NEARSHORING AND OFFSHORING FOR GLOBAL SUPPLY CHAIN NETWORKS: A TOTAL LANDED COST PERSPECTIVE

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Abstract

Lengthy and highly variable customs’ clearance processes and service times at ports of entry, along with the associated emissions generated from transporting cargo from far away production sites can severely erode the efficiency of offshoring within global supply chain networks. Nearshoring, namely the practice of allocating manufacturing capacity next to demand points, is a corporate countermeasure to such issues. This paper proposes a novel, total landed cost decision-making methodology for the identification of the optimal mixture of near-shore/offshore production capacity allocation and the optimal port of entry taking into account free trade and sustainability-related issues for global supply chain networks. Various “what-if” analyses of interest to practitioners (C-level executives, corporate planners, and regulators) are conducted, and interesting managerial insights are discussed.

Keywords: Global supply chain network design, Logistics Performance Index - LPI, CO₂ emissions, Lead time variability, Nearshoring

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INTRODUCTION

One of the ten “flatteners” in the globalized landscape (“The World is Flat”, Friedman, 2007) is the supply chain practice of offshoring. Its success hinges upon: (i) reduction in tariffs, (ii) low production costs in low cost countries (LCC), and (iii) the development of cost efficient supply chain networks that exploit economies of scale utilizing containerized cargo. To that effect, global supply chain network design which has emerged as a critical issue for many global companies has a number of challenges to tackle. First, as supply chains are spreading spatially, they are even more exposed to unpredictability, while they need to maintain a low carbon footprint. As a result, the design of global supply chain networks needs to take into account systematically both the lead time variability when sourcing from offshore LCC countries and the greenhouse gas emissions generated from the transportation of cargo. In this work, we propose a novel methodological framework for the strategic design of global supply chain networks and evaluate the impact of free trade and sustainability on supply chain network design. The key issues related to the proposed methodology are introduced and/or discussed in the following paragraphs.

Cross-border trade has as critical bottlenecks customs’ clearance processes at entry points (often ports). Although effective trade facilitation policies, such as the European Commission’s “Customs 2013” Program, aim to reduce delays at customs, the relevant clearance and service times still vary significantly among different countries, often due to poor quality in their customs’ management, inefficient procedures, corruption, etc. These delays and their associated variability affect negatively the total lead times of a supply chain network (Arvis et al., 2007a, 2010). This trend is further exacerbated by the overutilization of ports globally. Port congestion and the hidden costs of delays are of extreme concern to globalized companies which should undertake several countermeasures to protect themselves against the relevant risks (Stalk, 2009). Consequently, total “door-to-door” lead times are characterized by
increased volatility and need to be captured in the strategic network design (Meixell and Gargeya, 2005). However, most existing research efforts tackling the problem of the strategic design of global supply chain networks take into account tariffs, duties, transfer prices, volatile exchange rates and other global market uncertainties (see Goetschalckx, Vidal, and Dogan, 2002; Meixell and Gargeya, 2005; Bookbinder and Matuk, 2009), while ignoring the impact of time variability and delays along the network’s nodes and paths. Furthermore, there are only few papers allowing for variable lead times (e.g. Das and Sengupta, 2009).

The World Bank in a comprehensive study (Arvis et al., 2007a), analyzed extensively a large number of indicators for 150 countries regarding their domestic logistics environment and supply chain performance and in conjunction with expert opinion, ranked the efficiency and responsiveness of a country’s national logistics system through the development of the “Logistics Performance Index” (LPI). This index is scaled between 1-5 and is based on a country’s: (i) customs clearance process efficiency, (ii) logistics infrastructure, (iii) ability to handle international shipments, (iv) local logistics industry competence, (v) ability to track and trace international shipments, (vi) domestic logistics costs, and (vii) timeliness of shipments in reaching destination. The Bank updated these indexes just recently with a follow-up study (Arvis et al., 2010). The LPI has been utilized in only a couple of research efforts other than global supply chain network design (Memedovic et al., 2008; Gogoneata, 2008).

