals. The author also compared the theoretical results obtained to a survey about shippers' choices for a number of existing terminals. The theoretical results appeared to be consistent with shippers' decisions. This conclusion strengthened the validity of the market area theory in the context of intermodal transportation. The model developed by Nierat (1997) was then refined by Janic (2008) to assess the impact of using longer trains for intermodal transportation in Europe. Limbourg and Jourquin (2010) also propose an application to evaluate the market area of intermodal rail-road container terminals in Europe. Kim and van Wee (2011) apply the model developed by Nierat (1997) to identify the most influential factors affecting the break-even distance between truck-only and intermodal transportation by using Monte Carlo simulation. Craig et al. (2013) use the model of Nierat (1997) with carbon emissions parameters to assess the carbon-optimal market area of intermodal transportation. Finally, Saeedi, Wiegmans, Behdani, and Zuidwijk (2017) propose a four-step methodology to evaluate the European intermodal freight market. The methodology embeds the market area theory to identify the transshipment submarket of each terminal.

Our contribution is threefold. First, this article is, to our knowledge, the first model-based contribution about PCL. Instead of studying this concept in isolation, we focus on the relationship between PCL and HIT in order to assess whether these two concepts are competing for the same market. Second, by applying the market area theory, we develop new analytical results to identify the optimal market areas of truck-only transportation, PCL and HIT. We identify necessary and sufficient conditions so that HIT is not impacted by PCL and we show that those conditions do not hold very often in practice. We conclude that the competition between PCL and HIT is likely to occur. Third, we evaluate if the use of continental containers might allow for reconciling PCL and HIT. We illustrate our results with some examples and we derive additional insights.

3 Model description

We consider an LSP in charge of serving shippers (both consignees and consignors) located in the hinterland of a single deep-sea port. Our objective is to assess under which conditions different transportation options would be most favorable to deliver a given demand zone. Therefore, we express the costs and time for serving the demand zone with one unit of flow, in accordance with the market area theory. This setting enables us to derive insights into the geographic area of interest for different transportation options. Modeling transport costs as linear in the number of containers handled is also in line with current practices as the transport rates proposed to the shippers are generally expressed “per container”. We further discuss in Subsection 6.3 how volume-dependent costs would affect our results. Let H be the area of operations of the LSP under consideration. The space is orthonormal and equipped with an x-y coordinate system. The deep-sea port is located at $(0,0)$. We assume that H is continuous and delimited by a straight coastline along the y-axis. Let $i \in H$ be a location in H identified through its coordinates (x_i, y_i) . (See e.g. Wang, Meng, & Miao, 2016, for more details on how to delimit the port’s hinterland.)

The maritime flows under consideration are containerized, which means the cargo reaches and leaves the deep-sea port for the maritime leg of its transportation in maritime containers. These maritime containers have standard dimensions, with the two most common types being 20 ft. and 40 ft. containers, of which the latter is mostly used. We account for both types of containers and for both import and export flows. We consider that one unit of demand equals one forty-foot equivalent unit (FEU). We consider a merchant haulage setting, as this setting is particularly relevant for the operations of many large LSPs. Under merchant haulage, the use of maritime containers in the hinterland is subject to detention fees. Shipping lines often propose detention-free periods, so shippers or their providers are paying detention costs in case they are not able to send the container back to the shipping line before the end of the detention-free period $F \geq 0$ (expressed in days). Let us denote the detention fees by $d \geq 0$ €/day.FEU (incurred after the detention-free period). We also account for empty container movements. Let $\alpha \in [0;1]$ be the empty container movement ratio modeled as the proportion of full container movements. In the case of $\alpha = 0$, no empty movements occur. In the case of $\alpha = 1$, the movements of empty containers equal the movement of full containers. Note that α is a measure of how effectively empty containers can be repositioned. It reflects an equilibrium of the container transport system. In practice, α is quite high. For instance, Lei and Church (2011) highlight that $\alpha = 0.9$ in the hinterland of Los Angeles/Long Beach. Overall, Braekers, Janssens, & Caris (2011) estimate that $\alpha \in [0.66;1]$ in practice. (See Legros, Bouchery, & Fransoo, 2019, for more details on empty container matching in the hinterland.)

Three options are available for delivering a container from origin to destination, namely direct shipment by truck (T), the use of HIT (H) via an inland terminal and the transloading of the cargo from a maritime container into a semi-trailer and vice versa based on port-centric operations (P). We assume that the same transport option is selected for all movements from and to a given demand zone. In what follows, we model the total costs for each transport option. These total costs are the combination of direct costs with time-

related costs obtained by multiplying the time spent for shipping the cargo by the value of time $\gamma \geq 0$ €/FEU.day. (See Appendix A for a detailed discussion of each transport option.) We focus here on highlighting the expressions that drive our analysis. (Note that we additionally account for the reliability of travel time as an extension in Appendix B.)

The first option involves direct truck transportation. The average costs per FEU of shipping to and from $i \in H$ by using direct shipment by truck are expressed as follows:

$$C_i^T = \delta_{p,i} C^T + D_i^T. \quad (1)$$

where:

$\delta_{p,i}$ = the distance from the port to i (expressed in km),

C^T = truck transportation costs (expressed in €/FEU.km),

D_i^T = detention costs (expressed in €/FEU).

Moreover, D_i^T can be expressed via the following formula:

$$D_i^T = (1 - \alpha) \max(0; \delta_{p,i} T^T + U - F) d + \alpha \max(0; 2\delta_{p,i} T^T + U - F) d, \quad (2)$$

where:

α = average empty container movement ratio,

$\delta_{p,i}$ = the distance from the port to i (expressed in km),

T^T = truck transportation time (expressed in day/km),

U = loading/unloading time at the shipper (expressed in day),

F = detention-free period (expressed in day),

d = detention fees (expressed in €/day.FEU).

The second option involves HIT. We assume that $n \in \mathbb{N}$ (where \mathbb{N} refers to the set of natural numbers) inland terminals are available in the hinterland for intermodal operations. We consider that terminal locations are predetermined in line with tactical decisions made by LSPs. Indeed, large LSPs often purchase the terminal-to-terminal service from railway companies or intermodal service providers, who offer services between a set of existing intermodal terminals. For all $j \in \{1, \dots, n\}$, terminal j is located at $(x_j, 0) \in H$, with $0 < x_j$. This is in line with practice as inland terminals are often located along a corridor that can be modeled as a line. Note also that our results can easily be extended to the case where terminals are located all over the hinterland. In what follows, we limit ourselves to terminals located along the x-axis for reasons of clarity. If $n > 1$ we assume, without loss of generality, that for all $j \in \{1, \dots, n-1\}$, $x_{j+1} > x_j$. Throughout this article, we focus on train transportation because this is the most developed HIT solution worldwide. However, the model is also valid for road or barge HIT systems. The average costs per FEU of shipping to and from i by using HIT via an inland terminal j are expressed as follows:

$$C_i^j = C^j + \delta_{j,i} C^T + D_i^j, \quad (3)$$

where:

C^j = train transportation costs from the port to terminal j (expressed in €/FEU),

$\delta_{j,i}$ = the distance from inland terminal j to i (expressed in km),

D_i^j = detention costs (expressed in €/FEU).

Similar to Expression (2), we can express the average detention costs for shipping to and from i by hinterland intermodal transportation as follows:

$$D_i^j = (1 - \alpha) \max(0; x_j T^H + T_j + \delta_{j,i} T^T + U - F) d + \alpha \max(0; 2x_j T^H + 2T_j + 2\delta_{j,i} T^T + U - F) d, \quad (4)$$

where:

T^H = train transportation time (expressed in day/km),

T_j = transfer time at terminal j (expressed in day).

