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OPTIMIZING VOYAGE COSTS IN MARITIME SUPPLY CHAINS: A HOLISTIC APPROACH TOWARDS LOGISTICS SERVICE IMPROVEMENT AND SUPPLY CHAIN FINANCE

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The multi-objective optimization for voyage planning, which aims to balance time, fuel utilization, and all other relevant service costs, is noticeably absent in the scientific literature. The reason behind this gap is closely linked to the involvement of a large number of participants with conflicting interests in the process. This complexity explains why modelling an optimization tool for maritime logistics services appears challenging. Although new technologies such as blockchains and smart contracts have helped reduce the number of participants and address some complexities, they cannot fully resolve the fragmentation observed in maritime transport.

To address the need for optimized voyage management for vessels, this study takes a holistic approach to voyage costs within the maritime supply chain, similar to how a single company would approach it. The study combines a case study from the container shipping industry, expert interviews, project results, and secondary empirical data research to develop a financial model for optimizing voyage costs. The research opens up opportunities for improving logistics services and developing new business models in the field of supply chain finance.

Keywords: Optimization, Supply chain, Finance, Business model, Maritime transport

1. Introduction

The actions and inactions of different interest groups, including cargo owners, shipping companies, financial institutions, and other logistics service providers, who primarily focus on their benefits, determine the dynamics of the maritime transport market. As a result, supply chain decisions tend to favour market participants with greater negotiation power. Consequently, the logistics service process primarily consists of individual optimizations within its value chain, falling short of achieving an optimal solution for the entire supply chain, although new technologies like blockchains and smart contracts can integrate the participants in maritime transport (Philipp *et al.*, 2019).

Logistics processes are typically considered in different contexts, either as internal processes within a single company or as external and cross-company processes within supply chains (Stefanou, 1999). Existing models already offer optimization approaches for both situations (e.g., Di Martino *et al.*, 2023; Sadeghi *et al.*, 2023). However, in the case of maritime transport, logistics processes are not fully internal due to several reasons.

Firstly, the interconnected nature of global trade often involves multiple ports and transshipment points, requiring a combination of internal and external logistics processes to ensure smooth goods flow throughout the entire supply chain (Vargas-Hernández, 2023). Secondly, port operations encompass various interfaces such as cargo handling, customs procedures, storage, and other related activities (Stefanou, 1999). While these operations are internal to the port itself, they extensively interact with external entities such as shipping companies, customs authorities, freight forwarders, and transport operators (Marlow & Casaca, 2003). Furthermore, multimodal transportation involves the use of multiple interconnected modes of transport (e.g., sea, rail, road, and air), necessitating coordination between various internal and external logistics processes to ensure seamless cargo movement across different transport modes (Crainic & Kim, 2007). Additionally, stakeholders (e.g., shippers, freight forwarders, shipping lines) and external stakeholders (e.g., suppliers, customers, regulatory authorities) play a role in optimizing overall supply chain

performance. Furthermore, regulatory and legal considerations, as well as risk management (Al Zaabi, 2013), contribute to the complex interrelationships within supply chain systems. The intricacy of this system explains why logistics models often prioritize the partial interests of supply chain members, which may be suboptimal for the rest of the system (Crainic & Kim, 2007).

A significant portion of the literature on process management focuses on finding a balance between time and costs, which should also be applied to maritime logistics. Maritime transport, as part of the logistics sector, should consider time as a crucial dimension because it not only influences the perception of service quality but also affects costs (Cariou, 2011). For example, Maloni *et al.* in (2013) observe that faster voyages lead to time savings but increase voyage costs due to higher fuel consumption.

Already, various studies in maritime literature, such as those by Cariou (2011), Maloni *et al.* (2013), and Ferrari *et al.* (2015), explore the advantages and disadvantages of "slow steaming" and attempt to assess its economic implications in terms of time-related losses while Prause & Olaniyi (2019) point out the additional costs related to maritime emission control regulations. This dilemma of process organization serves as a driving force in supply chain operations research.

On another hand, engineering literature extensively studies models that aim to find the right balance between time and costs in operations, while such studies are scarce in business literature. Concepts like economic order quantities (EOQ) or economic production quantities (EPC) are discussed in management literature, as seen in Jacobs & Chase (2017), but more advanced concepts like the logistics curve theory have only recently started to gain traction in business literature (e.g., Nyhuis & Wiendahl, 2009). This situation is unfavourable because these concepts can provide valuable insights into maritime logistics. Hence, the objective of this study is to develop a financial model capable of optimizing voyage costs and time to improve logistics services and facilitate the development of new business models in the field of supply chain finance.

In this paper, the authors utilize a value chain-based framework to accurately target voyage management and optimization by considering the right balance between time and costs. The authors employ various operating summaries of different ships to calculate the relevant costs associated with a ship's actual sailing profile. Additionally, the authors conduct a business impact analysis of operating costs (OC), capital costs (CC), and interest costs of transported cargo (ICC) on total fuel consumption to determine the optimal service time for a typical vessel voyage. The work also includes a sensitivity analysis to demonstrate how the ever-changing variables in the maritime industry affect the proposed model.