The challenge for efficient offshoring is further complicated as transporting cargo over long haul distances with a variety of transportation modes causes an increased release of CO₂ and other emissions. The IBM Institute for Business Value (2010) surveyed 664 supply chain management executives in 29 countries around the world to identify the key issues for global supply chain design and operations. One of the results of this survey is that elite globalized companies model their supply chain networks with volatility and sustainability in mind. Indeed, sustainability has appeared during the last few years at the top of the corporate agenda,
and has established itself as a critical issue affecting the strategic design of supply chain networks. Researchers have attempted to assess the cost of carbon dioxide emissions (e.g. Howarth, 2006) and to integrate environmental issues in supply chain network design (e.g. Ramudhin, Chaabane, and Parquet, 2009).

Globalized companies have been employing Total Landed Cost (TLC) methodologies in order to make decisions based on a comprehensive cost methodology. TLC is the sum of all costs associated with manufacturing and delivering products to the point where they produce revenue, capturing both obvious and hidden costs associated with sourcing and logistics (Third-Party Logistics Study, 2010). Thus, with the adoption of TLC, there are cases where offshoring may be suboptimal when capturing comprehensively the impact of: (i) order lead times on pipeline and strategic emergency stock holding costs, and (ii) the increased emissions produced due to transportation.

Strategic emergency stock is the additional inventory needed throughout the strategic planning horizon that is used as a “hedge” against irregularly high delays due to production or supply disruptions without considering specific inventory policies employed, as it differs from the common safety stock maintained to mitigate demand variability (Sheffi et al., 2003). Such systemic perspectives have led managers to scrutinize the merit of new practices for supply chain network design. A corporate countermeasure to this, is the practice of nearshoring, namely the allocation of the supply chain’s manufacturing capacity relatively close to its serving markets (The Economist, 2005).

Despite its extended utilization in practice, there are only few papers assessing the nearshoring practice. Bock (2008) proposes a model, in order to evaluate the resulting trade-off between wages and worker skills in offshore and nearshore production facilities for mass customization manufacturing systems. Li, Porteus, and Zhang (2001) consider an overseas and a home-based plant and decide on which facilities to operate under varying exchange rates and
uncertainties in demand. Warburton and Stratton (2005) and Fredriksson, Jonsson, and Medbo (2010) demonstrate that under certain conditions a strategic combination of onshore and offshore manufacturing can be more profitable than a 100% offshore approach.

This work proposes a novel methodological decision-making framework for the strategic design of global supply chain networks that can identify the optimal nearshore/offshore production capacity allocation and the optimal supply chain path (generally determined by the port of entry), while capturing the effect of lead time variability and sustainability. To our knowledge, it is the first time that offshoring/nearshoring, trade facilitation and sustainability are investigated comprehensively while designing a supply chain network.

The rest of the paper is organized as follows. In the next section we describe the problem under study. We then present the developed analytical models that capture quantitatively the impact of free trade and sustainability-related parameters on supply chain network design. To that effect, we investigate indicatively six rather simplistic problem instances. In the subsequent section a “what-if” numerical analysis is provided and various interesting managerial insights are discussed. Finally, the last section summarizes the findings of this research.

**PROBLEM UNDER STUDY**

In this section we tackle a problem that we have encountered in a number of manufacturing companies based in the EU. More specifically, assuming offshore and nearshore production facilities and one or multiple markets, we are aiming to determine the optimal mixture of production capacity allocation between the production facilities and the optimal path that minimize Total Landed Cost for “green” and traditional supply chains. To that effect, we first consider a single market that may be served by two factories, one offshore and one nearshore.

Figure 1a depicts the supply chain network under study. Specifically, a regional market (M₁) located within the European Union (EU), is served from one offshore factory (F₁) located in S.E. Asia, and one nearshore factory (F₂) located within the EU. To access the market, contai-
nerized cargo originating from the offshore factory and using an intermodal network may employ two alternative paths passing through either one of two distinct ports of entry with customs P₁ or P₂, respectively. The ports have differently efficient and responsive customs and port service systems.

(Insert Figure 1 here)

The designer for such a supply chain network needs to decide comprehensively using a TLC approach for the optimal mixture of production from the offshore and nearshore facilities and the optimal port of entry for the offshore supply source. Additionally, it would be of great interest to a C-level executive and/or a corporate planner to further explore design changes when sustainability issues are also taken into account.