The third option involves port-centric operations. This involves transloading the containers into road vehicles (and vice versa) at the deep-sea port. We consider that the cargo loaded into one FEU is on average reloaded into $\beta \in (0; \infty)$ semi-trailers. The average costs per FEU of shipping to/from i via PCL are then expressed as follows:

$$C_i^P = C^0 + \delta_{P,i} \beta C^P, \quad (5)$$

where:

C^0 = the costs of port-centric operations (expressed in €/FEU),

β = average transloading ratio,

C^P = semi-trailer transportation costs (expressed in €/FEU.km).

Throughout the article, when i refers to a specific point in the hinterland, we replace it in the notation by its coordinates; that is, C_{x_i, y_i}^T refers to C_i^T for $i = (x_i, y_i)$.

4 Market areas of the transportation options

In the remainder of the article, we assume that the distance between two points $(x_k, y_k) \in H$ and $(x_l, y_l) \in H$ is evaluated by the Manhattan (or rectilinear or taxicab) distance:

$$\delta_{k,l} = |x_k - x_l| + |y_k - y_l|. \quad (6)$$

The Manhattan distance is often selected to evaluate distances in the literature. The Manhattan distance enables clear and meaningful insights of the market areas of the different logistics options we consider. Bouchery and Fransoo (2015) use both the Euclidean and the Manhattan distance for an intermodal hub

location problem. They show that the results obtained are quite similar in both cases. Equation (6) enables us to express $\delta_{p,i}$ and $\delta_{j,i}$ for all $j \in \{1, \dots, n\}$ as follows:

$$\delta_{p,i} = x_i + |y_i|, \quad (7)$$

$$\delta_{j,i} = |x_j - x_i| + |y_i|, \text{ for all } j \in \{1, \dots, n\}. \quad (8)$$

In this section, we aim at separating the hinterland region into different zones. Each zone is optimally served via one of the three options considered. We analytically identify below the best option to serve a given demand zone. We start by stating some additional assumptions and by highlighting some preliminary results for detention costs. First, we assume that for all $j \in \{1, \dots, n\}$, $x_j T^T \leq x_j T^H + T_j$, namely that hinterland intermodal transportation is not faster than direct truck. Indeed, transfer time at the inland terminal and the departure frequency limit the perceived speed of hinterland intermodal transportation. This assumption implies that detention costs for HIT are equal to or higher than detention costs for direct truck as stated in Lemma 1.

Lemma 1.

$D_i^T \leq D_i^j$ for all $i \in H$.

(All proofs appear in Appendix C.)

We further assume that $U < F$; that is, the loading/unloading time at the shipper is strictly less than the detention-free period. We can then express D_i^T as follows:

$$D_i^T = \begin{cases} 0 & \text{if } \delta_{p,i} \leq d_1 \\ (2\alpha\delta_{p,i}T^T + U - F)d & \text{if } d_1 \leq \delta_{p,i} \leq d_2, \\ ((1+\alpha)\delta_{p,i}T^T + U - F)d & \text{if } \delta_{p,i} \geq d_2 \end{cases} \quad (9)$$

where:

$$d_1 = \frac{F-U}{2T^T}, \quad d_2 = \frac{F-U}{T^T}.$$

Note that Expression (9) implies that D_i^T is increasing and convex in $\delta_{p,i}$ (as $2\alpha \leq 1+\alpha$). The following lemma highlights the variation of D_i^j and $D_i^j - D_i^T$.

Lemma 2.

Let $j \in \{1, \dots, n\}$. Then:

- 1) D_i^j is increasing and convex in $\delta_{j,i}$.
- 2) $D_{x_i,0}^j - D_{x_i,0}^T$ is decreasing in x_i for $x_i \in [0; x_j]$ and increasing in x_i for $x_i \geq x_j$.
- 3) $D_{x_i,y_i}^j - D_{x_i,y_i}^T$ is increasing in $|y_i|$.

The results of Lemma 2 will be used in the following subsections to identify the market areas of each transportation option.

4.1 Direct truck versus hinterland intermodal transportation

We aim at characterizing demand zones for which the cost of HIT is strictly less than the cost of direct truck shipment. We start by identifying the demand zones for which $C_i^j < C_i^T$ when $x_i \geq x_j$.

Theorem 1:

Let $j \in \{1, \dots, n\}$. If $C^j - x_j C^T + (1 + \alpha)(x_j T^H + T_j - x_j T^T)d < 0$, then $C_i^j < C_i^T$ for all $x_i \geq x_j$ and for all y_i .

Else, there exists $B_{\geq}^{T,j}$ such that $C_i^j < C_i^T$ for all $(x_i, y_i) \in H$ such that $x_i \geq x_j$ and $\delta_{i,j} > B_{\geq}^{T,j}$.

Theorem 1 highlights a possible tension between transportation costs and detention fees in the hinterland for locations farther away from the inland terminal. Indeed, intermodal transportation would outperform direct trucking for such locations unless the time penalty of HIT ($x_j T^T \leq x_j T^H + T_j$) leads to excessive detention fees. The condition for such a tension to occur is $C^j - x_j C^T + (1 + \alpha)(x_j T^H + T_j - x_j T^T)d > 0$. Note that shipping lines, which control detention fees, would be reluctant to create conditions that deter a larger use of HIT. We conclude that $C^j - x_j C^T + (1 + \alpha)(x_j T^H + T_j - x_j T^T)d < 0$ in many practical cases. We focus on such a setting in what follows. Theorem 1 thus implies that $C_i^j < C_i^T$ for all $x_i \geq x_j$ and for all y_i ; that is, that HIT shows higher performance than direct trucking for locations farther away from the inland terminal.

We focus next on the behavior of $C_{x_j,0}^j - C_{x_j,0}^T$ when $x_i \leq x_j$. We start with a lemma.

Lemma 3.

$$C^j - x_j C^T + (1 + \alpha)(x_j T^H + T_j - x_j T^T)d < 0 \Rightarrow C_{x_j,0}^j < C_{x_j,0}^T$$

Theorem 2 enables an understanding of the behavior of $C_{x_i,0}^j - C_{x_i,0}^T$ when $x_i \leq x_j$.

Theorem 2:

There exists a unique $0 < B^{T,j} < x_j$ such that $C_{x_{T-j},0}^j = C_{x_{T-j},0}^T$ for all $j \in \{1, \dots, n\}$. Moreover,

$$B^{T,j} \geq \frac{x_j C^T + C^j}{2C^T}.$$

Theorem 2 implies that for locations along the x-axis with $x_i \leq x_j$, direct trucking is more effective up to a certain threshold distance $B^{T,j}$. Note that C_{x_{T-j},y_i}^j and C_{x_{T-j},y_i}^T can be different for some y_i , as Lemma 2

states that $D_{x_i, y_i}^j - D_{x_i, y_i}^T$ is increasing in $|y_i|$. This implies that the border between direct truck and HIT is not a straight line if there exists y_i such that $D_{B^{T,j}, y_i}^j - D_{B^{T,j}, y_i}^T > D_{B^{T,j}, 0}^j - D_{B^{T,j}, 0}^T$. However, approximating this border by a straight line is acceptable in practice as long as $T^T d$ remains small. Indeed, $D_{B^{T,j}, y_i}^j - D_{B^{T,j}, y_i}^T \leq D_{B^{T,j}, 0}^j - D_{B^{T,j}, 0}^T + 2|y_i|T^T d$. Therefore, if we take $y_i = 300$ km, if a truck runs on average 1,000 km/day and if detention fees are €60/day, this leads $D_{B^{T,j}, y_i}^j - D_{B^{T,j}, y_i}^T \leq D_{B^{T,j}, 0}^j - D_{B^{T,j}, 0}^T + 36$. If we further assume that $C^T = €2.5/\text{FEU.km}$, the maximum difference in x-coordinates for the border between direct truck and HIT is 14.4 km for a difference in y-coordinates of 300 km, thus equaling less than 5%. Therefore, we approximate the border between direct truck and HIT as a straight line in what follows.