The study addresses three questions in this process: (1) What are the performance characteristics of different cost categories concerning different time variables for a typical voyage? (2) What is the optimal service time for a long-haul voyage? (3) How does the proposed model respond to changing variables in the maritime industry? The first two questions pertain to the construction of the optimization model, while the third question relates to the accuracy of the optimization model constructs. An important feature of the proposed model is its consideration of not only the economic analysis of shipping operations but also cargo volume analysis and holistic voyage costs.

Furthermore, the study analyses ship journeys holistically, considering relevant expenses and addressing the complexity and fragmentation of marine transport operations. To improve logistics services and develop a new business model in the field of supply chain finance, the authors incorporate a case study from container shipping, expert interviews, project results, and secondary empirical data research, aiming to identify best practices for ship operations that align with the goals of the International Maritime Organization's (IMO) recommendation on vessel performance monitoring systems.

The motivation behind this analysis is that by examining the performance of different cost categories concerning time variables using historical data and operating summaries to develop predictive analytics techniques, efficient routes can be identified, fuel consumption can be estimated, and voyage timeliness can be calculated. This enables the model to make informed decisions that strike a balance between cost minimization and time optimization.

The following subsection analyses the integration of optimization models for logistic systems and the associated benefits. The subsequent section presents the methodology used to model the optimization tool. The study then proceeds to present the results and discuss them in the fourth section, followed by a case study that empirically validates the optimization model in the fifth section. Finally, the conclusion section summarizes the study.

2. Background

2.1. Shipping Optimization

For the maritime industry, it is crucial to develop techniques and systems that bridge the gap between stakeholders' perceived expectations and actual ship operations (Yu *et al.*, 2021). An effective way to

address this is through the implementation of key ideas and procedures in maritime operations. One essential aspect is the development of a robust voyage planning system, which can enhance the competitiveness and sustainability of maritime shipping operations. Such a system should focus on maximizing value and optimizing costs, as minimizing costs alone is often not a viable choice. As Blaik & Matwiejczuk (2009) aptly stated, strategic decisions regarding logistics should lead to the continuous exploration and development of logistic potentials for creating added value for shipping lines and their customers, particularly in the context of long-term logistic process and structure development.

Optimization encompasses various technical disciplines and is known by different names, including applied artificial intelligence, operations research (OR), and business analytics (Yu *et al.*, 2021). In the supply chain, voyage optimization is a process that carefully plans a ship's performance qualities (Lu *et al.*, 2013). This process takes into account factors such as safety, energy consumption, and environmental impact, enabling ships to determine routes by predicting their performance under different sea conditions (Bartolacci, 2012). Recent studies investigate the impact of sustainable factors comprising renewable energy issues on the optimization processes of voyages (Olaniyi *et al.*, 2022).

Optimizing ship journeys provides crucial theoretical and technological insights for efficient shipping operations (Yu *et al.*, 2021), and accessing economies of size and scope is essential in this endeavour (Walters & Lancaster, 2000). A voyage refers to the route taken from one port to another, starting and ending at their respective ports (IMO, 2009).

Reducing bunker fuel consumption throughout each journey is typically one of the primary priorities in voyage optimization for shipping lines. Existing literature demonstrates that several factors, including sailing speed, displacement, trim, weather, and sea conditions, affect a ship's fuel consumption while at sea. Among these factors, sailing speed has been extensively studied, and it is well-known that a ship's fuel consumption rate is inversely correlated with its sailing speed (Du, 2019). Other studies have focused on identifying the most fuel-efficient speed based on factors such as wind and current conditions (Psaraftis & Kontovas, 2013). A promising strategy is minimizing the ship's displacement by carrying only the necessary cargo and ballast water, and trim optimization has also proven useful in reducing fuel consumption (Yang *et al.*, 2013). Sherbaz & Duan (2014) explain that by adjusting the distribution of weight and ballast throughout the ship, the trim can be optimized to reduce drag and improve fuel efficiency. Integrating weather routing technology into a ship's navigation system has also been used to optimize the ship's route, avoid adverse weather conditions, reduce fuel consumption, and minimize the risk of vessel damage (Yu *et al.*, 2021).

However, while reducing vessel speed does result in savings, the impact is minor. Vessels must be kept within a certain speed range to maintain a "healthy" fuel expenditure (Notteboom, 2006). This current practice for ship speed during a voyage remains basic and cannot significantly improve operational costs (Du, 2019). In a voyage optimization system, the most optimal voyage must be selected based on pre-defined objectives. Shipping lines deal with a considerable number of stakeholders, each with different specifications for their objectives and interests (Tran *et al.*, 2017). Therefore, reducing transaction costs, as is the case with most voyages, requires calculating the value of time based on the current journey and considering the holistic objectives of the journey, accounting for all relevant expenses associated with it, thereby offsetting the cost of sailing at any given speed (Speranza & Ukovich, 1994; Frémont, 2009).

As e-commerce activities become more widespread, the demand to reduce overall costs (beyond just fuel costs) will become increasingly important (Caputo *et al.*, 2005) and so will calculating shipping efficiency with the total cost of transportation. However, in most studies, cargo-handling costs are often overlooked. If one of the targets of the optimization process is to reduce overall expenses, then the strategy should include all relevant costs, encompassing cargo and its handling costs, as they are inversely correlated with the total voyage value (Zhou, 2013; Tran *et al.*, 2017).