To that effect, we investigate sequentially the system’s behavior for three problems. In the first problem we investigate the issue of optimal sourcing mixture, in the second we add the issue of optimal port selection, while in the third problem the issue of sustainability is further taken into account.

More specifically, the first problem under study involves the determination of the optimal mixture of production capacity allocation between the offshore (having only one port of entry to be channeled from) and the nearshore production facilities that minimizes Total Landed Cost as this is comprised by: (i) production, (ii) transportation, (iii) pipeline holding, and (iv) strategic emergency stock holding costs. The system is examined on a strategic time horizon assuming deterministic demand and stochastic lead times; thus, it captures the impact of lead time variability on the strategic emergency stock holding cost. The variability of total lead time is captured by utilizing the LPI index.

On the second problem, we allow an alternative port of entry for the offshore facility, thus creating two possible transportation paths (as shown in Figure 1a) to study the additional impact of trade facilitation issues. The strategic decision involves both the optimal mixture of
production capacity allocation and the identification of the optimal path that minimize Total Landed Cost.

Finally, the third problem investigates the additional impact of sustainability taking also into account the cost of transportation-related emissions.

All three problems are studied for two different networks. In the first network (Network 1) we consider a single market (M₁) (Figure 1a), while in the second network (Network 2) we consider two markets (M₁ and M₂) which can be sourced directly by the two factories (F₁ and F₂) (Figure 1b).

The combination of the three problems and the two networks lead to six (6) problem instances which are studied in the next section (Table 1).

(Insert Table 1 here)

MODEL DEVELOPMENT

Main assumptions and nomenclature

We assume that demand \( D_k \) is deterministic for market \( M_k \), \( k = 1, 2 \). Lead times are comprised of the transportation time, the delays in total transportation caused by the logistics network infrastructure limitations, and the clearance and service times in customs. The total lead time for shipping a container from factory \( F_i \) to the market (“door-to-door”) is a random variable and is denoted by \( t_i \) with cumulative distribution function \( G_i(\cdot) \). Two alternative supply paths are predefined, as well as the appropriate transportation modes (ship and truck) for each segment of a path.

We assume that all costs are proportional to the volume of products produced or transported. The pipeline inventory cost per container transported depends on total order lead time. We further allow the charging of holding costs for maintaining strategic emergency stocks. These stocks are used only in case of irregularly high values of the total lead time (due to quality issues and production or supply disruptions). We assume that the level of strategic emergency
stock is set so as to ensure the same protection level \( r \), namely the probability of no disruption (adequate sourcing) during the lead time, for both markets. Finally, when sustainability issues are included in the analysis, the emissions cost \( c_e \) is assumed proportional to the \( \text{CO}_2 \) emissions of each path. In Table 2 we display all the employed nomenclature.

(Insert Table 2 here)

The sole decision variable in all problem instances is the portion of demand that is to be satisfied by the nearshore factory \( F_2 \), denoted by \( \gamma \).

We utilize the LPI World Bank study (Arvis et al., 2010) to: (i) capture accordingly the service and clearance mean time, in order to estimate customs’ mean processing times, and (ii) adjust the transportation time by expressing the LPI level into equivalent additional days over the net transportation time. To that effect, we estimate delays in ports of entry by adopting the suggested practice of Arvis et al. (2007a, 2010) according to which a difference of one unit in the LPI ranking is mapped into four additional days in import and two additional days in export.

In the following paragraphs we present the optimization models developed for each of the six problem instances under investigation.

**Problem 1: Offshoring vs. nearshoring**

**Instance I.1: Offshoring vs. nearshoring for a single market**

The expected Total Landed Cost \( E\left[ TC_{I,1}^1(\gamma_{I,I,1}) \right] \) for the strategic planning horizon of the system under study when the first alternative path that includes port of entry \( P_1 \) is employed is given in (1). Superscript 1 corresponds to the index of port of entry \( P_1 \) and subscript 1 corresponds to the index of market \( M_1 \).