Theorem 1 and Theorem 2 enable identifying the locations for which direct truck and HIT outperform each other. Indeed, if we exclude PCL, the results above show that H can be optimally split into two market areas. The first one, referred to as the DT_{noP} market area, is served by direct truck shipments and includes the locations for which $x_i \leq B^{T,j}$ with $j=1$ (as $C_{x_i, 0}^j - C_{x_i, 0}^T$ is strictly decreasing in x_i for $x_i \in [0; x_j]$ and the border between direct truck and HIT is assumed to be a straight line). The second one, referred to as the HIT_{noP} market area, is served by HIT (via various inland terminals) and includes the locations for which $x_i \geq B^{T,j}$, with $j=1$, that is:

$$DT_{noP} = \{(x_i, y_i) \in H \mid 0 \leq x_i \leq B^{T,1}\}, \quad (10)$$

$$HIT_{noP} = \{(x_i, y_i) \in H \mid x_i \geq B^{T,1}\}, \quad (11)$$

These results are in line with the literature stating that HIT requires a certain distance to break even.

4.2 Direct truck versus port-centric logistics

In this subsection, we will characterize demand zones for which port-centric logistics is strictly more costly than direct truck shipment. By combining Expression (1) and Expression (5), we obtain:

$$C_i^P - C_i^T = \delta_{p,i}(\beta C^P - C^T) + C^0 - D_i^T, \quad (12)$$

Expression (12) enables us to derive the following theorem:

Theorem 3.

If $\beta C^P - C^T \geq (1 + \alpha)T^T d$, $C_i^P > C_i^T$ for all $\delta_{p,i}$.

Else, there exists a unique distance $B^{P,T}$ such that $C_i^P = C_i^T$ when $\delta_{p,i} = B^{P,T}$. Moreover, $C_i^P > C_i^T$ for all $\delta_{p,i} < B^{P,T}$ and that $C_i^P < C_i^T$ for all $\delta_{p,i} > B^{P,T}$.

In what follows, we assume that $\beta C^P - C^T < (1 + \alpha)T^T d$, as otherwise, $C_i^P > C_i^T$ for all $i \in H$ and PCL is not viable. In case $\beta C^P - C^T < (1 + \alpha)T^T d$, PCL is less costly than direct truck transportation for locations

farther away than $B^{P,T}$ kilometers from the port. This implies that PCL requires a certain distance to break even as the fixed costs of port-centric operations need to be compensated by the reduction in transportation costs. Note also that this is a first sign of potential tension between PCL and HIT as they both will be competitive over direct trucking for locations distant enough from the port. Theorems 1, 2 and 3 imply that the direct truck (DT) market area (i.e., the demand zone for which direct truck shipment is optimally used) can be obtained as:

$$DT = \left\{ (x_i, y_i) \in H \mid 0 \leq x_i \leq B^{T,1}, x_i + |y_i| \leq B^{P,T} \right\}. \quad (13)$$

4.3 Hinterland intermodal transportation versus port-centric logistics

We aim here to characterize locations for which PCL is cheaper than HIT. Let $j \in \{1, \dots, n\}$. We focus first on locations for which $x_i \geq x_j$. By combining Expression (3) and Expression (5) and by taking $\delta_{p,i} = x_j + \delta_{j,i}$, we obtain:

$$C_i^P - C_i^j = C^0 - C^j + x_j \beta C^P + \delta_{j,i} (\beta C^P - C^T) - D_i^j, \quad (14)$$

Expression (14) enables us to derive the following theorem:

Theorem 4.

Let $j \in \{1, \dots, n\}$ and let $x_i \geq x_j$. Assume that $C^0 - C^j + x_j \beta C^P - D_{x_j,0}^j > 0$. There exists a unique $B_{\geq}^{P,j}$ such that $C_i^P = C_i^j$ when $\delta_{j,i} = B_{\geq}^{P,j}$. Moreover, $C_i^P > C_i^j$ for all $\delta_{j,i} < B_{\geq}^{P,j}$ and $C_i^P < C_i^j$ for all $\delta_{j,i} > B_{\geq}^{P,j}$.

Note that if $C^0 - C^j + x_j \beta C^P - D_{x_j,0}^j \leq 0$, the terminal will be more efficiently served by PCL than by HIT, which is unreasonable for the viability of the terminal. Therefore, we assume that $C^0 - C^j + x_j \beta C^P - D_{x_j,0}^j > 0$ in what follows. Theorem 4 implies that in case $x_i \geq x_j$, PCL performs better than HIT for locations farther away than $B_{\geq}^{P,j}$ kilometers from the inland terminal. This highlights a second sign of possible tension between HIT and PCL for distant locations. HIT is often considered as efficient for long distance transportation (Kim and van Wee, 2011), but our model shows that a different pattern may occur if PCL is considered. We now focus on situations for which $x_i \leq x_j$ and we derive the following theorem:

Theorem 5.

If $C^0 - C^j - x_j C^T - D_{0,0}^j \geq 0$, $C_{x_i,0}^P \geq C_{x_i,0}^j$ for all $x_i \leq x_j$.

Else, there exists a unique $B_{\leq}^{P,j}$ such that $C_{B_{\leq}^{P,j},0}^P = C_{B_{\leq}^{P,j},0}^j$. $C_{x_i,0}^P < C_{x_i,0}^j$ for all $x_i < B_{\leq}^{P,j}$ and $C_{x_i,0}^P > C_{x_i,0}^j$ for all $x_i > B_{\leq}^{P,j}$. Moreover, $\beta C^P - C^T < 0 \Rightarrow C_i^P < C_i^j$ for all $x_i < B_{\leq}^{P,j}$.

Theorem 5 first implies that if PCL is more expensive than HIT for serving the port ($C^0 - C^j + x_j C^T - D_{x_j,0}^j = C_{x_j,0}^P - C_{x_j,0}^j > 0$), HIT will be more competitive than PCL for all $i \in H$ such that $x_i \leq x_j$ and $y_i = 0$. The fact that HIT might be more competitive than PCL in the port area is quite unreasonable. Therefore, we focus on the situations for which $C^0 - C^j - x_j C^T - D_{0,0}^j < 0$. In such a case, Theorem 5 implies that there exists a threshold $B_{\leq}^{P,j}$ for HIT to become competitive against PCL along the x-axis (for $x_i \leq x_j$). Note also that $\beta C^P - C^T$ is likely to be negative in practice. Indeed, truck transport costs are often comparable for containers and semi-trailers and $\beta \leq 1$ in many practical applications. We consequently assume that $\beta C^P - C^T < 0$ in what follows. In such a case, Theorem 5 additionally implies that $C_i^P < C_i^j$ for all $x_i < B_{\leq}^{P,j}$. Let $\Omega^{P,j} = \{i \in H \mid x_i \leq x_j, C_i^j = C_i^P\}$. Theorem 5 implies that $\Omega^{P,j}$ is piecewise linear and convex. Note also that in case $D_i^j = 0$ for all $\{i \in H \mid x_i \leq x_j\}$, $\Omega^{P,j} = \{i \in H \mid |y_i| = Sx_i - L_j\}$ with $S = \frac{\beta C^P + C^T}{C^T - \beta C^P}$ and $L_j = \frac{x_j C^T + C^j - C^0}{C^T - \beta C^P}$. We further define $HITB^{P,j} = \{i \in H \mid x_i \leq x_j, C_i^j \leq C_i^P\}$.