To optimize a voyage, Wang (2021) listed various objectives that must be taken into account, such as trade-offs between fuel consumption and reduction, estimated time, minimizing fuel consumption, and overall operating costs. Other goals include balancing cargo delivery delay and charter costs (Neagu *et al.*, 2006), prompt arrival, safety, passenger comfort, or a combination of these factors (Lu *et al.*, 2013). All of these objectives should be achieved within a profitable scope for the shipping line. Thus, voyage optimization should not be solely assessed in terms of fuel usage.

Given that the effects of value and cost drivers are crucial strategic and operational factors influencing value delivery and cost structures in the supply chain (Walters & Lancaster, 2000), it is necessary to consider costs and value when constructing any optimization tool. All cost variables that affect the outcome of the voyage, especially in terms of value (such as time), should be thoroughly utilized, and elements like cargo operations costs should be incorporated to design an effective voyage optimization system.

2.2. Shipping Cost Categories

Starting with the cost side in the shipping sector, the authors followed Stopford (2007) in identifying the most relevant cost categories. In the case of running a ship, Stopford differentiates between them as Capital costs, Periodic maintenance costs, Operating costs, Voyage costs, and Cargo handling costs. For clarity, this study provides short descriptions of these costs:

Capital Costs for a shipping line are expenses associated with acquiring and maintaining the physical assets of a ship. This includes the purchase or construction of the vessel itself, containers, and other equipment necessary for maritime operations. Additionally, it encompasses financing expenses, depreciation costs, insurance, and any other costs directly related to the ownership and financing of the vessel (Atari *et al.*, 2019). Periodic Maintenance Costs on the other hand include all expenses made to keep the vessels and other equipment in working order. This involves regular checks, repairs, upgrades, and adherence to required legal requirements. Periodic maintenance costs are essential to ensure the safety, reliability, and longevity of maritime assets (Turan *et al.*, 2009).

Operating Costs are the daily expenses involved in managing maritime operations and operating ships. These expenses cover staff salaries (crew and others), fuel costs, lubricants, supplies, food, communication costs, overhead, and other ad hoc operating costs. Whether the vessel is at sea or in port, operating expenditures must be paid (Huang *et al.*, 2019).

Ting & Tzeng (2003) explained that the costs of a particular journey or trip made by a ship are known as voyage costs, and they are directly associated with a specific voyage or trip of that vessel. Expenses such as fuel consumption, port charges, canal transit fees, pilotage fees, tugboat services, and any other costs directly incurred during a particular journey. Costs of a voyage can vary and are often influenced by elements including distance, route, amount of time spent in ports, and particular operating requirements. Lastly, cargo-handling costs involve the expenses associated with the loading, unloading, and handling of cargo at ports or terminals. These fees might be for stevedoring, crane or equipment rentals, storage, customs, inspection, or any other expenditures associated with the actual transfer and storage of the goods. Cargo handling costs vary depending on the nature of the cargo, its volume, and specific handling requirements (Seedah *et al.*, 2013).

Note that not all costs are categorized as standalone. When it comes to periodic maintenance costs, they are usually subsumed under operating costs because they occur only yearly and represent only a small fraction of the overall costs (Jansson & Shneerson, 1982). Furthermore, in shipping financing, capital costs, and operating costs consist largely of fixed costs, including salaries, interests, depreciation, and insurance, so these cost categories are considered fixed costs (Albertijn *et al.*, 2011). The periodic maintenance costs are usually distributed over several periods and are also considered fixed costs (Turan *et al.*, 2009). Hence, the remaining two cost categories, consisting of voyage costs and cargo handling costs, represent the variable cost categories, i.e., they are proportional to the operational performance of the ship (Gkonis & Psaraftis, 2010).

The dimension of time appears in maritime transport at different junctions such as transit, seasons, JIT inventory requirements, lead-time, supply chain efficiency, and other potential charges related to delays to effectively manage and optimize shipping costs like demurrage and detention charges (Moon & Woo, 2014). Most of these factors are related to cargo handling, i.e., loading and unloading of cargo, waiting and queuing time, as well as voyage time.

The reason why most maritime logistics literature, consideration of the value of the transported cargo is often neglected is that cargo owners have different expectations from shipping companies. However, Psaraftis & Kontovas (2013) present an important exception and they discuss a holistic view of maritime transport, comprising time and costs for the vessel as well as for the cargo. Nevertheless, the neglect of cargo value in voyage management is surprising as time is a valuable resource, and the opportunity cost of time usually affects voyage costs. For example, delayed voyages can lead to missed market opportunities, contractual penalties, or customer dissatisfaction (Stopford, 2007). On the other hand, faster and more efficient voyages enable shipping companies to meet delivery deadlines, secure new business, and maintain customer satisfaction. A brief look at statistics reveals that in container shipping, the cargo value per 20-foot container (TEU) can reach a value of up to nearly 2 million US\$ (Rodrigue, 2017). Therefore, in addition to ship and port expenses, the current model considers all shipping costs, including cargo-handling costs.

3. Methodology

The study takes a rounded view of maritime transport by consolidating all parties of maritime logistics services that contribute to the total cost of a voyage. The authors obtained different technical and

economic ships' profiles as well cargo data from shipping companies involved in long-haul transportation through expert interviews and document reviews. The authors carried out eight interviews with three shipping lines that are involved in long voyage destinations around Europe, China, and Singapore. From each port, two executive officers (from both the shipping line and the port management) were targeted. Fuel parameters as well as their related costs were obtained from results from EU projects ("EnVisum" and "Connect2SmallPorts) results and other secondary empiric data that would be later mentioned in this section. Finally, a case study of a container ship provides the bases for the predictive validity of a real operating profile of a container vessel.

