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Assessing the scheduling deviation impact on managing ports' congestion using a System Dynamics modelling approach

Name Student: Stylianos Paparizos,

Student ID Number: 520772

Supervisor: Prof. dr. Albert Veenstra

Second assessor: xxx

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Contents

I. Introduction

Seaborne transportation constitutes the preferred and most efficient way of moving cargo across the globe, both in terms of cost and sustainability, reaching nearly 80% of total trade. Around 20-25% of this trade is conducted through container liner services, where a set of vessels makes a specified number of roundtrips following a similar pattern in the order of port calls and the time interval between them, often at a frequency of one vessel per week (Notteboom, 2006). According to the work of Gutierrez, Lozano, and Furio (2013) container traffic is the fastest growing sector of the maritime industry, with considerable increases across all main routes: trans-Atlantic, trans-Pacific and Europe-Asia. Over the years this considerable increase of the container flow has led to the creation of shipping alliances and vessel upsizing, which in turn caused a reduction on the number of port calls and higher levels of congestion in the larger ports (Xu et al., 2021).

The congestion in such liner services can originate from delays in three stages of the cycle, namely in: i) the transport, ii) port service, and iii) landside operations (Xu et al., 2021). Moreover, these delays have a knock-on effect on the successive ports of call, creating problems within the liner service such as higher time costs, greater levels of container detention, operation disorder and complicated supply chain management, as well as delayed deliveries (Xu et al., 2021). For instance, the blockage of the Suez Canal by the Ever Given in 2021 caused a disruption in liner services and significant issues in the supply chain overall, affecting all the aforementioned stages. According to Allianz the blockage could have caused a decline in the annual trade growth of 0.2 – 0.4% on its own, while adding up to 15 more days to the Europe-Asia route for that period (Russon, 2021; Berger et al., 2021). In another case, the lack of containers during the pandemic had caused prices to soar, while the recent oversupply of containers caused further disruption in the container shipping industry leading to a reduction in vessel capacity and suspension of services by the carriers (Jay, 2022). Hence, port congestion acts as a bottleneck on the container trade volume, negatively affecting the container flows from one port to another.

Sailing delays are caused mostly due to mechanical errors, weather, or one-off events, meaning that there is little room to wiggle. Whereas, in the hinterland delays are caused because of the container circulation problem, where the repositioning of empty units or imbalances in the container supply volume may lead to hold ups in the port. The fixed equipment capacity in ports, at least in the short run, is another factor adding to port congestion especially in periods of high demand and trade volume (Notteboom, 2004). Unlike sailing delays, which are caused by unexpected external factors, the hinterland process hold ups can be foreseen and corrected. The issue at hand is how are the two causes of delays related, and how an unexpected delay during sailing affects the hinterland process and the container circulation problem, which in turn impacts the container flow, and vice versa.

So, understanding the interrelation and interaction of each leg of the liner service process is essential in assessing the overall effect of congestion on the system. However, in the OR literature these issues are treated independently from one another because solving the joint optimization and the container circulation problem is extremely challenging (Brouer et al., 2018). System dynamics (SD) modelling effectively explores the interrelations between the various parameters, which occur concurrently at the different stages, because of its ability to depict this complexity in a way that can be studied. Thus, an SD model is the ideal tool to address the following question:

How to integrate the ships' scheduling with the container circulation problem to manage congestion in ports?

In essence, this exploration will assess: 1) How effective is an SD model in providing a realistic depiction of container liner service? 2) How effective is it in analysing port congestion caused by scheduling deviations? 3) What is the impact of delays at the sailing stages on the overall container flow? 4) To what extent does the container circulation problem affect the container flow?

These questions set the path for examining and addressing the RQ. In Section II, the literature review, recent works related to the use of SD modelling in container shipping are provided, discussing its strengths and weaknesses. Section III, the methodology, showcases the steps undertaken to construct the model. Section IV, establishes the model, presenting its assumptions, framework, and causal relationships. Section V, the results of the benchmark scenario are presented along with four alternative scenarios introducing different internal and external shocks in the system. Section VI offers a discussion on the impact of the model's adjustment to accommodate external shocks. Section VII presents the conclusions answering the RQ.

II. Literature Review

System dynamics (SD) modelling is based on the Control and System Theories, setting the appropriate boundaries for the definition of a system, with focus on the cause-and-effect relationship between its elements, and their feedback linkages (Bala, 2017). It is extremely helpful in interpreting nonlinear systems through a combination of causal loop diagrams and equations, explaining complex systems according to endogenous variables, not exogenous (Sterman, 2000). This constitutes its main advantage over the traditional modelling approaches for transportation systems, with 11 more being mentioned in the work of Abbas and Bell (1994).