4.4 Market area split between consecutive inland terminals

In this subsection, we aim at identifying the split in market areas between the various inland terminals. We further define the train transportation costs via terminal j for all $j \in \{1, \dots, n\}$ as follows (see Appendix A for a more in-depth discussion):

$$C^j = x_j \left[\gamma T^H + (1 + \alpha) Z^H \right] + (1 + \alpha) K_j + \gamma T_j, \quad (15)$$

where:

T^H = train transport time (expressed in day/km),

Z^H = average train transportation costs for containers (expressed in €/FEU.km),

K_j = transfer costs at terminal j (expressed in €/FEU),

T_j = transfer time at terminal j (expressed in day).

We assume for the remainder of this article that inland terminals have similar operating conditions, namely that in case $n \geq 2$, $T_{j+1} = T_j$ and $K_{j+1} = K_j$ for all $j \in \{1, \dots, n-1\}$. Furthermore, we limit ourselves to $n \geq 2$ through this subsection. We start by stating the following lemma:

Lemma 4.

$$C_i^j < C_i^{j+k} \text{ for all } j \in \{1, \dots, n-1\}, \text{ for all } k \in \{1, \dots, n-j\} \text{ and for all } i = \left\{ (x_i, y_i) \in H \mid x_i \leq \frac{x_{j+k} + x_j}{2} \right\}.$$

The following theorem enables characterization of the borders between two consecutive inland terminals j and $j+1$ for all $x_i \leq x_{j+1}$:

Theorem 6.

For all $j \in \{1, \dots, n-1\}$ and all $k \in \{1, \dots, n-j\}$:

If $C_{x_{j+k},0}^{j+k} \geq C_{x_{j+k},0}^j$, then $C_i^{j+k} \geq C_i^j$ for all $i \in H$.

Else, then there exists a unique $B^{j,j+k}$ such that $C_{x_i,0}^j < C_{x_i,0}^{j+k}$ for all $x_i < B^{j,j+k}$ and $C_{x_i,0}^j > C_{x_i,0}^{j+k}$ for all

$B^{j,j+k} < x_i \leq x_{j+k}$. Moreover, $\frac{x_{j+k} + x_j}{2} < B^{j,j+k} < x_{j+k}$.

The following lemma shows that $C_{x_{j+1},0}^{j+1} < C_{x_{j+1},0}^j$ based on the assumptions previously made:

Lemma 5.

$C^j - x_j C^T + (1+\alpha)(x_j(T^H - T^T) + T_j)d < 0 \Rightarrow C_{x_{j+k},0}^{j+k} < C_{x_{j+k},0}^j$ for all $j \in \{1, \dots, n-1\}$.

Note that by applying Lemma 5 and as we assume that $C^j - x_j C^T + (1+\alpha)(x_j(T^H - T^T) + T_j)d < 0$, there exists a unique $B^{j,j+1}$ such that $C_{x_i,0}^j < C_{x_i,0}^{j+1}$ for all $x_i < B^{j,j+1}$ and $C_{x_i,0}^j > C_{x_i,0}^{j+1}$ for all $B^{j,j+1} < x_i \leq x_{j+1}$, according to Theorem 6. Note that $C_{B^{j,j+1},y_i}^j$ and $C_{B^{j,j+1},y_i}^{j+1}$ can be different for some y_i due to the potential delay in growth between D_i^j and D_i^{j+1} . This implies that the border between consecutive inland terminals is not a straight line if there exists y_i such that $D_{B^{j,j+1},y_i}^{j+1} - D_{B^{j,j+1},y_i}^j > D_{B^{j,j+1},0}^{j+1} - D_{B^{j,j+1},0}^j$. However, approximating this border by a straight line is acceptable in practice for the same reasons that led us to approximate the border between direct truck and HIT as a straight line. Therefore, we approximate the border between consecutive inland terminals as a straight line in what follows.

Theorem 7.

For all $j \in \{1, \dots, n-1\}$, if $C^T > (1+\alpha)(Z^H + d(T^H - T^T)) + \gamma T^H$ then $C_{x_i,0}^{j+1} < C_{x_i,0}^j$ for all $x_{j+1} \leq x_i$. Else, there exists a unique $B_{\geq}^{j,j+1}$ such that $C_{x_i,0}^{j+1} < C_{x_i,0}^j$ for all $x_{j+1} \leq x_i < B_{\geq}^{j,j+1}$ and $C_{x_i,0}^{j+1} \geq C_{x_i,0}^j$ for all $B_{\geq}^{j,j+1} \leq x_i$.

Note that $C^j - x_j C^T + (1+\alpha)(x_j(T^H - T^T) + T_j)d < 0 \Rightarrow C^T > (1+\alpha)(Z^H + d(T^H - T^T)) + \gamma T^H$ and therefore, $C_{x_i,0}^{j+1} < C_{x_i,0}^j$ for all $x_{j+1} \leq x_i$, by applying Theorem 7. We conclude that $C_i^j < C_i^{j+1}$ for all $x_i < B^{j,j+1}$ and that $C_i^j > C_i^{j+1}$ for all $x_i > B^{j,j+1}$. We additionally show that two nonconsecutive inland terminals have nonadjacent market areas.

Corollary 1.

For all $j \in \{1, \dots, n-1\}$ and for all $k \in \{1, \dots, n-j\}$, $C_{x_i,0}^j = C_{x_i,0}^{j+k} \Rightarrow C_{x_i,0}^{j+1} < C_{x_i,0}^j$.

Based on the results presented through this section, we can define the market areas of each transportation option as follows:

$$HITB^1 = HITB^{P,1} \cap \{i \in H \mid B^{T,1} \leq x_i \leq x_1\}, \quad (16)$$

$$HITB^j = HITB^{P,j} \cap \{i \in H \mid B^{j-1,j} \leq x_i \leq x_j\}, \text{ for all } j \in \{2, \dots, n\}, \quad (17)$$

$$HITF^j = \{i \in H \mid x_j \leq x_i \leq B^{j,j+1}, x_i + |y_i| \leq \min(B^{T,j}, B_{\geq}^{P,j})\}, \text{ for all } j \in \{1, \dots, n-1\}, \quad (18)$$

$$HITF^n = \{i \in H \mid x_n \leq x_i, x_i + |y_i| \leq \min(B^{T,n}, B_{\geq}^{P,n})\}, \quad (19)$$

$$HIT^j = HITB^j \cup HITF^j, \text{ for all } j \in \{1, \dots, n\}, \quad (20)$$

$$HIT = \bigcup_{j=1}^n HIT^j, \quad (21)$$

$$PCL = H \setminus (DT \cup HIT), \quad (22)$$

with DT defined in (13). These expressions allow for an analytical characterization of the market areas of each transportation option in case PCL is available.

In the next section, we investigate the effect of PCL on direct truck shipments and HIT. To do so, we compare DT_{noP} with the DT market areas and HIT_{noP} with the HIT market areas. Then, we assess whether the use of continental containers might help to reconcile HIT and PCL.

5 Impact of port-centric logistics and use of continental containers

In this section, we start by studying the impact of PCL on direct truck shipment and on HIT. We show that the tension between PCL and HIT is very likely to happen in practice. Therefore, we assess whether the use of continental containers might help to reconcile the two practices. To do so, we assume that H is a rectangle of width x_{\max} and height $2y_{\max}$. Moreover, the deep-sea port is located in the middle of the rectangle's height.

5.1 Impact of port-centric logistics

The idea we focus on in this subsection consists of identifying whether HIT is affected by PCL. We start by identifying conditions such that direct truck shipment is not impacted by PCL.