The model is constructed in a manner that enables the user to determine the optimal voyage time of any vessel under cost aspects. All research activities were executed between 2016 and 2022. Usually, for business research, the quality approach plays an important role. Often the number of existing cases in research areas is limited so that underlying patterns for developments are not accessible by quantitative methods because the number of cases is too small or the research question is not quantifiable so that only quality approaches can deliver new insight (Peterson, 2019).

The starting point for all voyage research is a characterization of a vessel, the techno-economic frame conditions, and the cargo data. These parameters can be expressed in different ways and the authors decide to follow the model that is included in Table 1.

Table 1. Characterization of a Vessel, the Techno-Economic Frame Conditions, and its Cargo Data

Vessel Data	Economic Data	Cargo Data
Type of Vessel	Fuel costs per ton	Cargo in physical volume
DWT	Daily operating costs	Value of cargo
Main engine power	Daily capital costs	Loading volume per day
Type of marine fuel	Average fuel costs as part of voyage costs	Unloading volume per day
Design speed		Cargo handling costs
Operating load factor		
Operating days per annum		

3.1. Calculating the Total Costs of a Typical Maritime Voyage

The provided data allows the study to gain insight into the parameters that determine the costs. According to Stopford (2009), the operating costs and capital costs are considered fixed costs, meaning that their daily values remain constant throughout the year. These costs are calculated by dividing the annual cost values by the number of operating days per year.

To provide clarity and simplicity, the study focuses on the variable cost categories that represent the voyage costs and cargo handling costs. Among these, the main cost driver is fuel costs, which are determined by multiplying the main engine power in kW by the operating load factor and the average fuel consumption per kWh. The specific fuel consumption typically ranges between 170–180 g/kWh (Stapersma, 2017). Multiplying the hourly fuel consumption by 24 hours yields the daily fuel consumption in average operating mode. By multiplying the daily fuel consumption by the fuel price, the daily fuel costs and the percentage they represent as part of the voyage costs can be calculated.

Another crucial parameter for the optimization process is the techno-economic frame conditions of the voyage, which involve considering the planned time in ports and the expected waiting time resulting from congestion during port calls or other destinations. These data allow for prototyping the underlying physical and economic circumstances of the voyage.

To characterize the vessel and the cargo from the perspective of a shipping company and cargo owners, the study combines the operating profiles of existing cargo vessels. This analysis provides insights into the physical state of the loaded cargo and the speed during the voyage, as depicted in Figures 1a and 1b.

With the following parameters: T_l - loading time; T_p - plying time; T_u - unloading time; T_w - waiting time; T_s - service time; T_t - transition time, the state of the voyage speed and loaded cargo during a voyage is shown on Figure 1.

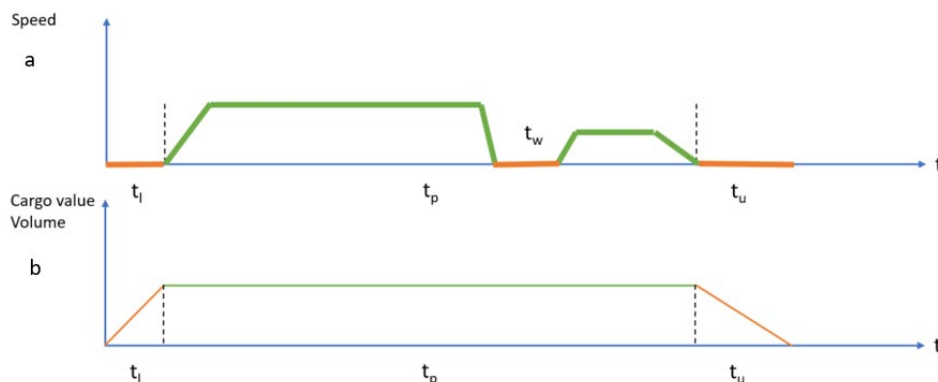


Figure 1. State of a) voyage speed; b) loaded cargo during a voyage

Where:

$$\text{Voyage time } T_v = T_l + T_p + T_u. \tag{1}$$

$$\text{Plying time } T_p = T_s + T_w. \tag{2}$$

$$\text{Transition time } T_t = T_l + T_w + T_u. \tag{3}$$

The voyage time represents the duration from the start of the loading process until the full cargo volume is unloaded at the final destination. It is calculated as the sum of the loading period, the plying time, and the unloading period. The plying time is further divided into the service time, during which the vessel travels at a speed greater than zero, and the waiting time, which increases the overall voyage time but does not reduce the distance to the final destination. The transition time encompasses all stationary periods of the voyage, including loading, unloading, and waiting.

To translate this model into a reliable economic framework, it is necessary to describe the financial aspects during different phases of the voyage. A crucial component of this translation process is the relationship between voyage speed and fuel consumption. Various models have been proposed in the literature for the shipping sector, such as the analytical approach based on the cubic law advocated by Adland *et al.* (2020), as well as statistical regression models relying on second-degree polynomial equations derived from the physical law of water resistance, as proposed by Maloni *et al.* (2013) and Mersin *et al.* (2017). A recent review of ship fuel consumption models can be found in the work of Fan *et al.* (2022). In this study, the approach of Adland *et al.* (2020) is adopted, using the cubic law to estimate ship fuel consumption.