\[
E\left[ TC_{I,1}^1(\gamma_{I,I,1}) \right] = \int_0^\infty \int_0^\infty \left\{ p_1 + c_{111} + (h_1 \cdot t_1) \cdot \left( 1 - \gamma_{I,I,1}^1 \right) \cdot D_1 \cdot T \right\} \cdot g_1(t_1) \cdot g_2(t_2) \cdot dt_1 \cdot dt_2 +
+ \int_0^\infty \int_0^\infty \left\{ p_2 + c_{201} + (h_2 \cdot t_2) \right\} \cdot \gamma_{I,I,1}^1 \cdot D_1 \cdot T \right\} \cdot g_1(t_1) \cdot g_2(t_2) \cdot dt_1 \cdot dt_2 +
+ \int_0^\infty \int_0^\infty \left\{ \left( 1 - \gamma_{I,I,1}^1 \right) \cdot h_1 + \gamma_{I,I,1}^1 \cdot h_2 \right\} \cdot SES(\gamma_{I,I,1}^1) \right\} \cdot g_1(t_1) \cdot g_2(t_2) \cdot dt_1 \cdot dt_2
\]
which after few algebraic simplifications leads to:

\[
E \left[ TC_{i,1}^{I} \left( y_{i,1,1}^{I} \right) \right] = \left[ p_{1} + c_{1i} + \left( h_{i} \cdot L_{1}^{i} \right) \right] \cdot \left(1 - y_{i,1,1}^{I} \right) \cdot D_{i} \cdot T + \\
+ \left[ p_{2} + c_{2i} + \left( h_{2} \cdot L_{2}^{i} \right) \right] \cdot y_{i,1,1}^{I} \cdot D_{i} \cdot T + \\
+ \left(1 - y_{i,1,1}^{I} \right) \cdot h_{i} + y_{i,1,1}^{I} \cdot h_{2} \right] \cdot SES \left( y_{i,1,1}^{I} \right) 
\]  

(2)

The optimal \( y_{i,1,1}^{I^*} \) is the value of \( y_{i,1,1}^{I} \) that minimizes (2), namely:

\[
y_{i,1,1}^{I^*} = \arg \min_{0 < y_{i,1,1} \leq 1} \left\{ E \left[ TC_{i,1}^{I} \left( y_{i,1,1}^{I} \right) \right] \right\} 
\]  

(3)

The first and second terms of (2) are the production, transportation and pipeline expected holding costs realized by the offshore and the nearshore factory, respectively. The last term captures the expected holding cost (weighted average of pipeline holding costs) of the strategic emergency stock that is needed over the longer strategic planning horizon in order to hedge against variability of dual sourcing replenishment. Since the two sources have different lead time variabilities, the strategic emergency stock \( SES \left( y_{i,1,1}^{I} \right) \) depends on the portion of each one of them. The necessary strategic emergency stock for a protection level \( r \) is calculated through equation (4), using the methodology for estimating the optimal \( SES(\gamma) \) proposed by Iakovou et al. (2010).

\[
-G_{1} \left( L_{1} + SES(\gamma)/D \right) \cdot G_{2} \left( L_{2} + SES(\gamma)/D \right) + G_{3} \left( L_{2} + SES(\gamma)/D \right) + (1 - \gamma) \cdot T \cdot \\
G_{1} \left( L_{1} + SES(\gamma)/D \right) + G_{2} \left( L_{2} + SES(\gamma)/D \right) \cdot G_{1} \left( L_{1} + SES(\gamma)/D + \gamma \cdot T \right) = r 
\]  

(4)

An analytic expression of \( SES \left( y_{i,1,1}^{I} \right) \) for general lead time distributions is mathematically intractable due to the complexity of (4), and thus, it is not possible to replace \( SES \left( y_{i,1,1}^{I} \right) \) in (2) and apply first order conditions to calculate \( y_{i,1,1}^{I^*} \). Therefore, the optimal solution is obtained numerically using appropriate mathematical software and more specifically the MS Excel Solver® tool.