Lemma 6.

$DT_{noP} = DT$ if and only if $B^{P,T} \geq B^{T,1} + y_{\max}$.

Lemma 6 explains that the DT market area is not affected by PCL in case the area of interest for PCL corresponds to the area for which HIT performs better than direct truck shipment. If the condition of Lemma 6

holds, the market area of PCL is either empty, or PCL is in pure competition with HIT by capturing part of the HIT_{noP} market area. This is a sign of possible tension between HIT and PCL.

We now identify conditions such that HIT is not affected by PCL. For all $j \in \{1, \dots, n\}$, let $x_{\max}^{P,j} = x_i \mid i \in \Omega^{P,j} \cap \{i \in H \mid y_i = y_{\max}\}$.

Theorem 8.

$$HIT_{noP} = HIT \text{ if and only if } \begin{cases} x_{\max}^{P,j} \leq B^{T,1} \\ x_{\max}^{P,j} \leq B^{j-1,j}, \forall j \in \{2; n\} \\ x_n + B_{\geq}^{P,n} \geq x_{\max} + y_{\max} \\ x_j + B_{\geq}^{P,j} \geq B^{j,j+1} + y_{\max}, \forall j \in \{1; n-1\} \end{cases}.$$

Theorem 8 states that HIT is not affected by PCL if the catchment area of each inland terminal is not affected by PCL. If the conditions of Theorem 8 hold, HIT and PCL can be implemented in synergy. In such a case, either the PCL market area is empty, or this market area is taken solely from the DT_{noP} market area. In this setting, HIT is used to serve distant locations, and PCL enables improvement of operations in the surroundings of the port. Indeed, if there are fewer semi-trailer movements than that of trucks transporting containers, which is quite likely to happen in practice, the number of trucks needed in the hinterland is reduced if PCL is implemented instead of direct truck shipment and, therefore, congestion in the port surroundings can be reduced. Many port authorities and actors of the hinterland supply chain target this setting when implementing PCL. However, Corollary 2 highlights a critical feature.

Corollary 2.

Conditions of Theorem 8 hold only for small values of x_{\max} and y_{\max} for large values of C^0 .

We show in Corollary 2 that the conditions of Theorem 8 hold only for small hinterlands with large port-centric operations costs. In such a case, the condition of Lemma 6 is likely to hold. Therefore, PCL is not likely to be used. This implies that if PCL is a viable option in the hinterland of a port, this practice will compete with HIT in terms of market area. We conclude that the tension between PCL and HIT is very likely to happen in practice.

We further attempt to identify the conditions under which the market area of PCL is mainly taken from the HIT_{noP} market area (i.e., more than 50% of the market area of PCL comes from the HIT_{noP} market area). Some of these sufficient conditions are stated in Theorem 9. Note that the conditions stated in Theorem 9 are not mutually exclusive. Moreover, even in cases where none of the conditions stated in Theorem 9 hold, the combined market area of PCL can be predominantly taken from the HIT_{noP} market area.

Theorem 9.

More than 50% of the market area of PCL comes from the HIT_{noP} market area if any one of the following conditions holds:

$$x_{\max} - x_n - B_{\geq}^{P,n} > B^{T,1} - B^{P,T} \geq 0 \text{ and } B_{\geq}^{P,n} \geq B^{P,T},$$

$$\text{or } x_{\max} - x_n - B_{\geq}^{P,n} > B^{T,1},$$

$$\text{or } 2B^{T,1} < B_{\leq}^{P,1}.$$

Define $HITB_{noP}^1 = \{(x_i, y_i) \in H \mid B^{T,1} \leq x_i \leq x_1\}$ and $HITF_{noP}^n = \{(x_i, y_i) \in H \mid x_i \geq x_n\}$. Theorem 9 describes two extreme cases, namely when the PCL area taken from DT_{noP} is smaller than the area taken from $HITF_{noP}^n$ (in the first two cases) and when the PCL area taken from DT_{noP} is smaller than the area taken from $HITB_{noP}^1$ (in the third case). The first two cases hold if x_n is not large enough (compared to x_{\max}). In this case, HIT is penalized by a long haulage distance by truck to reach locations far away in the hinterland, and PCL becomes more favorable. In the third case, the area taken from $HITB_{noP}^1$ is larger than DT_{noP} . This happens when PCL is efficient for quite short distances (i.e., if $B_{\leq}^{P,1}$ is large) and when DT_{noP} is small.

5.2 Reconciling PCL with HIT by using continental containers

Using a maritime container in the hinterland seems straightforward and simple. However, several disadvantages might appear. First, the regulations differ from one country to another and therefore the dimensions of the maritime containers are not always optimal for hinterland transportation. For instance, the maximal size of an intermodal unit in North America is 53 feet. Therefore, the contents of three maritime containers (40 ft. each) can often be transferred into two North American continental containers (Rodrigue & Notteboom, 2009). Second, the shipping lines that own (or lease) the maritime containers are reluctant to let their containers be used in the hinterland as this is associated with perceived opportunity costs. Therefore, they charge detention fees that reduce the efficiency of hinterland operations. Third, empty container repositioning in the hinterland will lead to considerable costs.

The reason for using continental containers is to combine the advantages of an intermodal unit without the drawbacks of a maritime container used in the hinterland. In this subsection, we aim at assessing whether the use of continental containers might help in reconciling PCL and HIT. This idea is quite straightforward as the use of continental containers induces port-centric operations (i.e., transloading from maritime containers to continental containers and vice versa) as well as HIT. In what follows, we model the costs associated with the use of these continental containers. Note that even if we refer to a continental container for clarity reasons, the modeling applies to any type of continental intermodal unit. Moreover, we assume that a continental container is used only for intermodal movements, as there is no difference with PCL from a modeling perspective in case of truck-only movements. (See Appendix A for more details of the modeling of continental container

transportation.) The average cost per FEU of shipping to and from i via a continental container through an inland terminal $j \in \{1, \dots, n\}$ is expressed as follows:

$$C_i^{Cj} = C^{0'} + \beta' C^{j'} + \delta_{j,i} \beta' C^{P'} . \quad (23)$$

In what follows, we limit our analysis to the special case of $C^{0'} = C^0$, $\beta' = \beta$, and $C^{P'} > C^P$. In such a setting, the continental container can be used for intermodal operations, in contrast to the road-only transportation unit considered previously, but doing so will induce higher truck transportation costs. The average cost per FEU of shipping to and from i via a continental container through an inland terminal $j \in \{1, \dots, n\}$ can be rewritten as:

$$C_i^{Cj} = C^0 + \beta C^{j'} + \delta_{j,i} \beta C^{P'} , \quad (24)$$

We start by proving that the use of continental containers via inland terminal $j \in \{1, \dots, n\}$ will be viable only if $\frac{C^{j'}}{x_j} < C^P$.

Lemma 7.

For all $i \in H$, $\frac{C^{j'}}{x_j} \geq C^P \Rightarrow C_i^{Cj} > C_i^P$ for all $j \in \{1, \dots, n\}$.

Based on Lemma 7, we assume that $\frac{C^{j'}}{x_j} < C^P$ in the remainder of the article; that is, there is an advantage in using train instead of truck to move continental containers to terminal j . Otherwise, the analysis made in Section 4 can be directly transposed in case continental containers are available. In case $\frac{C^{j'}}{x_j} < C^P$, using HIT enables reducing transportation costs to the terminal but induces larger costs for the final leg of transportation by truck (as $C^{P'} > C^P$). There is then a trade-off in using continental containers by HIT for locations farther away from the terminal as compared to truck-only transportation. In Theorem 10, we state a sufficient condition such that the use of continental container helps to reconcile PCL and HIT.