Furthermore, the financial modelling of voyage cost optimization also takes into account the service time during which the vessel travels at a speed greater than zero, reducing the distance to the final destination. The speed of the vessel impacts both fuel consumption and interest costs associated with capital commitment. Additionally, the cargo handling time depends on the cargo volume and the efficiency of loading and unloading devices. Hence, the proposed model assumes a continuous and constant loading process, where the timing of cargo handling remains the same per unit of time.

All these parameters are integrated into the development of a financial model for the voyage of a vessel operating between ports. The optimization model will be formulated as a linear equation dependent on the service time. The various costs involved are consolidated, without considering the specific participants in the maritime logistics processes that bear these costs. Based on this model, the optimal voyage time can be calculated, and different optimal periods can be determined by stratifying the various cost categories. To validate the model constructs, the authors plan to use a case study based on empirical data collected.

4. Findings and Discussion

Costs consisting of operating costs and capital costs are considered fixed costs for a voyage, meaning that they remain constant on a daily basis. Therefore, in terms of the total voyage time, these costs are influenced by the transition time and the service time. To express this relationship more clearly, the respective terms in the linear model can be defined as follows:

$$\text{Operating cost OC: } OC(T_v) = OC(T_s) + OC(T_t) = OC(T_s + T_t). \tag{4}$$

$$\text{Capital costs CC: } CC(T_v) = CC(T_s) + CC(T_t) = CC(T_s + T_t). \tag{5}$$

The interest costs for the capital commitment associated with the transported cargo are also influenced by the transition and service time proportionally. However, it should be noted that the cargo value being charged on the vessel starts from zero during the loading time and returns to zero at the end of the unloading time. Assuming a continuous loading and unloading process at the ports, there is a gain for the interest costs related to the transported cargo, which can be expressed by the following term in the equation.

Interest Cost of handled Cargo ICC:

$$ICC(T_v) = ICC(T_s) + ICC(T_w) + 0.5 \times ICC(T_l + T_u) = ICC(T_s + T_w + (T_l + T_u)/2). \tag{6}$$

The fuel consumption in maritime voyages is primarily influenced by the speed of the vessel during the service time. Speed can be described as the distance travelled over a given period, which allows for the derivation of a term that represents fuel consumption. A literature review conducted by Barras (2004) and Bialystocki & Konovessis (2016) revealed that fuel consumption estimation approaches commonly involve the speed variable raised to the power of two or higher, resulting in a fuel consumption term that is inversely related to the time variable. This research presents two types of formulas for fuel consumption, including the classical formula known as the cubic law proposed by Barras (2004).

i.e. Cubic Law: $fuel\ consumption = \lambda \times V^3 \times \Delta^{2/3}.$ (7)

With V as the speed of the vessel and Δ as the displacement of the vessel, the next formula represents a statistical estimation presented by Bialystocki & Konovessis (2016) in the form of a polynomial of the second degree:

i.e. Statistic Law: $fuel\ consumption = \alpha \times V^2 - \beta \times V.$ (8)

In the literature, both the cubic law and other regression parameters α and β have been proposed for estimating fuel consumption, providing acceptable approaches for different vessels. For this study, the cubic law will be utilized to calculate fuel consumption.

Using the selected estimation for fuel consumption allows for the determination of voyage costs. However, as vessel speed is typically expressed in knots and the service time T_s is measured in days, an adjustment is necessary to ensure consistency. This adjustment involves converting the vessel speed to an hourly basis, taking into account the fact that fuel consumption calculations require consistent time units,

i.e. $Speed = \frac{distance}{24 \times T_s}.$ (9)

Promptly, it becomes feasible to determine the term for the fuel consumption with D representing the travel distance between two considered ports as shown:

Fuel consumption FC per h: $FC(Speed) = FC\left(\frac{D}{24 \times T_s}\right).$ (10)

Total fuel consumption TCF: $TFC(Speed) = FC\left(\frac{D}{24 \times T_s}\right) \times T_s \times 24.$ (11)

To calculate the voyage costs, the total fuel consumption per hour, which is determined based on the vessel's speed in knots, is multiplied by the travel time in hours. To ensure consistent units, the travel time in days is first multiplied by 24 hours per day. Next, the fuel consumption is evaluated by multiplying it by the fuel price per unit of fuel (FP). To incorporate the additional costs related to the service time of the voyage, a fixed constant ψ is used. These costs are then added to the fuel costs. The formula for calculating the voyage costs can be summarized as follows:

Voyage costs VC: $VC(T_s) = \psi \times FP \times TFC(Speed) = \psi \times FP * FC\left(\frac{D}{24 \times T_s}\right) \times T_s * 24.$ (12)

By summing up all parts of the model we gain the following equation that we call the holistic voyage costs HVC:

$$HVC(T_s) = VC(T_s) + ICC\left(T_s + T_w + \frac{T_l + T_u}{2}\right) + CC(T_s + T_t) + OC(T_s + T_t) \tag{13}$$

$$= VC(T_s) + [ICC + CC + OC](T_s) + ICC\left(T_w + \frac{T_l + T_u}{2}\right) + CC(T_t) + OC(T_t) \tag{14}$$

$$= VC(T_s) + [ICC + CC + OC](T_s) + Const(T_w, T_l, T_u, T_t). \tag{15}$$

With a constant term *Const* that depends on the time variable T_w, T_l, T_u and T_t .