SD modelling has been used extensively in past research for the seaborne transportation. A prime case has been its use to calculate the impact of port congestion on the LPG transportation (Bai et al., 2021). Muravev, Rakhmangulov, Hu and Zhou (2019), on the other hand, measured the efficiency and sustainability of dry ports with a goal to optimize both, by adjusting the main parameters of such ports through an SD approach. The SD methodology has also been applied in the liner shipping industry, often with a focus on specific stages of a service. The analysis of the operational processes of container terminals, and the effect of planning decisions on them, using an SD approach has gained the interest of researchers recently with various publications (Briano et al., 2009; Abdel-Fattah et al., 2013; Soares & Neto, 2016; Huang et al. 2021). Xu, Liu, and Yang (2021) shifted their attention towards port congestion at container terminals, attempting an SD analysis that assesses the effect of governance measures on port congestion. The port-service has been the emphasis of the SD approach in container shipping research (Fu et al., 2018). Nevertheless, it has been used also to examine the modal shift in the transportation of containers from the hinterland to ports, and vice versa (Zhong et al., 2023).

Despite of the widespread appearance of SD modelling in the liner shipping industry, it has not yet been attempted to create model for an entire service. To integrate the main parameters under one system, though, it is paramount that the composition of liner services is sufficiently exhibited. Notteboom (2004) offers an overview of the components of liner services and ports. The time factor is a crucial such component, since it affects heavily the efficiency of the entire system (Notteboom, 2006). As a result, mathematical models calculating transit times have been established, with one being provided in the work of Du, Meng, and Wang (2017). Yahalom and Guan (2022), offered a new method calculating the sea time for containerships to evaluate its efficiency and performance. Delayed voyage times may lead to port congestion, which has negative effects in the operations of container terminals reducing the overall efficiency (Jiang et al., 2017). Talley and Ng (2016) also offer insights on the causes of port congestion and its impact on multiple port services, mentioning the container circulation issue as a factor that may contribute to congestion.

Because of the gaining importance of port congestion on the liner service efficiency, there are different approaches in the existing research. The efficiency evaluation of actual liner services operating at different routes has been a common practice for researchers, with the goal to gain insight on the best practices of each one (Verny & Grigentin, 2009; Gutierrez et al., 2014; Munim & Schramm, 2017; Brouer et al., 2018). Others have focused on the policies that ports can undertake to improve their operational efficiency, and thus limit the congestion (Kaselimi et al., 2011; de Langen & Heij, 2014; Wang & Cullinanne, 2015). These papers tend to highlight that the adversity to change due to rigidities, caused by established best practices, of port authorities, liner service providers and lawmakers result in delayed decision making. Lastly, research attempting to improve the hinterland connection to the ports both in terms of efficiency and sustainability has gained ground (van der Horst & van der Lugt, 2011; Guo et al., 2022). According to these works, the hinterland connection modal shift is necessitated by the need of adapting to new sustainable business models, limiting the congestion at ports as well in the process.

The model proposed on this paper, attempts to bridge a gap that currently exists in the literature for container shipping. Although, SD modelling has been used effectively in specific function of liner services, it has not yet been used to integrate the delays occurring either during the voyage times or at the hinterland connection and analyse their effects. This process is undertaken by combining past models and insights from past literature.

III. Methodology

To construct the model, a simple liner service of two ports will be integrated into a cycle of seven separate actions which after the initial trip occur simultaneously.