Theorem 10.

If $\left| \begin{array}{l} x_{\max} + y_{\max} > x_n + B_{\geq}^{P,n} \\ B_{\geq}^{P,n} < \frac{x_n C^P - C^{n'}}{C^{P'} - C^P} \end{array} \right.$, there exists $i \in H$ such that $C_i^P < C_i^n$ and $C_i^{Cn} < C_i^P$.

The locations $i \in H$ such that $C_i^P < C_i^n$ and $C_i^{Cn} < C_i^P$ identified by Theorem 10 have the following features:

- i) They belong to the hinterland.
- ii) They are far enough from terminal n so as to make PCL cheaper than HIT.
- ii) They are not too far away from terminal n so as to make HIT valuable for moving continental containers.

6 Illustrative example and insights

In this section, we apply the results obtained above to an example. We derive insights and we include a brief analysis of how different stakeholder groups are affected.

6.1 An illustrative example

We consider the data from Table 1. These data have been obtained from discussions with professionals in a Western European context. Note first that the hypotheses we made through the article are consistent with these data; that are, $x_j T^T \leq x_j T^H + T_j$ for all $j \in \{1, \dots, n\}$, $C^j - x_j C^T + (1 + \alpha)(x_j T^H + T_j - x_j T^T) d < 0$ for all

$$j \in \{1, \dots, n\}, \quad C^P - C^T < 0 < (1 + \alpha) T^T d, \quad C^0 - C^j + x_j C^P - D_{x_j, 0}^j > 0 \quad \text{for all } j \in \{1, \dots, n\},$$

$$C^0 - C^j - x_j C^T - D_{0,0}^j < 0 \text{ for all } j \in \{1, \dots, n\}, \quad C^{P'} > C^P \text{ and } \frac{\beta C^{j'}}{x_j} < C^P \text{ for all } j \in \{1, \dots, n\}.$$

x_{max}	1,000	km
y_{max}	300	km
x_1	250	km
x_2	600	km
C^1	612	€/FEU
C^2	1,232	€/FEU
C^0	250	€/FEU
$C^{1'}$	392	€/FEU

$C^{2'}$	760	€/FEU
C^T	2.87	€/FEU.km
C^P	1.83	€/FEU.km
$C^{P'}$	2.05	€/FEU.km
α	0.95	
β	1.1	
F	2	days
U	0.2	days

d	60	€/FEU.day
γ	100	€/FEU.day
T^T	0.00139	day/km
T^H	0.00104	day/km
Z^H	0.9	€/FEU.km
T_1	0.5	days
T_2	0.5	days
K_1	50	€/FEU
K_2	50	€/FEU

Table 1: Data of the illustrative example.

The results from Subsection 4.1 lead to $B^{T,1} = 232$ km. Consequently, we find that $DT_{noP} = \{(x_i, y_i) | 0 \leq x_i \leq 232, |y_i| \leq 300\}$ and $HIT_{noP} = \{(x_i, y_i) | 232 \leq x_i \leq 1000, |y_i| \leq 300\}$. Moreover, the results from Subsection 4.4 lead us to $B^{1,2} = 534$ km. We refer to Figure 1 for an illustration. By applying the results of Subsection 4.2, we learn that $B^{P,T} = 292$ km; that is, PCL is competitive against direct trucking only over distances longer than 292 km. Indeed, trailers are much more competitive than direct trucking of maritime containers ($\beta C^P = 2.02$ €/FEU.km, i.e., 30% lower than C^T). However, port-centric operations are costly ($C^0 = 250$ €/FEU). Therefore, PCL requires 292 km to break even. This enables us to define $DT = \{(x_i, y_i) | 0 \leq x_i \leq 232, x_i + |y_i| \leq 292\}$.

The results of Subsection 4.3 lead to $B_{\geq}^{P,1} = 106$ km, $B_{\leq}^{P,1} = 221$ km., $B_{\geq}^{P,2} = 200$ km and $B_{\leq}^{P,2} = 560$ km. Note that the border between HIT and PCL for $x_i \leq x_j$ is well-approximated by

$$\Omega^{P,j} = \{i \in H | |y_i| = S x_i - L_j\} \text{ with } S = \frac{\beta C^P + C^T}{C^T - \beta C^P} = 5.71, \quad L_1 = \frac{x_1 C^T + C^j - C^0}{C^T - \beta C^P} = 1262 \text{ and } L_2 = 3159.$$

Figure 2 illustrates the results when excluding the continental container option.

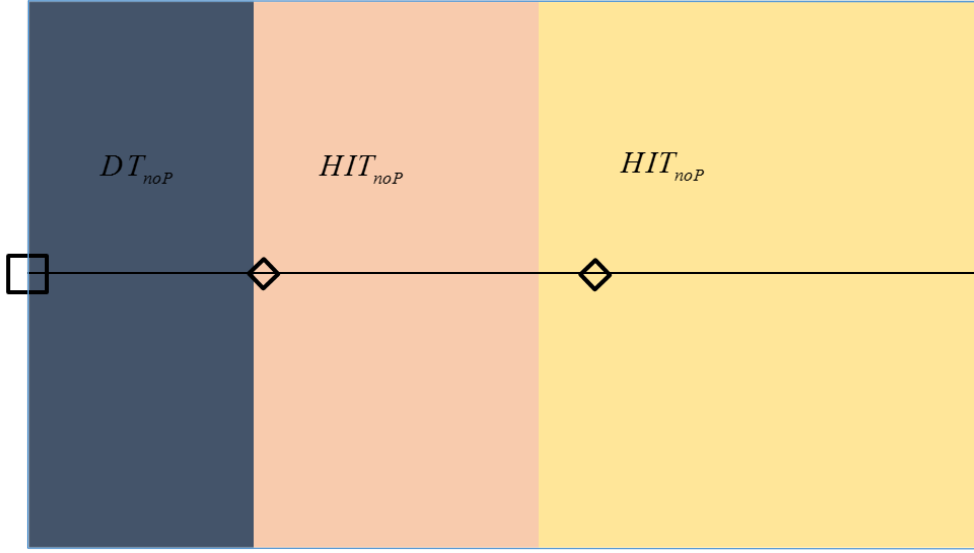


Figure 1: The market areas of DT and HIT (excluding PCL and continental containers).

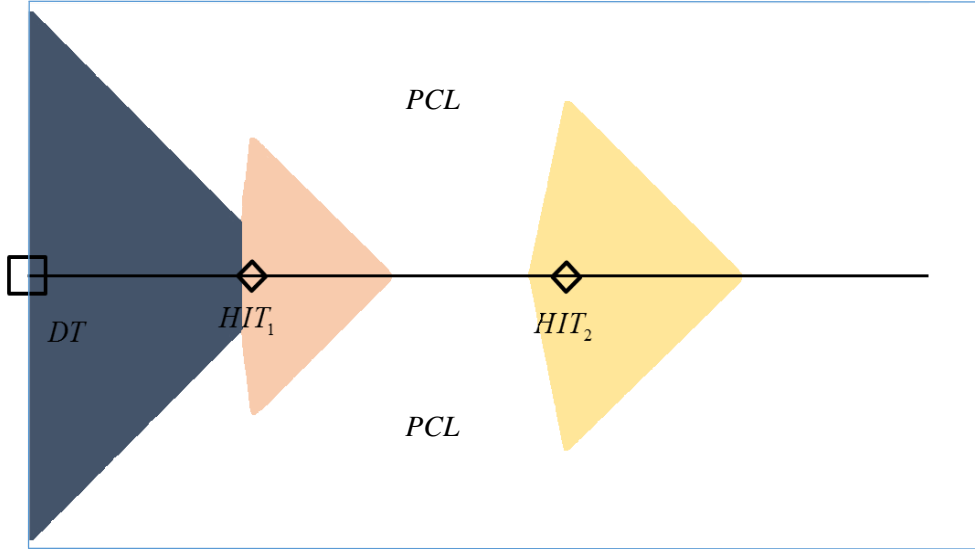


Figure 2: The market areas of DT and HIT (excluding continental containers).