In the equation, the variable of interest is the service time (T_s), while other time parameters are considered fixed constants during the optimization process. These fixed time parameters are treated as constants to simplify the equation and focus on the optimization of the service time.

It is important to note that the holistic voyage costs equation presented in the study is a simplified model that excludes certain cost items such as cargo handling costs and the fuel burned during the voyage, which can affect the vessel's displacement as discussed by Mersin *et al.* (2017). However, these factors will be addressed later in the paper.

To analyze the impact of the first deviation of the holistic voyage costs (HVC) function, the study adopts a fuel consumption function that correlates fuel usage with the vessel's speed. As mentioned earlier, the cubic law is employed in this study to estimate fuel consumption, as it provides more detailed insights into the vessel's characteristics. Using this approach, the voyage costs resulting from the vessel's speed can be calculated using the following formula:

$$VC(V) = \psi \times \lambda \times FP \times V^3 \times \Delta^{2/3} = \psi \times \lambda \times FP \times (D/24T_s)^3 \times \Delta^{2/3}, \text{ with the distance } D \quad (16)$$

This leads to the following equations that are optimized on variable T_s :

$$HVC(T_s) = \psi \times \lambda \times FP \times (D/24T_s)^3 \times \Delta^{2/3} \times 24T_s + [ICC + CC + OC](T_s) + Const(T_w, T_l, T_u, T_t). \quad (17)$$

Deviating HVC and setting the deviation to equal zero yields the following equation to determine T_s :

$$0 = HVC'(T_s) = [\psi \times \lambda \times FP \times D^3 / (24T_s)^2 \times \Delta^{2/3}]' + [ICC + CC + OC]. \quad (18)$$

$$0 = -2 \times 24 \times \psi \times \lambda \times FP \times D^3 / (24T_s)^3 \times \Delta^{2/3} + [ICC + CC + OC]. \quad (19)$$

Leading to the equation for optimal service time for the voyage between two ports:

$$T_s = \sqrt[3]{\frac{2 \times 24 \times \psi \times \lambda \times FP \times D^3 \times \Delta^{2/3}}{24^3 \times (ICC + CC + OC)}} = \frac{D}{12} \times \Delta^{2/9} \times \sqrt[3]{\frac{6 \times \psi \times \lambda \times FP}{ICC + CC + OC}}. \quad (20)$$

The results of the analysis indicate that increasing operating costs, capital costs, or interest costs for cargo lead to a decrease in the service time and voyage time. This suggests that higher costs prompt the optimization process to prioritize shorter service times. On the other hand, a higher cargo load results in an increased service time, possibly due to the larger displacement caused by the increased cargo volume. This implies that both the value and weight of the cargo have an impact on the optimal voyage time.

The fuel price (FP) is found to directly influence the service time, as a higher fuel price leads to a longer service time for the vessel. Additionally, the factor ψ , which represents the proportion of voyage costs in the fuel costs, influences the service time. A lower fuel cost share corresponds to a higher ψ factor, which in turn increases the optimal voyage time.

The additional costs associated with loading and unloading do not have a significant influence on the calculations, as they are treated as constants that do not affect the deviation process of the holistic voyage costs (HVC). The parameter λ , which is specific to the ship, is also considered a constant and does not affect further calculations. Therefore, λ can be disregarded in the impact analysis.

The theoretical considerations are depicted graphically, where the holistic voyage costs are plotted against time. The graph illustrates that with each cost category, the optimal service time decreases. This indicates that the fuel-saving benefits achieved through slow steaming are outweighed by the increasing importance of other cost categories.

The graph in Figure 2 presents above exhibits a similarity to the concept of throughput-oriented lot sizing, which is well-known in production logistics as described by Nyhuis & Wiedahl (2009). However, in the case of shipping, it is being applied to the context of maritime operations. In production logistics, the constant term is typically zero, and the financial aspects of the processes are easier to describe since they occur within a single company, allowing for better control and monitoring of costs and processes internally. The shipping environment presents a more complex scenario. Nevertheless, the holistic perspective examined in this research offers an opportunity to enhance existing business models and discover synergistic effects that can benefit all participants within a maritime supply chain.

