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Container Port Pricing Structure

A Vertical Market Model

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Abstract

A three-stage game is used to model interactions between users, a shipping company, and a container port. Emphasis is placed on modelling the many services provided and priced by a port in order to compare pricing structures and price levels, and the subsequent division of surplus between agents under different port objectives (profit maximisation, efficiency, and second best). We find a strong trade-off between the benefits of the shipping company and those of the port, where the access price (a proxy for a fixed fee) is the preferred instrument to extract/inject surplus, while the other prices induce desired behaviours downstream.

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1.0 Introduction

Along with telecommunications, maritime transport is one of the fastest growing industries, playing a decisive role in the economic development of countries and world economies. More than 80 per cent of all business trading uses maritime transport at some stage (Stopford, 1997; Haralambides, 2007; UNCTAD, 2008). Surprisingly little has been done to understand the economic interaction between the main actors involved: ports, users, and shipping companies. This paper is an attempt at analysing and understanding how the pricing structure of port services might be used to induce behaviour down the market chain so that the port might achieve its goal, either some form of welfare or profit. This is clearly of importance from a policy perspective given the size of this transport market; from a methodological point of view, our contribution is the proposition of a full vertical market model that includes the main technological features of port services. This, in fact, is a necessity; only in such a model — where both the port and the shipping company are represented — is our objective feasible.

Maritime transport is usually categorised according to how the goods are stored in the ships (Stopford, 1997; Haralambides, 2004, 2007; Sjostrom, 2004). *Bulk shipping* refers to goods directly stored in the ship and loaded using systems that are good-specific: fuel, agricultural products, metals, chemicals, or raw materials. Liner shipping deals with shippers who have lower volumes and that do not justify a bulk shipping operation; vessels operate on a scheduled basis, with fixed frequencies between pairs of ports. Liner shipping underwent a radical technological revolution in the mid-1960s with the introduction of containers, which induced changes in vehicles and port infrastructure (Gilman and Williams, 1976; Stopford, 1997; Haralambides, 2004, 2007; Notteboom, 2004; Sjostrom, 2004). While in terms of volume, bulk shipping is still larger than liner shipping, in terms of value, containerised shipping is the main maritime market, with a relative participation of over 80 per cent — the largest transport market in the world. The introduction of the container had a deep impact on the market structure, inducing the formation of shipping companies' alliances interacting with shippers and ports (UNCTAD, 1998).

Maritime transport is a highly complex industry where many agents participate and interact, including shippers — firms that demand maritime transport services to move goods to distant markets — shipping companies, and ports. Their interactions occur along what can be seen as a supply chain: port supplies services that are essential to shipping companies, which in turn sell the end product — transport — to users. Being at the top of the supply chain, it is natural to assume that the port might act strategically to induce specific behaviour on others through prices and characteristics of its services, thus shaping the division of benefits. In other words, port decisions affect the distribution of surplus and wealth along the chain — that is, between shipping companies, users and, obviously, the port. Yet, despite the importance this market has for global trade, the economic research aimed at modelling and understanding the interactions between these agents in general, and the importance of port decisions on the whole chain in particular, is scarce; most of the literature on maritime transport has focused on the optimisation of processes using the tools of operations research and management.

The research on the economics of maritime transport that has been undertaken to date can be roughly grouped in two sets. One deals with the relationship between shipping companies and users — the lower part of the vertical chain — and the other focuses on the interaction between a port and shipping companies — the upper part of the vertical chain. In the former, the emphasis has been usually placed on the importance of competition and service quality on demand (for example, Fox, 1994); while in the second, the main focus has been on the pricing of the different services that a single port offers to the ships. Along this second line, Kim and Kim (2007) estimate pricing structures in two parts that meet different economic criteria for the storage service, whereas Holguín-Veras and Jara-Díaz (1999, 2006, 2010) examine optimal price structures for entrance and storage under several assumptions on demand. However, to our knowledge, no paper has yet considered that the full set of interactions can be seen as a supply chain involving port services, shipping companies, and users. Zan (1999) recognises a hierarchical relation in container shipping, with ports as the market's top players and with shipping companies above the users, acknowledging that the market must be depicted as a two-level problem, although his own market model does not follow this approach (in his model, port behaviour is given). What we want to stress here is that without a vertical model it is short of impossible to try to understand how different prices can be used to send different signals downstream, as discussed below.

Vertical market models have been indeed used for other transport markets, particularly air transport; see, for example, Brueckner (2002), Pels and Verhoef (2004), Zhang and Zhang (2006), and Basso (2008). The air transport literature, however, cannot be applied to the maritime sector by simply relabelling variables, because it has been motivated by runway congestion, and, therefore, efforts have been devoted to model this effect and to find an adequate way of pricing it; for short, only one price, the runway's, has been considered.[1] In our case, we pay careful attention to the technical characteristics of all relevant services that are specific to container ports, and which are indeed priced. We thus model and consider pricing of five different services which enables us to look not only at the *level* of prices (as is the focus on the airport literature), but also at the *structure* of the price vector. Particularly important is to sort out which prices are better suited to transfer surplus without affecting (much) operational decisions, and which prices are better suited to actually induce desired operational behaviour.

Given that we focus on port pricing, a second concern that may arise is whether previous papers — those that only looked at the upper part of the chain — can make our effort redundant. The answer again is no, and the reasons are twofold. On one hand, because without formally modelling the downstream part of the chain, we cannot observe changes in shipping companies' behaviour following changes in port prices; on the other, because not even the distribution of surplus can be well studied since, as proved by Basso and Zhang (2008b), and Basso (2013), the condition that must occur for both approaches — full vertical model and partial upper level model — to be equivalent is perfect competition at the lower level among carriers, which must have constant marginal costs. This is a strong condition unlikely to prevail in maritime transport, where high levels of concentration are observed at ports. Without this condition, the area under the demand curve for ports imperfectly captures shipping companies' profits and final consumers' surplus, making surplus distribution analysis impossible.

[1]A few exceptions are Basso and Zhang (2008a), who consider two prices for peak and off-peak; and Silva and Verhoef (2013), who consider two airport prices: one per plane and one per passenger.