**Instance I.2: Offshoring vs. nearshoring for two markets**
The system under study is split into two independent single-market networks, the first one serving only market $M_1$ with demand $D_1 = D \cdot (1 - \delta)$, and the other one serving only market $M_2$ with demand $D_2 = D \cdot \delta$, respectively, where $\delta$ is the portion of the total demand for market $M_2$. If $E[TC_{I,1}^1(\gamma_{1,1,1}^*)]$ and $E[TC_{I,1}^1(\gamma_{2,1,1}^*)]$ are the optimal expected Total Landed Costs of problem instance I.1 when the logistics network utilizes entry point $P_1$ for supplying $M_1$ and $M_2$, respectively, then the optimal expected Total Landed Cost $E[TC_{I,2}^1(\gamma_{1,2}^*)]$ of the system under study is the sum of $E[TC_{I,1}^1(\gamma_{1,1,1}^*)]$ and $E[TC_{I,1}^1(\gamma_{2,1,1}^*)]$ and the optimal mixture $\gamma_{1,2}^*$ for the entire network is obtained from (5).

$$\gamma_{1,2}^* = (1 - \delta) \cdot \gamma_{1,1,1}^* + \delta \cdot \gamma_{2,1,1}^*$$  \hspace{1cm} (5)

**Problem II: Offshoring vs. nearshoring including port selection**

**Instance II.1: Offshoring vs. nearshoring including port selection for a single market**

If $E[TC_{I,1}^1(\gamma_{1,1,1}^*)]$ and $E[TC_{I,1}^2(\gamma_{1,1,1}^*)]$ are the optimal expected Total Landed Costs of problem instance I.1 when the logistics network utilizes the paths with entry points $P_1$ and $P_2$, respectively, the optimal value of $\gamma (\gamma_{1,1,1}^*)$ is the value of $\gamma_{1,1,1}^*$ that corresponds to the minimum of these two costs, where $j = 1, 2$ stands for the two alternative paths with entry points $P_1$ and $P_2$, respectively.

**Instance II.2: Offshoring vs. nearshoring including port selection for two markets**

If $E[TC_{I,2}^1(\gamma_{1,2}^*)]$ and $E[TC_{I,2}^2(\gamma_{1,2}^*)]$ are the optimal expected Total Landed Costs of problem instance I.2 when the logistics network utilizes the paths with entry points $P_1$ and $P_2$, respectively, the optimal value of $\gamma (\gamma_{1,2}^*)$ is the value of $\gamma_{1,2}^*$ that corresponds to the minimum of these two costs, where $j = 1, 2$ stands for the two alternative paths with entry points $P_1$ and $P_2$, respectively.
Problem III: Offshoring vs. nearshoring including port selection and sustainability issues

Instance III.1: Offshoring vs. nearshoring including port selection and sustainability issues for a single market

Equation (6) provides the expected Total Landed Cost \( E\left[ TC^{i}_{III,1}\left(\gamma^{i}_{III,1}\right)\right] \) for this problem instance that includes the expected Total Landed Cost of problem I.1 with the emissions costs, where \( j = 1, 2 \) stands for the two alternative paths with entry points P1 and P2, respectively. The optimal value of \( \gamma \left(\gamma^{*}_{III,1}\right) \) is the value of \( \gamma^{*}_{III,1} \) that corresponds to the path with the minimum expected Total Landed Cost.

\[
\min_{0 \leq \delta \leq 1} E\left[ TC^{i}_{III,1}\left(\gamma^{i}_{III,1}\right)\right] = E\left[ TC^{i}_{I,1}\left(\gamma^{i}_{I,1}\right)\right] + c_e \cdot T \cdot (1 - \gamma^{i}_{III,1}) \cdot e_{i,j} \cdot D_1 + \\
+ c_e \cdot \gamma^{i}_{III,1} \cdot T \cdot e_{201} \cdot D_1, \quad j = 1, 2
\]

Instance III.2: Offshoring vs. nearshoring including port selection and sustainability issues for two markets

Similarly to the problem instance I.2, the optimal expected Total Landed Cost

\[
E\left[ TC^{j}_{III,2}\left(\gamma^{*}_{III,2}\right)\right] \text{ for the strategic planning horizon of the system under study, where } j = 1, 2 \text{ stands for the two alternative paths with entry points P1 and P2, respectively, is the sum of }
\]

\[
E\left[ TC^{j}_{III,1}\left(\gamma^{*}_{III,1}\right)\right] \text{ and } E\left[ TC^{j}_{II,1}\left(\gamma^{*}_{II,1}\right)\right] \text{ and the optimal mixture } \gamma^{*}_{III,2} \text{ is obtained from (7).}
\]

\[
\gamma^{*}_{III,2} = (1 - \delta) \cdot \gamma^{*}_{III,1} + \delta \cdot \gamma^{*}_{II,1}
\]

Similarly to the problem instance III.1, the optimal value of \( \gamma \left(\gamma^{*}_{III,2}\right) \) is the value of \( \gamma^{*}_{III,2} \) that corresponds to the path with the minimum expected Total Landed Cost.