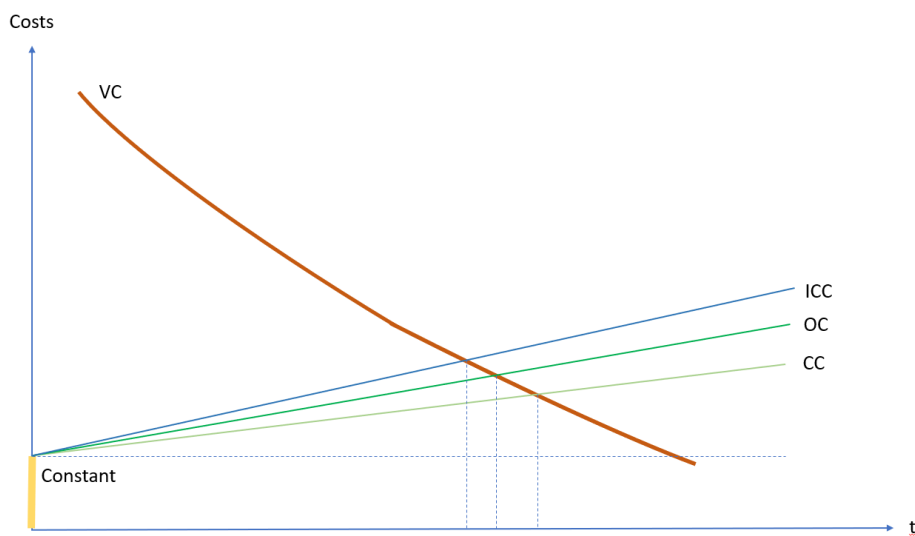


Figure 2. Impact Analysis of an Optimal Service Time for a Vessel Voyage

4.1. Case Study and Empiric Validation

For a case study, the study considers the E-class containership launched in 2006 as the largest container ship in the world. She is also one of the longest container ships around. The main characteristics of the vessel are listed in Table 2.

Table 2. Main Characteristics of the Case Vessel

Vessel's Characteristics	Figure
Vessel	Containership
Tonnage	170,794 GT; 55,396 NT; 156,907 DWT
L/B/D	397m; 56m; 16.02m
Depth	30m (deck to keel)
Propulsion	80800 kW Wärtsilä 14RT-Flex96c
Design Speed	25.5 knots
Capacity	14,770 TEU + 1000 TEU for reefers
Crew:	13 persons
Price	185 Million US\$

Economic Analysis of Case Containership Operations: Depreciation, Interest, and Operational Costs

In theory, containerships typically have a lifespan of 20 years, resulting in annual depreciation of approximately 9.25 million US\$. Assuming an annual operating time of 340 days, the daily depreciation amounts to 27,200 US\$. With an annual interest rate of 6%, the annual interest payment for the vessel is estimated to be around 5.6 million US\$, resulting in daily interest payments of 16,300 US\$. Consequently, the daily capital costs for the vessel amount to approximately 44,000 US\$, denoted as $CC = 44,000$ US\$. The crew costs for shipping sum up to a daily expenditure of approximately 1,000 US\$, while the operational costs are estimated to be around 6,000 US\$ per day, denoted as $OC = 6,000$ US\$ per day.

Cargo Volume and Value Analysis

The cargo volume consists of approximately 14,500 TEUs (Twenty-foot Equivalent Units), with an average weight of 11 tons per TEU, based on EU statistics. This coincides with the vessel's Deadweight Tonnage (DWT) of approximately 157,000 tons. Assuming an average value of 100,000 US\$ per TEU, the total cargo value amounts to approximately 1.5 billion US\$. Applying the standard annual interest rate of 6%, the daily interest cost for the cargo is estimated to be around 250,000 US\$, denoted as $ICC = 250,000$

US\$. Within the case company, the standard loading and unloading times for a full vessel are approximately 3 days, $T_l = T_u = 3 \text{ days}$. Additionally, an extra waiting time of 2 days is considered due to congestion during the voyage, denoted as $T_w = 2 \text{ days}$.

Fuel Consumption Analysis and Cost Implications in Vessel Operations

The brake-specific fuel consumption (BSFC) at full power for the vessel at 25 knots is reported as 14.2 tons of Marine Gas Oil/Very Low Sulfur Fuel Oil (MGO/VLSFO) per hour, which corresponds to fuel consumption of 0.171 kg/kWh. At an economic speed of 19 knots, the fuel consumption can be reduced to 6.4 tons of MGO/VLSFO. Steaming at 20 knots would decrease fuel consumption by 37%, and at 17.5 knots, it would be halved. However, slower speeds result in longer voyage times, which are also associated with costs. Based on these considerations, it is assumed that the vessel consumes between 150 and 340 tons of MGO/VLSFO per day, depending on its speed. The marine fuel used during the voyage is assumed to be VLSFO, which is suitable worldwide. The fuel price per ton is estimated to be around 600 US\$, referred to as the flash point (FP) = 600 US\$ per ton.

Fuel Consumption Function Assessment using the Cubic Law

The study continues to follow the cubic law approach, but in this case, it is necessary to determine the vessel's displacement Δ and define the parameters ψ and λ . Through document review and interviews, it is found that the empty displacement of the case vessel is 55,396 tons, representing its lightweight, while the displacement of a fully loaded vessel amounts to 218,788 tons, denoted as Δ . Further analysis of the case vessel's fuel consumption reveals a lambda value of approximately $\lambda = 2.37 \times 10^{-7}$ for the daily fuel consumption during a fully loaded voyage.

Fuel Costing as Part of the Voyage Costs

Currently, the global shipping industry is grappling with high fuel costs and the global Sulphur CAP, causing fuel prices to exceed 600 US\$, which account for over 80% of the total operating costs of a vessel voyage (Gu *et al.*, 2022). However, in our case, we have chosen a parameter ψ , representing the share of fuel costs as part of the voyage costs, with a value of 1.67. This implies that the total voyage costs are approximately 1.6 times higher than the fuel costs of the voyage.