The purpose of this work is to explore and compare pricing structures, and the subsequent division of surplus in port containerised cargo services under different economic objectives: maximising port profit, maximising social welfare, and maximising social welfare subject to cover port costs. Note that social welfare in this case is associated with an international view promoted by influential entities interested in worldwide well-being (as UNCTAD's declared purpose); this also obviously covers the case in which shippers and the shipping firm are the port's co-nationals.[2] For this, we depart from previous unintegrated models to propose a full vertical structure model where a single port interacts with a single shipping company, which in turn interacts with shippers. The choice of monopoly companies along the chain is, we believe, reasonable: on one hand, all previous upper-level models looked at a single port and we remain in that framework; on the other hand, including shipping companies' competition would distract us from our goal (port price structure), while not necessarily being more realistic — as we discuss below. In our game agents move sequentially as follows: (i) the port selects its prices for its services of access, berth provision, unloading, and forwarding cargo; (ii) based on these, the shipping company determines its charges and service levels (frequency of ships and use of cranes) to serve users; (iii) finally, taking into account the shipping company prices and transport times, users decide on the number of containers to dispatch. In our model, operational restrictions relating to the capacity of ships and the port's docking site are considered, so that congestion is a core element. Using reasonable values for all variables in the problem — that is, values that represent an actual route — we numerically obtain the subgame perfect Nash equilibrium, using the analytical solutions of the problem to help build intuition.

Our results show a strong trade-off between the benefits of the liner shipping company and those of the port, where one of the prices — the access price — is the preferred instrument to extract/inject surplus, as it is the one that affects less other (marginal) decisions of the shipping company; in other words, it works as a sort of proxy for a fixed fee. A private port would then attempt to induce profit maximisation downstream using the rest of the prices, while using the access price to extract those monopoly profits. In a sense, the use of a large vector of prices enables the port to diminish the double marginalisation problem and force surplus up the chain, although, importantly, the access price is an imperfect substitute for the fixed-fee, since all other prices are set above marginal costs. A welfare maximising port will, on the other hand, choose to use some prices below the relevant cost to fight back allocative inefficiency caused by market power downstream — at the carrier level — while using the access price to recover costs and achieve exact self-financing. Importantly, the technical relations play a key role: if demand levels and service conditions lead to system saturation (that is, full ships and ports), the port is able to reach maximum social welfare making positive profit, as subsidising to increase traffic is no longer desirable.

The following section contains the formulation of the vertical market model and the analytical developments that help finding equilibrium. Section 3 contains the numerical application, results and comparative analysis. The final section concludes.

[2]Moreover, pursuing the national interest (maximising local welfare) may be better served by profit maximising gateways, as shown by Mantin (2012), and Matsumura and Matsushima (2012), for the case of competing international airports.

2.0 A Simple Model for Maritime Transport

2.1 Stylised facts of the maritime sector

In this part, we describe the way the container port market works nowadays, in order to identify what the main stylised features are, and that we subsequently model. Many economic agents interact in the maritime transport industry: shipyards, business operators, *brokers*, banks, shipping operators, stevedores, land carriers, and so on. Modelling all interactions, however, would preclude a clear understanding of relations; instead, we choose to focus on the interactions among what we consider to be the fundamental economic agents: users (shippers), shipping companies (carriers), and ports. Over the years, shipping companies have become specialised in the transportation and handling of certain kinds of cargo, according to the physical and logistical characteristics thereof. Like shipping companies, ports have also specialised their services, developing complex handling and storage systems for different kinds of cargo, in order to increase their own productivity and that of the whole system (Cullinane and Khanna, 2000; Haralambides, 2004; Midoro *et al*., 2005).

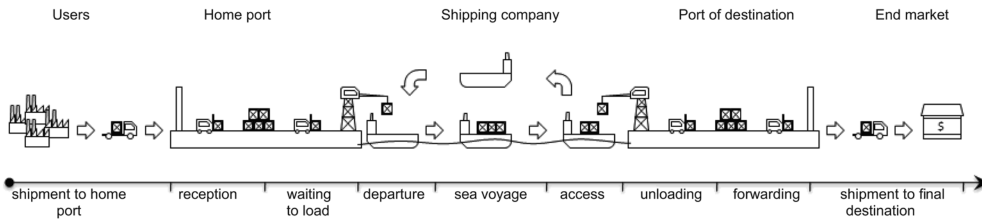
Most ports operate under the *landlord* concept, where the port authority (typically a government public entity) provides the gross infrastructure, while external agents provide the machinery, logistics, and the management required, to carry out the necessary port services. Within this wide range of services, there are three basic ones necessary to transfer cargo from maritime transport to land transport, and vice versa; namely, access to/exit from the port facility, ship loading/unloading, and cargo dispatch/reception via ground transport.

Before the 1960s, this market was dominated by conferences or cartels among shipping companies that served a specific trade route. On the port side, cargo handling was labour intensive (stevedores), such that ships loading–unloading became the most time consuming link in the transportation chain. Since the end of World War Two, trade between continents had been growing at a pace that this system could not cope with, which led to the emergence of the container and of the associated specialised equipment. This had a deep impact in the industry, as its capital intensive nature pushed towards market concentration of both shipping and cargo-handling companies; liner shipping became one of the most concentrated industries in the world (UNCTAD, 1998). Together with concentration, new forms of interactions between agents have emerged in recent years. First, it is common that shipping companies sign arrangements with ports for the exclusive use of (part of) their facilities in the form of dedicated terminals (Haralambides *et al*., 2002). Second, it has become customary in the use and promotion of confidential contracts between shipping companies and shippers, in such a way that shippers can get discounts or benefits by compromising a horizon-based minimum cargo to be shipped (Sjostrom, 2004); in practical terms, this allows shipping companies to price discriminate.

2.2 Modelling

We consider a single origin–destination pair with n shippers (firms or people requesting cargo to be shipped) and a monopolistic shipping company. We assume that the process previous to the arrival of the containers at the home port is not influenced by the shipping company, which only interacts with the users through the prices it charges and the waiting time resulting from the frequency it supplies.

Figure 1
Logistical Schematics of the 'Door-to-door' Transport for a Container



As shippers look for a combination of a cheap and fast transport service, the demands faced by the carrier are not only affected by prices, but also by the times involved in the shipping process. We capture this through the use of a generalised price, defined as the money price for the service, plus the monetary valuation of the time it takes to carry out the door-to-door transport; that is:

$$\rho_i = p_i + VT_i t_i, \quad \forall i, \tag{1}$$

where p_i is the unit shipping charge for shipper i, VT_i is the time value for i, and t_i is the total time of transport, from the moment that the cargo is received at the home port until it is forwarded to the final destination — as depicted in Figure 1. We assume that prices for shippers can be differentiated, based on the fact that many contracts between shippers and carriers are confidential.