“WHAT-IF” ANALYSES

Herein, we demonstrate the application of the developed models on a series of problem instances. We consider a supply chain of white goods into two regional EU markets. We set the
desirable protection level at $r = 95\%$. For the offshore facility we assume that the shortest path to the markets utilizes the port of entry $P_1$, while the longer path employs $P_2$, a port with more efficient and responsive customs. The transportation costs from node to node are estimated based on the transportation mode, taking also into account the distances between the nodes and today’s market prices prevalent in the EU.

Quantifying the cost of emissions is still an evolving process; according to Kanter (2010), the EU considers new taxes to achieve at least a 20% reduction in greenhouse gas emissions by 2020 compared to 1990. More specifically, Commission officials have suggested a tax of €4 to €30 per ton of carbon dioxide. In our numerical investigations, we assume at first, a moderate fee level of €17 per ton of CO$_2$ emitted, while in the “what-if” analyses we assess the response of the system under different fee levels.

The nearshore production cost is estimated to be 20% greater than the offshore cost. In addition to the traditional inventory-dependent costs that are encapsulated into the holding cost, pipeline holding costs are also dependent on the type of transportation mode employed (Arvis, Raballand, and Marteau, 2007b). We conducted various numerical experimentations assuming that the lead times for shipping a container from the nearshore factory $F_2$ to the markets follow a normal distribution with a rather low coefficient of variation $c_v=0.2$, while the lead times for shipping a container from the offshore factory $F_1$ to the markets follow an exponential distribution that has a higher variability ($c_v=1$).

Table 3 displays the input data and the model parameters for the six problem instances that we developed mapping the six optimization models presented in the previous section. Data were obtained by Orphee Beinoglou Intl. Forwarders S.A., a 3PL company with headquarters in Thessaloniki, Greece, while CO$_2$ emissions data were obtained by Ebert (2005). Furthermore, the distances (in km) amongst all nodes in the networks (see Figure 1) were set so as to pro-
vide a realistic case for markets located in Central Europe with two ports of entry in Northern Europe (Table 4).

(Insert Table 3 here)

(Insert Table 4 here)

The resulting optimal mixture of production capacity allocation for each problem instance is exhibited in Table 5. The results reveal that the optimal solution assigns production to both the offshore and nearshore factories. Optimal policies suggest a combined offshore and nearshore production due to the inclusion of the strategic emergency stock in the optimization models. Myopic models that take into account only production, transportation and pipeline inventory holding costs would prescribe network configurations with exclusive offshore or nearshore production. Naturally, for certain values of the system parameters the optimal solution could also lead to the exclusive offshore or nearshore production.

(Insert Table 5 here)

Figure 2 displays the resulting optimal strategic emergency stock level for different values of \( \gamma \) for problem instances I.1 and I.2. We observe that the optimal level of the strategic emergency stock is a decreasing function of \( \gamma \). Therefore, the higher value of strategic emergency stock is obtained for \( \gamma=0\% \) (exclusive offshore production). This is intuitively sound as even small portions of nearshore production, can act as a hedge against lead time variability. For a specific level of \( \gamma \) (about 18\% for the network realizations that we investigate) and for higher values of \( \gamma \), the strategic emergency stock is practically zero, since the corresponding nearshore production undertakes most of the “burden” of ensuring the desired protection level for the supply chain.

(Insert Figure 2 here)
For all problem instances allowing for two alternative paths, the optimal solution picks the more efficient port of entry (P2). Additionally, the inclusion of a CO2-emissions penalty cost clearly makes nearshoring more attractive.

The results provided by the sensitivity analysis of the optimal mixture to the efficiency of the port of entry (LPI) depict that as the efficiency of the port of entry improves the level of $\gamma^*$ decreases. Figure 3 displays the resulting optimal mixtures for different LPIs for problem instances II.1 and II.2. As Figure 3 exhibits, low LPIs may lead to even a 100% nearshore production, while very efficient and responsive ports of entry may lead to exclusive offshore production.