When summing up the calculated daily costs for the trip with the nearly fully loaded case vessel, the study arrives at a daily cost of approximately 300,000 US\$, which includes daily capital costs, daily operating costs, and average daily voyage costs. By distributing these costs to the level of transported TEUs, we obtain a daily cost rate per transported TEU of about 20 US\$, representing an average value that depends largely on the fuel price and vessel speed. It is worth noting that the daily interest costs for the financial commitment of the cargo, calculated at around 250,000 US\$, nearly match the daily costs of operating the ship. This highlights the significant impact of ICC, which must be considered in voyage management.

Validation of the Optimization Model

Now that the crucial technical and economic parameters of the container vessel are clarified, it becomes possible to examine a specific voyage. The study focuses on a trip from Shanghai to Singapore, covering approximately 2,240 nautical miles. The ship is fully loaded in Shanghai with containers, some of which will be unloaded in Singapore for transshipment. It is assumed that the loading time in Shanghai will be 3 days, and the reshuffling of containers in Singapore will require 2 days. An additional day is added to account for potential congestion during the voyage. The constant costs associated with loading, unloading, and waiting times amount to 1,175,000 US\$, which includes capital costs, operating costs, and interest costs for the capital commitment of the cargo.

$$\begin{aligned}
 Const &= ICC \left(T_w + \frac{T_l + T_u}{2} \right) + CC(T_t) + OC(T_t) = ICC \left(1 + \frac{3+2}{2} \right) + CC(3 + 2 + 1) + OC(3 + 2 + 1) \\
 &= 1,175,000 \text{ US\$}.
 \end{aligned}
 \tag{21}$$

The estimation of the optimal service time can be done by inserting the already presented data into the service time equation:

$$T_s = \frac{D}{12} \times \Delta^{2/9} \times \sqrt[3]{\frac{6 \times \psi \times \lambda \times FP}{ICC + CC + OC}} = \frac{2240}{12} \times 2,187,88^{2/9} \times \sqrt[3]{\frac{6 \times 1.67 \times \lambda \times 600}{250,000 + 44,000 + 6,000}}.
 \tag{22}$$

With the value $\lambda = 2.37 \times 10^{-7}$, the calculations yield a service time for the voyage of $T_s = 4.82$ days and an average vessel speed of 19.37 knots. Thus, when considering the waiting time for congestions (1 day), loading time (3 days), and unloading time (2 days) in both ports, the total voyage time from Shanghai to Singapore will be nearly 11 days.

The voyage speed of 19.37 knots may appear relatively fast, so it is scientifically prudent to conduct a sensitivity analysis. Firstly, the study examined the holistic voyage costs (HVC) of 3.3 million US\$, which encompass loading, unloading, congestion, and the voyage itself. A change in fuel price from the current 600 US\$ per ton of VLSFO to 400 US\$, as it was before the conflict in Ukraine, results in slightly lower holistic voyage costs of approximately 3 million US\$, a slightly shorter service time of 4.21 days, and a higher voyage speed of 22.18 knots.

Secondly, the value of the cargo initially assumed to be 1.5 billion US\$ with an average value of 100,000 US\$ per transported TEU, is evaluated. If there is a reduction in the value per TEU to 50,000 US\$ while maintaining all other initial data, the holistic voyage costs amount to 2.2 million US\$, and the vessel shifts towards slow steaming, with a service time of 5.77 days and an average speed of 16.12 knots. The complete voyage encompasses cargo loading at the departure port, transportation between the ports, and cargo unloading at the destination port.

Based on these results, the presented approach offers valuable insights into the financial aspects of maritime transport by considering the economic perspectives of all participants in the value chain. By adopting a holistic view, shipping companies can offer more client-oriented services and develop new business models in the realm of supply chain finance, effectively balancing the interests of maritime logistics providers and cargo owners. While not addressed in this research, cargo owners might also consider the storage time of cargo at the port, although this aspect is typically not within the purview of shipping companies.

5. Conclusions

In this paper, a holistic view of the economic situation of a vessel on a voyage is considered and analysed, taking into account the capital commitment of the cargo as well as the voyage costs. The study addresses the complexity and fragmentation of marine transport operations and examines relevant costs.

The key findings of the optimization model, which is a real-life application, indicate that increasing operating costs, capital costs, or interest costs for cargo leads to a decrease in both service time and voyage time. Additionally, a higher cargo load increases the service time, and the fuel-saving benefits of slow steaming diminish as other cost categories become more significant. The realism testing of the optimization model, using a containership as an example, reveals a voyage cost (HVC) of 3.3 million US\$ (including loading, unloading, congestion, and the vessel's trip), a voyage service time of 4.82 days, and an average vessel speed of 19.37 knots. A sensitivity test demonstrates a change in results when the fuel cost is adjusted from 600 US\$ per ton of VLSFO to 400 US\$, resulting in a voyage cost of approximately 3 million US\$, a slightly shorter service time of 4.21 days, and a higher voyage speed of 22.18 knots. Moreover, there is also an impact on the results when the value of the handled cargo is modified.

The underlying mathematical model in this study demonstrates its versatility and adaptability to various maritime transport scenarios. Furthermore, it holds the potential for expansion to encompass other logistics-related services, including inventory management and distribution tasks. An intriguing avenue for future research would be the optimization of speed profiles to minimize emissions and fuel costs in both long and short-voyage operations. The current case study serves to empirically validate the model and showcase its practical applicability. Ultimately, this study presents a compelling and high-quality commercial solution for addressing supply chain finance challenges.

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