The demand x_i of a daily flow of containers with cargo type i is represented as:

$$x_i \equiv F_i(\rho_i) = a - b\rho_i, \quad \forall i = 1, \ldots, n. \tag{2}$$

The user benefit, perceived by each shipper (cargo type) as a result of using maritime transport, is given by the Marshallian surplus; that is:[3]

$$UB_i = \int_{\rho_i}^{\infty} F_i(z)dz, \quad \forall i = 1, \ldots, 1n. \tag{3}$$

The shipping company, on the other hand, has expenses related to two items: moving ships and paying the port for its services. In particular, the carrier will pay R for the access price to enter the port; will pay D for each of m cranes it uses per day; will pay E daily as a charge for occupying a docking site; and will pay P_i per hour to forward the i-type cargo from port to destination. We denote by $\mathbb{P}$ the port price vector — that is, $\mathbb{P} = (R, D, E, \boldsymbol{P})$ — and let f be the sailing frequency, C_0 the fuel consumption by round trip, θ each ship's daily spending on maintenance, t_c the cycle time, tu the unloading time, m the number of cranes the carrier decides to use, and Q_i the forwarding time. We can then write the costs of the shipping company as:

$$CSH(\boldsymbol{x}, f, m, \mathbb{P}) = f(C_0 + \theta t_c + R + (Dm + E)tu) + \Sigma_i P_i Q_i x_i. \tag{4}$$

[3]As transport is a derived demand, consumers' surplus in the case of freight captures welfare variations in the markets where the transported goods are produced and consumed. Production under competitive conditions makes shippers' consumer's surplus exactly equal to total welfare variation in the originating markets, and it is an approximation otherwise (Jara-Diaz, 1986). Imperfectly competitive conditions are studied by Basso (2013).

The shipping company's profit is equal to:

$$\Pi_{sh}(\boldsymbol{p}, \boldsymbol{x}, f, m, \mathbb{P}) \equiv \Sigma_i p_i x_i - CSH(\boldsymbol{x}, f, m, \mathbb{P}). \tag{5}$$

For the (destination) port, costs are:

$$CP \equiv CMa_0 + f(CD_0 + (\tau m + \nu)tu) + \Sigma_i \omega_i Q_i x_i = CP(\boldsymbol{x}, f, m), \tag{6}$$

where CMa_0 represents fixed costs, related to depreciation and maintenance of the container terminal, CD_0 are the costs of dredging the access channel, τ is the daily spending on each (working) gantry crane, m is the number of cranes hired by the shipping company, ν is the daily cost of anchoring per ship, and ω_i is the daily cost of maintaining an i-type container at port. The port profit is then:

$$\Pi_p(\boldsymbol{x}, f, m, \mathbb{P}) \equiv f(R - CD_0 + ((D - \tau)m + E - \nu)tu) + \Sigma_i (P_i - \omega_i) Q_i x_i - CMa_0. \tag{7}$$

The social welfare function must consider the benefits of the three agents participating in the industry; that is, shippers, shipping company and the port:

$$\begin{aligned} SW(\boldsymbol{p}, \boldsymbol{x}, f, m, \mathbb{P}) &= \Pi_{sh}(\boldsymbol{p}, \boldsymbol{x}, f, m, \mathbb{P}) + \Pi_p(\boldsymbol{x}, f, m, \mathbb{P}) + \Sigma_i UB_i(\boldsymbol{p}, \boldsymbol{x}, f, m) \\ &= \Sigma_i (p_i - \omega_i Q_i) x_i - f(C_0 + \theta t_c + CD_0 + (\tau m + \nu)tu) \\ &\quad - CMa_0 + \Sigma_i \int_{\rho_i}^{\infty} F_i(\omega) d\omega. \end{aligned} \tag{8}$$

A key point is to represent adequately the physical and technological relations associated to the transportation process, particularly those involving times related to the different services (see Figure 1). First, a single type of ship characterised by its capacity K_0 (in containers) will be considered. Then an operational capacity constraint must be imposed; that is, the carrier transport capacity has to be enough to accommodate demand:

$$\Sigma_i x_i - K_0 f \leqslant 0. \tag{9}$$

Second, the total time spent by containers have four components: schedule delay at origin; sea voyage; time at port (which comprises access time, unloading, and forwarding); and final shipment to destination. Schedule delay at origin comprises from the beginning of the transport chain to ship departure, and represents the time difference between the actual and desired departure time. Thus, for each cargo i, schedule delay time at origin is represented by LDT_i (*Land Delay Time*), and depends only on the inverse of the sailing frequency:

$$LDT_i \equiv \frac{d_i}{f} \quad \forall i, \quad 1 \geqslant d_i > 0 \quad \forall i. \tag{10}$$

Sea voyage time t_v^0 will be considered as known and fixed, since the operational speed is constant in practice (Stopford, 1997), and the geographical distance between the ports involved is known. Once the ships arrive at the port of destination, the shipping company must hire the access, unloading, and forwarding services. Let us start with unloading time; an important aspect to capture here is that as the number of cranes used increases, their movements at the unloading site become more difficult. This congestion effect is captured through the parameter β in the following expression for unloading time, tu:

$$tu(\boldsymbol{x}, f, m) \equiv \alpha \frac{\Sigma_i x_i}{fm} + \beta m, \tag{11}$$

where α are the days required for a crane to unload a container in an uncongested case (an indicator of the technology's performance).

Access time to the port is modelled as a deterministic queue; the number of docking sites required by the shipping company are, by Little's Law, equal to $f \cdot tu$. We assume that the port has a total of N_0 sites and a base occupation rate of φ_0. The shipping company must operate in such a way that the berthing area does not collapse. This imposes the following constraint:

$$\frac{ftd(\boldsymbol{x}, f, m)}{N_0} + \varphi_0 \leqslant 1 \Leftrightarrow ftu(\boldsymbol{x}, f, m) - N_0(1 - \varphi_0) \leqslant 0. \tag{12}$$

Thus, the access time ta is given by:

$$ta(\boldsymbol{x}, f, m) \equiv \begin{cases} \gamma\left(\varphi_0 + \dfrac{f}{N_0} tu(\boldsymbol{x}, f, m)\right) & \text{if } ftu(\boldsymbol{x}, f, m) - N_0(1 - \varphi_0) \leqslant 0 \\ \infty & \text{if not} \end{cases}. \tag{13}$$

The constraint in equation (13) indicates that the expression is valid as long as the berth site does not become saturated. Finally, we assume that forwarding time Q_i is constant for all types of cargo.