The comparison between Figure 1 and Figure 2 clearly illustrates the tension between HIT and PCL. We can notice at first that the DT_{noP} market area is not strongly impacted by PCL, in opposition to the HIT_{noP} market area. We can also easily observe that more than 50% of the market area of PCL comes from the HIT_{noTR} market area (even if the conditions of Theorem 9 are not met). In the example, HIT is at best a slightly better performer than DT. For instance, reaching inland terminal 1 by using HIT is just 8% cheaper than using direct trucking (when excluding detention costs) and the cost advantage decreases as we move farther away from the terminal. On the other hand, the performance of PCL relative to DT increases as we move farther away into the hinterland. This explains why the market area of HIT is quite small in Figure 2. We conclude that all decision makers involved in the management of containerized cargo in the hinterland

should make themselves more aware of the interaction between HIT and PCL as the tension between these options is likely.

The results when including the possibility of using continental containers appear in Figure 3. Note that we distinguish between the area served by an inland terminal using maritime containers and continental containers in Figure 2. For inland terminal 1, both options are used (HIT_1 vs. C_1), while for inland terminal 2, only continental containers are used. We can observe that the use of continental containers helps extend the market area of HIT for faraway locations (in accordance with Theorem 10). Indeed, the cost advantage of reaching inland terminal 2 with a continental container is large as compared to PCL (1086€/FEU as compared to 1460€/FEU) and the difference between C^P and $C^{P'}$ is not large enough to compensate for this difference. As the impact of using continental containers is large in the example studied, we conclude that continental containers have a real potential in reconciling PCL and HIT.

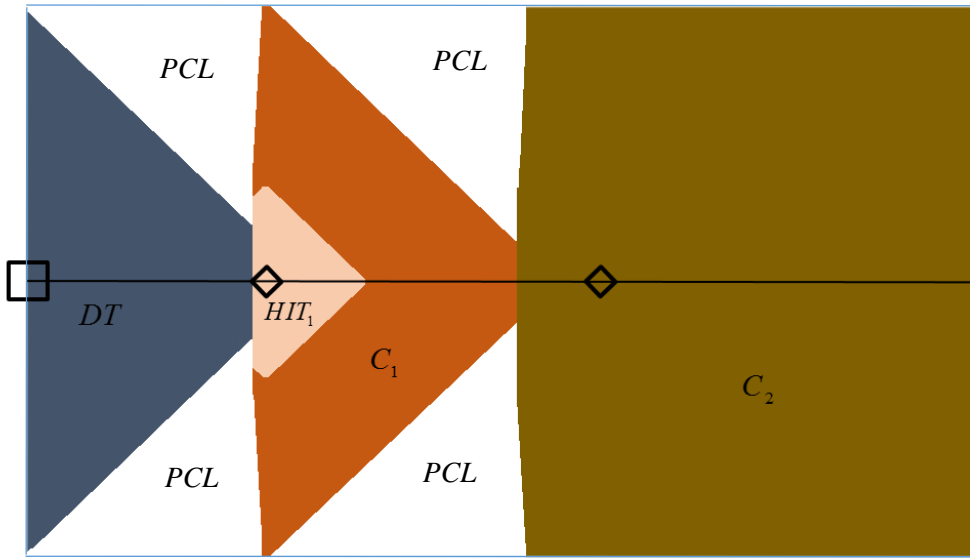


Figure 3: The market areas of DT and HIT (including continental containers).

6.2 Practices in some ports

We can draw some additional insights from the results we have obtained by comparing the settings of several types of hinterland following the recommendations by McCalla (1999), who compares developments at two Canadian ports in Halifax, Nova Scotia, and Vancouver, British Columbia, to show that the ports' responses to changes in global flows is highly contextual. Also, Ducruet and Lee (2006) identify local and regional factors that in combination affect ports' adaptation to globalization. First, consider the hinterland of the ports of Los Angeles/Long Beach. We mentioned previously that 53 ft. containers are allowed in the US. This implies that β is likely to be small (smaller than 1). As C_i^{Cj} is increasing in β , this is the first sign that continental containers might be of interest. Moreover, the hinterland of the ports of Los Angeles/Long Beach is large with inland terminals quite distant from the ports (to allow for east-west transfer). Therefore, the conditions of Theorem 10 are very likely to hold. Our model leads us to conclude that continental containers are likely to be used heavily. This is in line with the data, as in 2009, about 45% of the containers imported through Los Angeles/Long Beach were transloaded into domestic containers (Rodrigue & Notteboom, 2009).

Second, consider the hinterland of the Port of Le Havre. This one not being very large, there are a limited number of inland terminals, and rail transportation costs are high. Therefore, the market area of HIT is small. If we assume that the truck transportation cost data of the example above are relevant for a French setting and that the transloading costs are $\text{€}250/\text{FEU}$, our model leads us to conclude that (1) HIT will be limited to locations close to the inland terminals, (2) locations 200 km or less from the port will be served by direct truck, and (3) PCL will be used to serve those shippers located more than 292 km from the port (and out of the market area of an inland terminal). As β is quite large and rail transportation costs are high, the use of continental containers will not enable a reconciliation between PCL and HIT. We observe that this setting is consistent with the current situation in the hinterland of Le Havre.

Third, consider the hinterland of the Port of Rotterdam. The hinterland is of medium size, rail transportation costs are low, there is a very high density of inland terminals and β is quite large. Therefore, direct truck is used for locations close to the port and HIT is used for more distant locations. Our model leads us to conclude that PCL is not very likely to be developed. Note that we exclude short-sea shipping from our analysis; that is, we do not consider market areas overseas. In case of short-sea shipping, the port is a natural transloading point. This is in line with the practice in the Port of Rotterdam where the development of port-centric operations mainly targets short-sea market areas and central warehouses for distribution throughout Europe.

Fourth, the largest customer of the Port of Gothenburg, Stora Enso, uses an extreme form of continental container, the Stora Enso Cargo Unit (SECU), to move forest products by train from their four Swedish mills situated 160-450 km from the port of Gothenburg. Each SECU can carry almost 80 metric tons and each train up to 3000 metric tons, utilizing the full capacity of the rail infrastructure. This is required for managing large volumes on congested tracks but also for rail to compete with the generously sized trucks that are up to 25.25 m long and with a capacity of up to 64 metric tons allowed in Sweden. Most SECUs leave Gothenburg for continental Europe on RoRo ships, but, according to Hansen (2018), an annual amount of 30,000 FEUs of goods destined for overseas markets arriving in SECUs is transloaded into maritime containers within or in the vicinity of the port. This shows that there is room for specialized PCL solutions for certain products over both short and medium distances if the flows are large and concentrated. In addition, Gothenburg's general intermodal terminal, mostly used for domestic flows, was moved into the port area in 2018, improving the competitiveness of transloading in combination with hinterland transport by rail.

6.3 Effects of volume and value of time

We first discuss here how volume might affect our results. Indeed, our analysis assumes that all costs are linear for whatever the number of containers. This is in line with the tariffs faced by LSPs, but we additionally discuss here how volume might create economies of scale that would impact our results. Note that costs are differently affected by economies of scale. For instance, truck transport costs are quite insensitive to the volume effect.