(Insert Figure 3 here)

Various “what-if” analyses related to offshore production, transportation, holding and emissions penalty costs were also conducted, revealing that an increase in anyone of these costs (e.g. an increase in transportation costs due to increased oil prices) affects the optimal policy in pretty much the same manner. Figure 4 illustrates this pattern of optimal $\gamma$ values for various parameter changes.

(Insert Figure 4 here)

We observe that there are three levels for optimal $\gamma$ values: (i) exclusive offshore production (with $\gamma=0\%$) for low values of the various cost-parameters, (ii) exclusive nearshore production (with $\gamma=100\%$) for high cost levels, and (iii) combined offshore and nearshore production (for specific value of $\gamma$, $0\%<\gamma<100\%$) for a combination of the cost parameters. Additionally, the transition of $\gamma^*$ to another level is very abrupt. After conducting several runs for different parameter datasets for all problem instances, we documented that this intermediate level of $\gamma$ depends only on the offshore mean lead time. More specifically, as the offshore mean lead time increases, the level of $\gamma^*$ also increases.
Figure 5 exhibits the optimal values of $\gamma$ for various levels of the emissions penalty cost. These results correspond to problem instances III.1 and III.2. We observe that the optimal nearshore sourcing level increases as the fee level increases. For problem instance III.2 for a fee over €21 per ton of CO2 emitted, the optimal solution prescribes exclusive nearshore production. Moreover, for fee values of up to €21 per ton of CO2 the combination of nearshoring and offshoring continues to be optimal. Finally, the range of the emissions fee for problem instance III.1 leading to combined offshore and nearshore production is equal to (€0 - €20).

(Insert Figure 5 here)

CONCLUSIONS

Free-trade bottlenecks related to congested ports, inefficient cross-border clearance processes, and environmental-related costs can erode the effectiveness of offshoring, often leading to the nearshoring of a portion of the production capacity.

In this paper, we propose a novel Total Landed Cost methodology for the strategic design of global supply chain networks. The developed methodology identifies the optimal mixture of combined offshore and nearshore production and the optimal port of entry, while embedding the impact of trade facilitation-related variability and the cost of CO2 emissions into the TLC; all these are critical issues for the majority of globalized companies.

We demonstrate the applicability of the proposed methodology on six problem instances. Our extensive numerical investigation documents that: (i) holding costs affect the optimal mixture of nearshore/offshore production capacity allocation; (ii) the level of the optimal production mixture depends mostly on the offshore mean lead time; (iii) ports of entry with highly efficient and responsive customs’ processes are key drivers in the design of the supply chain networks as offshore allocation emerges more attractive; and (iv) increased CO2 emissions lead to an increased allocation of nearshore capacity. Moreover, we identify the range of break-even point values of CO2 emissions penalty fees for which the combined offshore and near-
shore production is optimal. Finally, the developed total landed cost methodology could be extended to allow for multiple offshore and nearshore facilities and more ports of entry so as to be applied to a real-world case study. Moreover, a fill rate type modeling could be explored for the strategic safety stock protection level, while the inclusion of volume-dependent transportation cost would further increase the validity and applicability of our research.

REFERENCES


### Table 1: Issues tackled at each problem instance

<table>
<thead>
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<th>I</th>
<th>II</th>
<th>III</th>
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<td>I.1</td>
<td>II.1</td>
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<tr>
<td>2</td>
<td>Two markets</td>
<td>I.2</td>
<td>II.2</td>
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### Table 2: Nomenclature