Now that the times involved have been introduced, an accurate expression for 'door-to-door' shipping time for each kind of cargo can be calculated. From equations (10), (11), and (13), we have that:

$$t_i(\boldsymbol{x}, f, m) = \frac{d_i}{f} + t_v^0 + \gamma\varphi_0 + \left(1 + \frac{\gamma f}{N_0}\right) tu(\boldsymbol{x}, f, m) + Q_i, \quad \forall i. \tag{14}$$

Finally, from equations (11) and (13), we can explicitly determine the cycle time t_c, which is of central importance since it determines the necessary fleet (given by f times t_c). Cycle time is:

$$t_c(\boldsymbol{x}, f, m) \equiv 2t_v^0 + ta + tu = 2t_v^0 + \gamma\varphi_0 + \left(1 + \frac{\gamma f}{N_0}\right) tu(\boldsymbol{x}, f, m). \tag{15}$$

The market process is modelled as a full information sequential game and, consequently, we look for Subgame Perfect Nash Equilibrium (SPNE). The economic timing of the game is as follows:

1. The port of destination sets prices for the different services it provides, based on its economic objective (profits, welfare, cost recovery).
2. Based on these prices, the shipping company determines the main characteristics of its service, which are the prices to charge each user, departure frequency from origin, and the number of cranes to be used for unloading cargo at the destination port.
3. Finally, shippers decide how much to ship, based on the service variables directly perceived from the shipping company's operation.

As usual for sequential games, we solve it using *backward induction,* thus considering first users (shippers) behaviour and obtaining their reaction function to the shipping company's decisions; we then move to obtain the shipping company's reaction function to the port's decisions, to calculate finally optimum port prices, considering the reactions of the users and shipping company simultaneously.

2.2.1 Users — shipping company interaction

Each user's demand depends on the generalised price, as defined in equation (1). The time component depends, in turn, on the total demand (because of unloading time), as shown by equation (14). This generates a fixed-point relationship given by:

$$x_i = F_i\left(p_i + VT_i\left(\frac{d_i}{f} + t_v^0 + \gamma\varphi_0 + \left(1 + \frac{\gamma f}{N_0}\right)tu(\boldsymbol{x}, f, m) + Q_i\right)\right) \equiv \Psi_i(\boldsymbol{x}, \boldsymbol{p}, f, m)\forall i. \quad (16)$$

This can be written as $G(\boldsymbol{x}, \boldsymbol{p}, f, m) = 0$, with $G: \mathbb{R}_+^{N+(N+2)} \to \mathbb{R}^N$ defined as:

$$[G(\boldsymbol{x}, \boldsymbol{p}, f, m)]_i \equiv x_i - \Psi_i(\boldsymbol{x}, \boldsymbol{p}, f, m), \quad \forall i = 1, \ldots, n. \quad (17)$$

From equation (17), one can obtain either a function $\boldsymbol{x}^e: \mathbb{R}_+^{N+2} \to \mathbb{R}^N$ depending on prices, frequency, and cranes, or a function $\boldsymbol{p}^e: \mathbb{R}_+^{N+2} \to \mathbb{R}^N$ that depends on demands, frequency, and cranes, depending on the assumptions made for the Implicit Function Theorem; the former will be referred to as the effective demand function, the latter being its inverse. The existence, uniqueness, and differentiability of both functions are guaranteed under some conditions, assumed here.[4]

The complete profit maximisation problem of the shipping company is given in equation (18), and includes three constraints: enough ship capacity; enough berth sites; and a maximum number of cranes per site, $m_{\max}$:

$$\begin{aligned}
&\max_{\boldsymbol{p},f,m} \Pi_{sh}(\boldsymbol{p}, \boldsymbol{x}^e(\boldsymbol{p}, f, m), f, m, \mathbb{P}) \\
&s.t. \\
&\Sigma_i x_i^e - fK_0 \leqslant 0 \qquad (\lambda)\ . \\
&f \cdot tu(\boldsymbol{x}^e, f, m) - N_0(1 - \varphi_0) \leqslant 0 \qquad (\mu) \\
&m \in \{1, 2, com_{\max}\}
\end{aligned} \quad (18)$$

Solving the optimisation problem (18) yields subgame perfect equilibrium prices $\boldsymbol{p}^*$, operation frequency f^*, and number of cranes m^*, all of which depend on the parameters $\boldsymbol{u}$ of the problem and on the port price vectors $\mathbb{P}$:

$$\begin{aligned}
\boldsymbol{p}^* &\equiv \boldsymbol{p}^*(\boldsymbol{u}, \mathbb{P}) \\
f^* &\equiv f^*(\boldsymbol{u}, \mathbb{P})\ . \\
m^* &\equiv m^*(\boldsymbol{u}, \mathbb{P})
\end{aligned} \quad (19)$$

If the effective demand $\boldsymbol{x}^e$ is evaluated at the (conditional) optimal values in equation (19), a new function (depending on $\mathbb{P}$ and $\boldsymbol{u}$) is obtained, which we refer to as a derived demand function; that is:

$$\boldsymbol{x}^e(\boldsymbol{p}^*, f^*, m^*) = \boldsymbol{x}^e(\boldsymbol{p}^*(\boldsymbol{u}, \mathbb{P}), f^*(\boldsymbol{u}, \mathbb{P})^*, m^*(\boldsymbol{u}, \mathbb{P})) \equiv \boldsymbol{x}^d(\boldsymbol{u}, \mathbb{P}). \quad (20)$$

[4] Existence, uniqueness, and differentiability for both $\boldsymbol{x}^e$ and $\boldsymbol{p}^e$ will hold if:
1. $G \in \mathcal{C}^\infty(\mathbb{R}^{(2N+2)}, \mathbb{R}^N)$.
2. Curve $\{(\boldsymbol{x}, \boldsymbol{p}, f, m) \mid G(\boldsymbol{x}, \boldsymbol{p}, f, m) = 0\}$ is continuous and differentiable.
3. The matrices $D_{\boldsymbol{x}}^G \equiv [(\partial G/\partial x_i)(\boldsymbol{x}, \boldsymbol{p}, f, m)]$ and $D_{\boldsymbol{p}}^G \equiv [(\partial G/\partial p_i)(\boldsymbol{x}, \boldsymbol{p}, f, m)]$ are invertibles in G's domain.

This is the demand function — in terms of number of containers — that the port faces when interacting with the shipping company. In other words, if the port changes one or more prices, it will eventually see container demand react according to equation (20).