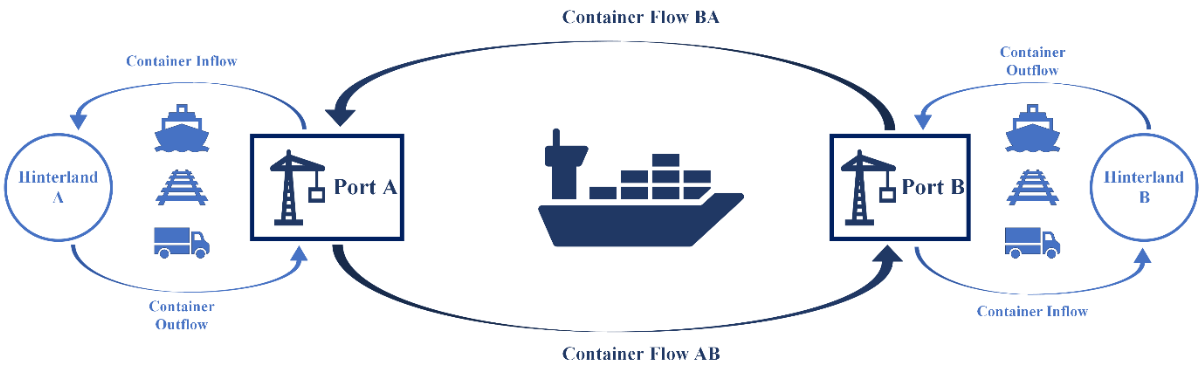

Figure I. The container liner service's model in seven stages.

Notes: The figure presents the stages and overall look of the liner service simulated in the proposed model. It was constructed using Microsoft Visio software, based on the basic principles of a two-port liner service.

The following seven stages are depicted in figure I:

1. Transporting containers to the port of origin (Port A).
2. Loading containers to the vessel at the port of origin (Port A).
3. Sailing to the port of destination (Port B).
4. Transporting containers from the hinterland to Port B.
5. Unloading containers from the vessel and loading containers on it, at Port B.
6. Sailing from Port B towards Port A.
7. Unloading containers from the ship and loading containers at Port A.

These stages represent the two legs of a roundtrip (inland and seaside legs) and can be placed into three separate service categories where a delay can occur. Specifically, stages 1 and 4 represent the hinterland services, and tackle the issue of optimizing the repositioning of empty containers to avoid delays or missed loadings. Stages 2, 5 and 7 refer to the port services, where the goal of independent models is to improve the ports' capacity utilization and productivity. Lastly, stages 3 and 6 give insights on how the main transportation services can be improved in terms of reliability.

The model includes parameters that have the largest impact on each stage, sourced from past papers in container shipping. After the basic model is constructed, certain real-life scenarios are examined to check whether the model can transform such exogenous events in endogenous parameters. The goal is to improve the ship-scheduling process in port to limit congestion, and thus a model that can take into consideration such unexpected events could provide an answer. The steps taken to construct the system dynamics model follow the procedure described in the work of Bala, Arshad, and Noh (2017). In particular:

1. Problem identification and formulation of the mental model.
2. Creation of a basic causal diagram depicting the mental model.
3. Augmenting the causal loop diagram into a system dynamics flow diagram.
4. Expressing the SD flow diagrams with a set of simultaneous equations, based on relevant simulation models.
5. Hypothetical values of parameters assigned to simulate real-life scenarios/ incidents to check the adaptability of the model.

After the shocks are introduced a scenario analysis is undertaken to examine and assess the effect that the ships' scheduling deviations and the container circulation problem have on the flow of containers between Port A and Port B. The effectiveness of the model will be judged based on the results of the simulation in each case in the scenario analysis and their difference from the theoretical expectations.

IV. Model

The model constructed in this paper integrates three distinct services into one SD simulation model. In fact, the interrelation and interaction of these three services with one another represent the principal focus of this simple liner service simulation model. These are: a) the container circulation in the hinterland and its inventory, b) the transfer time of containers on the vessel in open sea, and c) the handling time of containers at the port.

To approximate a simple liner service the SD model must integrate all the above for two ports, A and B. The former (A) is the initial port of loading, and the latter (B) is the initial port of discharge, and then both act as the two ports of call for the duration the liner service runs. The parameters that make up the model are given in Table 1.

Table 1. List of key model factors

Parameter	Description	Unit
CI_A	Container inventory at port A	TEUs
CI_B	Container inventory at Port B	TEUs
$CI_x^{hinterland}$	Container inventory at hinterland *x*	TEUs
CF_{AB}	Container flow from port A to Port B	TEUs

CF_{BA}	Container flow from Port B to port A	TEUs
CF_{xi}	Container flow from Port *x* to Port *i*	TEUs
VT_{xi}	Voyage time from Port *x* to Port *i*	Days
$PP\ Time_x$	Time needed from berthing to unberthing at Port *x*	Days
$TT\ Time_{xi}$	Sailing time at open sea from Port *x* to Port *i*	Days
HC_A	Container handling capacity at port A	TEUs/ Day
HC_B	Container handling capacity at Port B	TEUs/ Day
CDxit	Container demand at port x at time t	TEUs

Notes: The table contains all main parameters mentioned in the model structure below, any additional parameters used during the simulation for computational purposes can be sourced in Appendix A.