Conversely, the costs that are the most sensitive to volume in our model are K_j , Z^H and C^0 . Indeed, K_j and C^0 includes the fixed costs to operate the inland terminal or the facility and therefore, more volume

leads to a decrease in this cost. Similarly, train transportation costs depend on the average load factor of the train, that is, on the total volume handled. If more volume is handled by the LSP, our results show that $B^{T,j}$ and $B^{P,T}$ would decrease. This will result in a reduction of the *DT* market area. Therefore, volumes favor both HIT and PCL over direct truck and it is in line with the results of Crainic, Dell’Olmo, Ricciardi, & Sgalambro (2015), who designed a train system serving three ports and two dry ports in Italy based on aggregating volumes and adhering to time restrictions. Note that volume might also affect travel time by creating congestion (mainly affecting truck transport) or by enabling more frequent intermodal services. These two features tend to favor HIT. (See Bouchery and Fransoo, 2015, for an in-depth analysis of the effect of volume on direct truck vs. HIT). We would also like to stress that volume is double-edged. On one hand, volume favors both HIT and PCL over direct truck leading to what Hesse and Rodrigue (2004) identify as a concentration of distribution centers at either gateway ports or inland hubs as trade volumes increase. On the other hand, our results show that tension between HIT and PCL is likely to happen in practice. In such a case, the volume is shared between both options, and, therefore, K_j , Z^H and C^0 might increase. This could subsequently favor direct shipment by truck. We conclude that port authorities should carefully assess the cannibalization risks between PCL and HIT before investing in the development of both options. This is in line with Notteboom and Rodrigue (2005), who advise port authorities to do a thorough analysis of the truly port-related activities and what is better done in the hinterland. Also McCalla (1999) states that ports must respond to global trade changes but acknowledges the difficulty of “who or what is to define these responses?” (p. 253). Note also that the use of continental containers or semi-trailers is a promising solution to make use of HIT and PCL without compromising volumes for either option. Many ports in northeast Europe combine deep-sea container and short-sea semi-trailer flows. Transloading containerized goods into semi-trailers can then make up sufficient volumes for HIT services, as investigated by Woxenius and Bergqvist (2011).

We now discuss the impact of the increased value of time. Some shippers and some cargo are more sensitive to time than others (Finnsgård et al., 2019) and may well require more urgent delivery. This translates in our model to an increase in γ . We can easily show that the fastest option for all $i \in H$ is direct truck. Indeed, as compared to PCL, DT enables saving the time necessary for port-centric operations. Moreover, the total distance traveled when using HIT is greater or equal to the total distance traveled by truck. As we assume that hinterland intermodal transportation is not faster than direct truck (i.e., $x_j T^T \leq x_j T^H + T_j$ for all $j \in \{1, \dots, n\}$), we conclude that HIT is slower than direct truck. We conclude that an increase in γ leads to an increase in the *DT* market area. This is in line with practice where direct truck is used in case of urgent deliveries, at least over moderate distances.

6.4 Effects on other stakeholders

Our analytical results focus on an LSP, as LSPs’ decisions are pivotal in the development of the hinterland. We complement our results with a brief analysis of how the different options affect other stakeholders and their incentives for promoting them.

Municipalities are often involved in the governance of *port authorities* and the port-city interface is attracting a lot of attention (Monios et al., 2018). Conveying maritime containers directly to the hinterland by rail relieves city infrastructure from the presence of quite a few trucks and their associated external effects, whereas PCL creates jobs in the port city, albeit to a decreasing extent due to warehouse automation. *Container terminal operators* often prefer HIT as it improves the port's competitiveness in the hinterland, facilitates increased throughput with constant land use and offers efficient terminal operations (Roso et al., 2009). As an example, Brühl (2018) states that the interface with trucks at APM Terminals in Gothenburg requires four to five times more straddle-carrier resources than transferring to on-dock rail.

Browne and Woxenius (2019) argue that a stage of reintegration of the interests of the city and the port can be added to Hoyle's (1989) five stages of port development. Hoyle's division into stages is used by Ducruet and Lee (2006) in their analysis of port-city relationships, but they also criticize it as it offers no universal development path to follow. Nevertheless, Browne and Woxenius (2019) also identify potential tensions due to the significant land use requirements for new distribution property near ports and a complicated mix between public and private interests. The case of Gothenburg illustrates these somewhat unaligned stakeholder interests as the port authority focuses on PCL and extends its landlord role by investing in warehouses (Heitz et al., 2018), while the container terminal operator APM Terminals builds its growth strategy firmly on HIT (Kristensen, 2019).

Shipping lines might lose control of the transport chain with PCL, as the maritime container fleet they supply is used only port to port. The transport chain is divided at the PCL warehouse and it is not likely that the shipping line is engaged in the hinterland transport beyond that warehouse. A shipping line serving a single port in a port region, however, would prefer a PCL structure since it raises the barrier for the shipper and LSP of using an adjacent port. As the port's gates are often congested, *trucking companies* often prefer driving longer distances once they have loaded a container, thus lowering the risk exposure related to waiting times. However, they are surprisingly often in favor of HIT as they can avoid congestion in the port city as well as at the gates, as discussed by Roso et al. (2009). On the other hand, PCL might enable some companies to avoid picking up containers at deep-sea terminals and to focus instead on semi-trailer transportation from the port-centric facility to the shippers' locations. Moreover, there are examples of dedicated high-capacity shuttles between a port and PCL warehouses, as in Gothenburg where 3 FEU trucks are used, as the port area has private roads with generous legislation.

7 Conclusions

This article explores the impact of hinterland intermodal transportation and port-centric logistics on the efficiency of inland operations for international containerized cargo flow. This topic has attracted extensive attention in the maritime logistics and transport geography literature but predominantly with qualitative approaches and as case studies. To our knowledge, this is the first model-based research contribution on PCL. Instead of studying this concept in isolation, we focus on the relationship between PCL and HIT in order to assess whether these two concepts are competing for the same market area. Our analytical results enable the identification of the optimal market areas for each option. We also identify necessary and sufficient conditions

such that HIT is not impacted by PCL and we show that those conditions are not likely to occur in practice. Based on additional results, we conclude that tensions between PCL and HIT are quite likely to occur, as PCL tends to reduce the volume available for HIT. We additionally analyze how continental containers might help reconcile the two concepts. We show a high potential for continental containers if they can carry a lot of cargo, if the hinterland is large and if the inland terminals are located far away from the port. We draw further insights by proposing an illustrative example and by analyzing how our results can be interpreted in the case of different ports in Europe and in North America. The explanatory power of our model appears quite high and may help managers identify the key elements influencing the development of each option in a given setting.

We hope that this article will pave the way for future research. Some potential avenues of interest are detailed below. First, we focus only on the economic impacts of the different options considered. Other aspects, such as environmental impact or employment, could be additionally considered. Second, recall that as we take an LSP perspective, we consider a tactical model with fixed locations for the inland terminals. This approach might be complemented by a strategic study of where to locate inland terminals. In such a setting, accounting for flow-dependent economies of scale for HIT would be particularly relevant. Third, our study focuses solely on the LSP perspective. We additionally draw some preliminary insights of how the different options affect the other stakeholders. This shows that shipping lines and deep-sea terminal operators might be quite reluctant to accept the development of PCL if the concept is not implemented cautiously. A multiple actor analysis might lead to further findings. This might also complement our results on the potential use of continental containers. In Europe for instance, continental containers are not used extensively as part of intercontinental flows. We highlight some causes for this lack of efficiency, but additional reasons could be sought in the different stakeholders' incentives for using them. Overall, we consider that many new and interesting models could be derived from the development of the research on the inland transportation for containerized cargo.

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