2.2.2 Shipping company — port interaction

Irrespective of the port's objective function, the port is subject to capacity constraints related to the berth sites, number of cranes, and forwarding area. The former two were already considered by the shipping company. Letting E_0 be the total size (in sites) of the forwarding area and H_i be the pile height that may be formed with i-type containers, the third constraint is as follows (see the Appendix for details):

$$\Sigma_i \frac{x_i^d Q_i^2}{H_i} + \Sigma_i \frac{x_i^d Q_i}{f^d H_i} \leqslant E_0. \tag{21}$$

The port then chooses its price vector considering equation (21), its specific objective function, and the fact that the (private) shipping company must, at least, cover its costs; otherwise, it would choose not to participate in the market.

The problem that a private port solves to choose its price vector $\mathbb{P}$ is:

$$\begin{aligned} &\max_{\mathbb{P}} \Pi_p(\boldsymbol{x}^d, f^d, m^d, \mathbb{P}) \\ &s.t. \\ &\Sigma_i \frac{x_i^d Q_i^2}{H_i} + \Sigma_i \frac{x_i^d Q_i}{f^d H_i} - E_0 \leqslant 0 \quad (\tau) \\ &-\Pi_{sh}(\boldsymbol{p}^d, \boldsymbol{x}^d, f^d, m^d, \mathbb{P}) \leqslant 0 \quad (\eta) \end{aligned} . \tag{22}$$

A port that maximises social welfare subject to self-financing (second-best) solves:

$$\begin{aligned} &\max_{\mathbb{P}} SW(\boldsymbol{p}^d, \boldsymbol{x}^d, f^d, m^d, \mathbb{P}) \\ &s.t. \\ &\Sigma_i \frac{x_i^d Q_i^2}{H_i} + \Sigma_i \frac{x_i^d Q_i}{f^d H_i} - E_0 \leqslant 0 \quad (\tau) . \\ &-\Pi_{sh}(\boldsymbol{p}^d, \boldsymbol{x}^d, f^d, m^d, \mathbb{P}) \leqslant 0 \quad (\eta) \\ &-\Pi_p(\boldsymbol{x}^d, f^d, m^d, \mathbb{P}) \leqslant 0 \quad (\kappa) \end{aligned} \tag{23}$$

Finally, to maximise unrestricted welfare (the first best), the analytical problem to be solved is identical to equation (23), disregarding the port's cost coverage restriction.

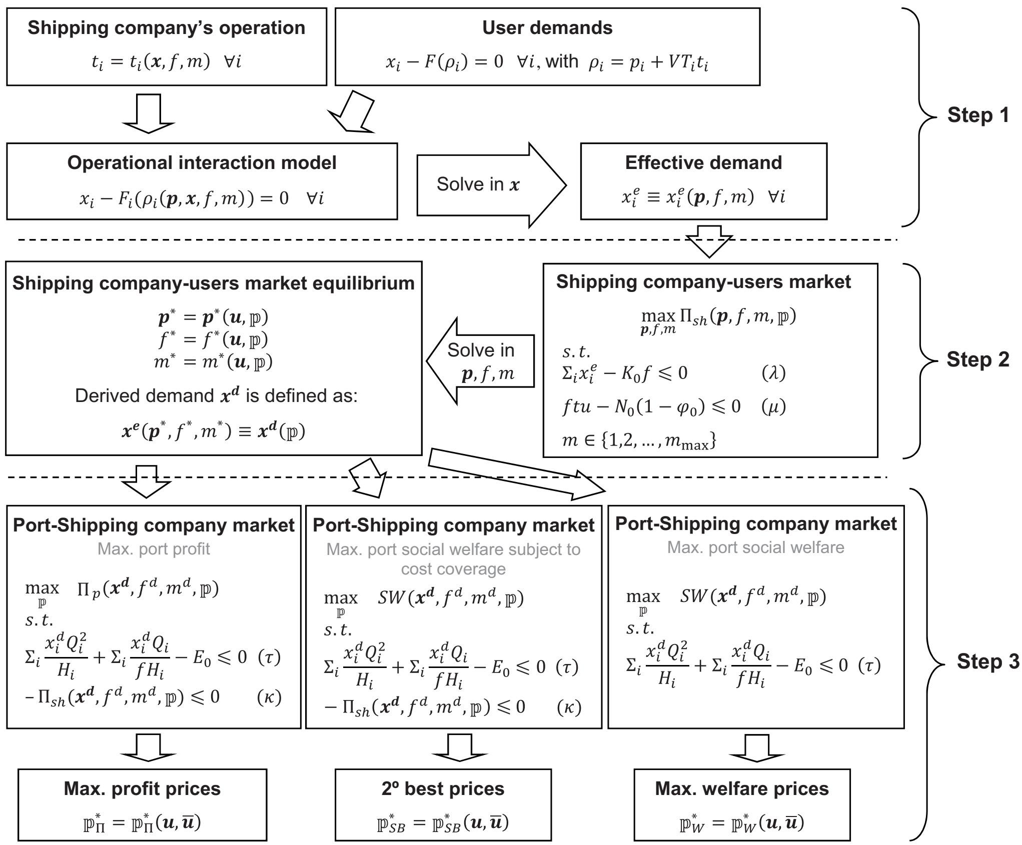
These problems yield the optimal port prices $\mathbb{P}^*$, which, in turn, fully determine the subgame perfect equilibrium by simply replacing them back into the previously obtained subgame shipping prices, frequency and number of cranes, and then into the effective demands.

3.0 Numerical Application and Discussion

3.1 Simulation and results

Figure 2 depicts the *backward induction* process we follow to solve for equilibrium. In Step 1, the effective demand function is obtained; then, in Step 2, the shipping company-

Figure 2
Backward Induction Process



user interaction is solved parametrically in port prices, which yields the optimal strategy for the shipping company (the reaction functions) and the derived demand functions faced by the port (***u*** represents the exogenous operational parameters). The port's optimal prices are finally obtained in Step 3 using the derived demands and the shipping company's reaction function or optimum strategy.

Next, we find the subgame perfect equilibrium numerically, taking input parameters from various sources using as a basis the characteristics of the route between New Jersey and Rotterdam ports, served by Maersk.[5] The values are shown in Table 1.