- $D_k$: Demand from location $k$ [TEU/day]
- $D$: Total system’s demand [TEU/day]
- $T$: Replenishment period [days]
- $p_i$: Production cost of factory $i$ [€/TEU]
- $c_{ijk}$: Transportation cost from factory $i$ to market $k$ through port of entry $j$ [€/TEU], $j=0$ used in paths starting from factory $F_2$
- $h_i$: Pipeline holding cost for replenishment from factory $i$ [€/TEU/day]
- $d_i$: Random variable for the total lead time from factory $i$ to the market(s)
- $g_d(\cdot)$: Probability density function of $d_i$
- $G_d(\cdot)$: Cumulative distribution function of $d_i$
- $j_{ik}$: Mean lead time from factory $i$ to market $k$ through port of entry $j$ [days]
- $SES(\gamma)$: Strategic emergency stock for $\gamma\%$ of the demand being satisfied by factory $F_2$ [TEU]
- $r$: Protection level from strategic emergency stock [%]
- $c_e$: CO2 emissions penalty cost [€/tn]
- $e_{ijk}$: CO2 emissions for transportation from factory $i$ to market $k$ through port of entry $j$ [tons/TEU]
- $\delta$: $D_2/D$ [%]

### Table 3: Data for the six (6) problem instances

<table>
<thead>
<tr>
<th>Holding cost</th>
<th>Offshoring</th>
<th>Nearshoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand data</td>
<td>37.00 €/TEU/day</td>
<td>24.50 €/TEU/day</td>
</tr>
<tr>
<td>Demand rate</td>
<td>13.70 TEU/day</td>
<td></td>
</tr>
<tr>
<td>Demand period</td>
<td>365.00 days</td>
<td></td>
</tr>
<tr>
<td>$\delta$</td>
<td>35.00 %</td>
<td></td>
</tr>
<tr>
<td>Production cost</td>
<td>Offshoring</td>
<td>Nearshoring</td>
</tr>
<tr>
<td>Transportation &amp; Handling cost</td>
<td>Ship</td>
<td>Truck</td>
</tr>
<tr>
<td>Ship</td>
<td>0.12 €/TEU/km</td>
<td></td>
</tr>
<tr>
<td>Truck</td>
<td>1.32 €/TEU/km</td>
<td></td>
</tr>
<tr>
<td>Ports of Entry</td>
<td>P1’s LPI</td>
<td>P2’s LPI</td>
</tr>
<tr>
<td>Efficiency data</td>
<td>2.90 Kg CO2/TEU/km</td>
<td></td>
</tr>
<tr>
<td>CO2 emissions</td>
<td>Ship</td>
<td>Truck</td>
</tr>
<tr>
<td>Ship</td>
<td>0.13 Kg CO2/TEU/km</td>
<td></td>
</tr>
<tr>
<td>Truck</td>
<td>0.60 Kg CO2/TEU/km</td>
<td></td>
</tr>
</tbody>
</table>
Table 4: Distances [Km] for the networks under study

<table>
<thead>
<tr>
<th>From:</th>
<th>F_1</th>
<th>F_1</th>
<th>F_2</th>
<th>F_2</th>
<th>P_1</th>
<th>P_1</th>
<th>P_2</th>
<th>P_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>To:</td>
<td>P_1</td>
<td>P_2</td>
<td>M_1</td>
<td>M_2</td>
<td>M_1</td>
<td>M_2</td>
<td>M_1</td>
<td>M_2</td>
</tr>
<tr>
<td>Network 1</td>
<td>14150</td>
<td>14500</td>
<td>960</td>
<td>--</td>
<td>730</td>
<td>--</td>
<td>800</td>
<td>--</td>
</tr>
<tr>
<td>Network 2</td>
<td>14150</td>
<td>14500</td>
<td>960</td>
<td>1260</td>
<td>730</td>
<td>1030</td>
<td>800</td>
<td>1100</td>
</tr>
</tbody>
</table>

Table 5: Optimal mixtures of production capacity allocation $\gamma$ (%)

<table>
<thead>
<tr>
<th>Problem</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network 1</td>
<td>I.1: 17%</td>
<td>II.1: 6%</td>
<td>III.1: 16%</td>
</tr>
<tr>
<td>Network 2</td>
<td>I.2: 17%</td>
<td>II.2: 9%</td>
<td>III.2: 16%</td>
</tr>
</tbody>
</table>
FIGURES

Figure 1: The supply chain networks under study

Figure 2: Strategic emergency stock for different mixtures of production allocation capacity $\gamma$ (%) with entry point $P_1$
Figure 3: Optimal mixtures for using different LPIs

Figure 4: Generalized qualitative diagram of the optimal mixture for using different cost values
Figure 5: Correlation of optimal mixtures and emissions cost levels