These values were used to solve (using the procedure summarised in Figure 2) the different port's objectives, adding a fourth case namely a free port (that is, $\mathbb{P} \equiv 0$), as a proxy for a vertically integrated (or dedicated) port. The results of the numerical optimisation process

[5]Sources for the parameters in Table 1 include, for example, Notteboom (2006) for the demand functions, Harrison and Figliozzi (2001) for fuel consumption, and Eisma (2005) for dredging. Technical information was obtained also from Maersk's, port of Rotterdam's and APM Terminal's web pages. For a detailed explanation of sources and figures, see Muñoz-Figueroa (2009).

Table 1
Numerical Values of the Model's Input Parameters

Parameter	*Value*	*Units*	*Parameter*	*Value*	*Units*	*Parameter*	*Value*	*Units*	*Parameter*	*Value*	*Units*
VT_1	270	$\frac{\text{US\$}}{\text{day}}$	t_v^0	11	days	H_1	5	$\frac{\text{container}}{\text{site}}$	a	2,000	$\frac{\text{container}}{\text{day}}$
VT_2	250	$\frac{\text{US\$}}{\text{day}}$	$m_{\max}$	4	$\frac{\text{cranes}}{\text{ship}}$	H_2	5	$\frac{\text{container}}{\text{site}}$	b	0.2	$\frac{\text{container}^2}{\text{US\$ day}}$
Q_1	1	$\frac{\text{days}}{\text{container}}$	C_0	1.47×10^6	$\frac{\text{US\$}}{\text{ship}}$	E_0	2,000	sites	K_0	4,800	$\frac{\text{container}}{\text{ship}}$
Q_2	1	$\frac{\text{days}}{\text{container}}$	θ	80,000	$\frac{\text{US\$}}{\text{ship}}$	CMa_0	15,000	$\frac{\text{US\$}}{\text{day}}$	γ	0.175	$\frac{\text{days}}{\text{ship}}$
d_1	0.5	$\frac{\text{ships}}{\text{container}}$	α	0.00138	$\frac{\text{days} \cdot \text{crane}}{\text{container}}$	CD_0	10,500	$\frac{\text{US\$}}{\text{day} \cdot \text{container}}$	φ_0	0.85	dimensionless
d_2	0.5	$\frac{\text{ships}}{\text{container}}$	β	0.12	$\frac{\text{days} \cdot \text{ship}}{\text{container}}$	τ	18,500	$\frac{\text{US\$}}{\text{crane} \cdot \text{day}}$	N_0	4	ships
ν	3,000	$\frac{\text{US\$}}{\text{ship} \cdot \text{day}}$	ω_1	200	$\frac{\text{US\$}}{\text{day} \cdot \text{container}}$	ω_2	200	$\frac{\text{US\$}}{\text{day} \cdot \text{container}}$			

Table 2
Optimum Port Prices for Each Port Service

Port objective	Access: R (US$/ship)	Unloading: D (US$/crane · day)	Unloading: E (US$/ship · day)	Forwarding: P_1 (US$/container · day)	Forwarding: P_2 (US$/container · day)
Maximum profit	4,369,515	52,762	663,612	1,488	1,721
Second best	812,500	1,716	87,500	12	38
Maximum welfare	401,937	−88,204	−234,259	−3,003	−3,325
Free port	0	0	0	0	0
Marginal costs	46,460	[1,971; 4,980]	1,440	227	227

Table 3
Shipping Company's Optimum Decisions and Equilibrium Demands

Port objective	User 1 price (US$/container)	User 2 price (US$/container)	Frequency (ship/day)	Cranes (cranes/ship)	User 1 demand (containers/day)	User 2 demand (containers/day)
Maximum profit	3,627	3,932	0.1110	4	259.14	273.44
Second best	3,040	3,215	0.2391	4	513.59	543.53
Maximum welfare	2,445	2,445	0.2809	4	641.98	706.34
Free port	3,056	3,214	0.2759	4	533.50	565.17

Table 4
Benefits by Agent and Social Welfare

Port objective	Shipping Company (US$/day)	Port (US$/day)	User 1 (US$/day)	User 2 (US$/day)	Social welfare (US$/day)
Maximum profit	87,785	1,407,281	167,880	186,927	1,849,857
Second best	2,228,111	0	659,447	738,569	3,626,127
Maximum welfare	6,852,735	−4,850,093	1,030,331	1,247,288	4,280,261
Free port	2,510,045	−277,016	711,558	798,556	3,743,143

are shown in Tables 2 (port prices and port marginal costs), 3 (shipping company decisions), 4 (benefits by agent), and 5 (system performance), for each objective of the port. In the Appendix, the procedure for the calculation of marginal costs is shown.

3.2 Analysis

Before analysing the results, it is important to highlight two things. First, there is the role of the private (profit maximising) shipping company as an intermediary between users and the port. Indeed, many of the port charges are passed-through to users, yet the fraction that is

Table 5
Shipping System's Performance and Shipping Company Multipliers

	Occupancy rate					
Port objective	*Ship*	*Dock*	*Forwarding area*	*Shipping time (days)*	λ	μ
Maximum profit	1	0.909	0.533	18.8	9.174	0
Second best	0.92	0.970	0.548	16.27	0	0
Maximum welfare	1	1	0.615	16.09	85.71	4,850,961
Free port	0.83	0.978	0.508	15.84	0	0

passed depends on the nature of the service hired from the port and on the flexibility of the shipping company to react to price changes. This can be clearly seen by looking at the first-order conditions related to the shipping company's maximisation problem (equation 18), which leads to the following shipping prices:

$$p_j^d = (Dm + E) f \frac{\partial tu}{\partial x_j} + P_j Q_j + \theta f \left(\frac{\partial ta}{\partial x_j} + \frac{\partial tu}{\partial x_j} \right) + \lambda + \mu f \frac{dtu}{dx_j} - \Sigma_i \frac{dp_i^e}{dx_j} x_i^d, \quad \forall j. \tag{24}$$

There are two relevant aspects to this equation. First, there is the ability of the shipping company to transfer to each user the marginal costs of the unloading and forwarding services induced by its own unloading capacity. Second, the fact that the access price R does not directly appear here, implying that access price changes will induce shipping price changes only indirectly through changes in frequencies, as can be seen from the following equation obtained from subgame first-order conditions:

$$f^d = \frac{\Sigma_i \frac{dp_i^e}{df} x_i^d + \lambda K_0 - R - C_0 - \theta ta - \left(Dm + E + \mu + \theta\right) tu}{\theta \frac{\partial ta}{\partial f} + \left(Dm + E + \mu + \theta\right) \frac{\partial tu}{\partial f}}. \tag{25}$$

The second issue we want to highlight is that, following equations (24) and (25), the port can induce changes both on the pricing and on the operation of the shipping company through price manipulation. However, these are linear prices and, therefore, the port faces a trade-off: it may use prices to induce a desired behaviour downstream, but this will imply losing control on the flow of surpluses; or it can use prices to capture downstream surplus, but this may imply inducing suboptimal behaviour. The typical and most extreme example of this is the double marginalisation phenomenon that occurs in the consecutive monopolies model. In that case, the upstream monopolist has to accept inducing sub-optimal behaviour to the downstream monopolist in order to capture surplus because, if it tries to induce profit maximisation downstream, it lacks an instrument to capture those profits later. The vertical control literature teaches us that if a second non-linear instrument — such as a fixed-fee — can be used, then things are solved for the upstream monopolist: it can use the linear price to induce any behaviour (for example, profit maximisation downstream), while using the fixed fee to capture all the surplus. It only needs to worry about leaving the downstream firm with positive (yet arbitrarily small) profits.

The point in our case is that the port acts as an upstream monopolist but lacks the fixed-fee instrument. However, it does have an important number of linear prices to use, which are linked to a number of different services that interact in complex ways. The central question then is how these prices can be used to induce both behaviour and surplus transfer simultaneously. We pursue this analysis now.

The results in Table 2 show that, as expected, the differences in prices across the different objectives are very large, and every port price diminishes as the port moves away from the maximum profit objective; some even take negative values under maximum welfare.

The private port — an upstream monopolist in this model — is characterised by very large values of both *R* and *E* prices: they are more than 100 times larger than the marginal costs. In essence, in the absence of a fixed fee, the port uses both the access and dock use prices as the best proxies. This occurs because the shipping company's demands for access and lay time at the port are rather inelastic, and, at the same time, higher charges on those two services are the ones that induce fewer distortions in the pricing of the shipping company. That these two prices are imperfect substitutes for a fixed-fee is shown by the fact that the remaining prices are still above the corresponding marginal costs, implying that the port still finds it optimal to sustain positive margins: the use of five linear prices enable to diminish but not to eliminate double marginalisation. One way to check that this is the case is to look at what happens when the port is free. In that case, the sum of profits of the port and the shipping company is higher, but the port itself obtains negative profits, meaning that either the port needs a fixed-fee to actually capture that surplus, or it would need to vertically integrate.

First and second-best ports face a specific task which is to reduce the allocative inefficiencies caused by the shipping company, a monopoly that exercises market power through distorted choices of price, frequency, and use of cranes. The way to overcome these deadweight losses is by inducing the shipping company to offer smaller prices and better service; in order to achieve this, the port has to *subsidise* the shipping company by artificially reducing its marginal costs through lower port prices. Indeed, in a simple two-layer chain and with only one upper level price, the welfare maximising level for that price will be below marginal cost and, depending on the severity of market power, might end up being below zero; this reduces downstream costs, inducing larger output, up to the efficient level. This intuition explains why for the first-best case, four out of five port prices are negative. But why does *R* remain positive? The issue here is technological: low forwarding and unloading prices increase demand, as desired, but both the ships and the dock end up working at capacity. The way the port deals with the threat of overflowing — given the capacity it features — is by charging more per ship that enters; that is, by increasing *R* above marginal cost.

The second best-port has to tackle two additional constraints in its quest to restore efficiency. First, it is not allowed to charge negative prices, a reasonable real-life constraint; second, it has to cover costs. Income made through a somewhat large *R*, though, is not enough to compensate the losses generated by prices equal to zero in the rest of the services. What the port does then is something similar to what a private port does: it uses *R* to draw more income and cover costs — doubling what the first-best port charges — but it also finds it optimal to use the other prices to some extent. Note that, as opposed to Ramsey pricing, where an optimal (positive) departure from marginal cost pricing can be calculated, here marginal costs are not the efficient charges but something below that, as the first-best shows and for the reasons explained above.

The analysis of the second-best case strengthens the conclusion regarding the role that R can play. On the one hand, we can see that R is indeed an imperfect substitute for a fixed-fee, because if the port could use one, it would be able to achieve cost recovery while charging zero in all other prices. However, as for the private port, R is far from being a useless tool: it enables capturing enough income so that, with the help of the other (smaller) port charges, frequency increases by 115.4 per cent and final prices for both user types diminish. These two effects together make equilibrium demands go up by nearly 100 per cent, which yields an important increase in welfare — as can be seen from Table 4: social welfare almost doubles.

Yet, how good is the second-best under these circumstances? Note first that for maximum profit, port prices explain half of the shipping charges; and for second-best, they mean only about 2 per cent — an improvement indeed. But under maximum welfare port prices actually represent a subsidy of about 60 per cent, a quite different outcome. This is reflected in the fact that the second-best only achieves 85 per cent of the first-best welfare level. And although the first-best might be an unattainable benchmark due to the required subsidies, what is interesting is the fact that a free port achieves higher social welfare than the second-best port. This means that the relatively small losses of the port are more than compensated by the increase in profits experienced by the shipping company, plus the gain in users' welfare. This suggests that vertical integration could be convenient — that is, a dedicated terminal where the shipping company owns the concession. This would not only increase profits for the company, but also would increase users' welfare.

Regarding the use of the different facilities involved in the process, Table 5 shows that, first, the dock is increasingly used as welfare increases because (as seen earlier) frequency increases. For maximum welfare, both the dock and the ship are used to maximum capacity because the combination of price and frequency experienced by the users makes demand high enough to saturate the system. As the ship and the port are operating at capacity, the corresponding multipliers in the shipping company optimisation problem (Step 2) are different from zero, but the dock multiplier is much larger than that of the ship. This means that an external increase in dock capacity would be more profitable for the shipping company than an external increase in ship size; this is due to the negative port prices that make it profitable for the shipping company to be able to unload more containers at the port. Lastly, as the port departs from profit maximising, total shipping time shortens, although the shortest time is achieved under the free port policy due to the low occupancy of the ships.

Time value is an inherent characteristic of users that may be related to their participation in international trade, reflecting the potential value goods have to the principal customer. So, what is the importance of users' time values in the market equilibrium? The role these elements play can be seen first by observing from Table 3 that the shipping company charges the lowest prices to the user with the largest time value, something that might look counter-intuitive. The explanation lies in that both users experience the same shipping time; thus the company may charge more for the less time-sensitive cargo (user 2). This very argument explains the pricing structure for the forwarding service: since the port knows that the shipping company will transfer these charges to the users, it is a useful tool to extract surplus from these latter agents. This only reflects the power held by the port because it is able to directly draw surplus from both the shipping company and the users, making use of its prices.

To explore further the role of values of time, we make the experiment of continuously decreasing them. Results show that shipping charges increase relative to the base case for both users, which is consistent with the observation that optimal prices are larger for the user with the smaller value of time. A most important result is that when time values are small *enough*, the welfare maximising port makes no losses — that is, first and second-best pricing coincide. The explanation is simple: smaller values of time mean smaller full-prices, which imply more demand, *ceteris paribus*. However, because in the first-best, both the ships and the mooring site work at capacity, high prices are needed to keep the port from overflowing. Those high prices enable port cost recovery under welfare maximisation.

In the case of an increase in time values, full-prices increase *ceteris paribus*, making demand smaller; this opens space for prices to decrease, at least up to the point where they induce usage at capacity. Overall, prices and service levels adjust, but there are no relevant additional insights.

4.0 Conclusions

The full set of interactions involving port services, shipping companies, and users has been represented in a game theoretical model, explicitly representing transport technology that captures congestion effects caused by ships' capacity and ports' docking site. The purpose is to explore and compare pricing structures and the subsequent division of surplus in port containerised cargo services under different economic objectives: maximising port profit, maximising social welfare, and maximising social welfare subject to cover port costs.

A vertical structure model where agents move sequentially is set to represent interactions between users and the shipping company, and between the shipping company and the port. The port selects its prices for access, berth provision, unloading, and forwarding cargo; a monopolistic shipping company sets its charges, frequency of ships, and use of cranes to serve users; users decide on the number of containers to dispatch, taking into account the shipping company prices and transport times. Using actual representative values for all variables in the problem, the subgame perfect Nash equilibrium is obtained for each case.

Results reveal a marked trade-off between the benefits of the liner shipping company and those of the port. The access price is the preferred instrument to extract/inject surplus, as it is the one that affects less other (marginal) decisions of the shipping company; in other words, it works as a sort of proxy for a fixed fee. A private port then attempts to induce maximum profits downstream using the rest of the prices, while using the access price to extract those profits, thus diminishing the double marginalisation problem and forcing surplus up the chain. The access price, though, is an imperfect substitute for the fixed fee, and, therefore, the other four prices remain above marginal cost. A welfare maximising port will choose prices below marginal costs to fight back allocative inefficiency caused by market power downstream — at the carrier level — while using the access price to either recover costs (if self-financing is imposed) or to control the use of port capacity. The technical relations play a key role: when the level of demand and service conditions lead to a system saturation (that is, full ships and ports), the port might be able to reach maximum social welfare making positive profit, as subsidising to increase traffic is no longer desirable. The free port — that is, a dedicated terminal where the shipping company owns the concession — is shown to be an interesting case that may yield higher social welfare than second-best, increasing both profit for the company and users' welfare, which makes the case of a dedicated terminal or vertical integration superior to a public port that has to self-finance.

The vertical maritime transport model presented here could be used as a basis to move forward in various directions. One is to consider inter and intra port competition, which would bring into the picture horizontal strategic interactions. Also, the introduction of demand and cost uncertainty would be a necessary element if investment paths become part of the analysis. As seen here, frequency plays a multi-faceted role, which suggests that introducing different types of ships could be an interesting addition to the model as well. Finally, we have explored here the use of prices as a mechanism to distribute surplus, but this could be achieved by other means that should be explored as well, such as the analysis of vertical arrangements, as previously examined in the air literature (see Yang *et al*., 2015; and references therein).

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Appendix

Derivation of the forwarding area constraint

Each ship that arrives at port will unload $k_i = x_i/f$ i-type containers in the forwarding area, and each of these containers will remain Q_i days, inducing the use of $k_i Q_i/H_i$ sites in the forwarding area. Besides, if the forwarding time Q_i is greater than the time elapsed between consecutive ship arrivals, $T = 1/f$, the space requirements for i-type containers are larger than the $k_i Q_i/H_i$ sites per ship. These will be captured by the floor function of the ratio between dwell time Q_i and inter-arrival time T; in that case, the space requirement of the i-type cargo is $\lceil Q_i/T \rceil k_i Q_i/H_i$, and the total space use in the forwarding area is equal to:

$$\Sigma_i \frac{k_i Q_i}{H_i} \left\lceil \frac{Q_i}{T} \right\rceil = \Sigma_i \lceil Q_i f \rceil \frac{k_i Q_i}{H_i} = \Sigma_i \frac{\lceil Q_i f \rceil}{f} \frac{x_i Q_i}{H_i}.$$

Finally, we use that $\lceil a \rceil \leqslant a + 1$ to write the space constraint as:

$$\Sigma_i \left(Q_i + \frac{1}{f} \right) \frac{x_i Q_i}{H_i} = \Sigma_i \frac{x_i Q_i^2}{H_i} + \Sigma_i \frac{x_i Q_i}{f H_i} \leqslant E_0,$$

where E_0 is the capacity (in sites) of the forwarding area.

Calculation of port marginal costs

The port cost function given by equation (6) can be separated into five parts:

$$CP(x_1, x_2, f, m) = CMa_0 + \overbrace{fCD_0}^{CP_0} + \overbrace{fm\tau tu}^{CP_1} + \overbrace{f\nu tu}^{CP_2} + \overbrace{\Sigma_i \omega_i Q_i x_i}^{CP_3}.$$

We then have to associate each port charge to a service. Note that both R and E are charges per ship, while D is a charge per crane, and P_1 and P_2 are charges per container. We therefore calculate marginal costs as follows:

$$\frac{\partial (CP_0 + CP_1)}{\partial f} \Rightarrow \mathrm{MgC}_R,$$

$$\frac{\partial CP_1}{\partial m} \Rightarrow \mathrm{MgC}_D,$$

$$\frac{\partial CP_2}{\partial f} \Rightarrow \mathrm{MgC}_E,$$

$$\frac{\partial CP}{\partial x_i} \Rightarrow \mathrm{MgC}_{P_i}, \quad \forall i.$$

It immediately follows that both MgC_R and MgC_E are constant, given the functional form for tu, since $tu + f(\partial tu/\partial f) = \beta m$. Also, MgC_{P_i} are constant, since both ω_i and Q_i are. Finally:

$$\mathrm{MgC}_D = f\tau \left(tu + m\frac{\partial tu}{\partial m} \right) = f\tau \left(\alpha \frac{\Sigma_i x_i}{fm} + 2\beta m \right),$$

being the only variable marginal cost.