Model Assumptions

The model is based on the following assumptions, some of which are heavily unrealistic: (1) the overall demand is an external parameter that is fixed throughout the duration of the liner service; (2) the container supply and the container handling capacity for each port are also fixed during the duration of the liner service; (3) the number of vessels and their cargo capacities are fixed; (4) the container demand, the voyage times between Port A and Port B, and the handling capacity of each port influence the container flow; (5) the voyage times are influenced by the container inventory at each port; and (6) the container inventory at each port affects the container flows.

Model Structure

So, the model is structured through distinct systems of equations, each system depicting one aspect of the entire system.

$$CF_{AB} = \min\left(HC_A, CI_A, CD_A, \frac{1}{VT_{AB}}\right) \quad \textbf{(1a)}$$

$$CF_{BA} = \min\left(HC_B, CI_B, CD_B, \frac{1}{VT_{BA}}\right) \quad \textbf{(1b)}$$

Equations 1a and 1b represent the number of containers that can be transported from Port A to Port B within a specific time frame, which is occurring after the handling capacity, the container inventory and demand of port are minimized to ensure that the flow will not exceed the limits of the port's capacity. Also, the inverse of the container transfer time is minimized, to account for the fact that shorter time travels will lead to higher container flows between the ports, and thus greater container volume, a realistic condition for any liner service. Likewise, equation 1b portrays the container flow from Port B to Port A.

The second system focuses on changes that are caused in the container inventory during its lifespan after the initialization of the model.

$$CI_A(t) = CI_A(t-1) + CF_{BA}(t-1) - CF_{AB}(t-1) + CI_A^{hinterland} \quad \mathbf{(2a)}$$

$$CI_B(t) = CI_B(t-1) + CF_{AB}(t-1) - CF_{BA}(t-1) + CI_B^{hinterland} \quad \mathbf{(2b)}$$

The inflow and outflow of containers from Port A and B is accounted for in equation 2a. The available number of containers in inventory at a given time (t) at Port A is determined through the addition of containers flowing from Port B in the previous period (t-1) to the inventory of Port A at that period (t), while the containers that are sent to Port B at the previous time period (t-1) are subtracted from the inventory of Port A. The changes in inventory for Port B are calculated in the same way in equation 2b.

The issue of container circulation in the hinterland can be sourced in the $CI_x^{hinterland}$ parameter of the equation, where x denotes the port in question. The hinterland connection to most large ports is split into three modes of transport: roadway, waterway, and railway with a respective ratio of 5:3:2 (Guo et al. 2022). The status of the containers (full/ empty) does not play a role in the model, since solely the overall container demand for the port of discharge (CD_{xit}) determines the container outflow from the hinterland. As the model progresses there is an additional parameter acting as an inflow to the hinterland container inventory, the container flow. So, using this information the parameter can be rewritten as follows:

$$CI_x^{hinterland} = (0.5_{road} + 0.3_{water} + 0.2_{rail}) \times (-CD_i + aCF_{ix}) \quad \mathbf{(2c)}$$

Equation 2c calculates the effect of a potential delay in each mode of transport in the container inventory at a specific time. This equation also shows the initial container inventory, with the limit being the maximum handling capacity of the port.

The total voyage time is affected by various factors which include port congestion, the availability of handling equipment, and the efficiency of operations at the port amongst others. This model is a simplified combination of the parameters that were seen in various past works, using the harbour waiting time (PWT) and the pier-to-pier time (P2P Time) additional to the transit time (TT) itself to calculate the total voyage time for each trip (Alvarez, 2012; Du et al., 2017; Yahalom & Guan, 2022). This is portrayed in equation 3a:

$$VT_{xi} = Port\ Waiting\ Time_x + PP\ Time_x + Transit\ Time_{xi} + \ Port\ Waiting\ Time_i + PP\ Time_{\boldsymbol{i}}\ (\mathbf{3a})$$

The PWT refers to the waiting time of a vessel before the berthing which represents a deviation from the expected schedule, either due to an early or late arrival of a vessel and must be considered for both ports. Moreover, given assumption 5 of the model the container inventory of one port is affecting indirectly the VT, meaning that the PP Time must have CI(t) as an endogenous parameter. PP Time refers to the time it takes the vessel from berthing to unberthing, meaning that an insufficient CI can lead to further delays in the whole process. This can be described in the following equation 3b.

$$PP\ Time_x = Berthing\ Time + Unloading\ Time + f(CI) = P\left(delay\ in\ CI_x^{hinterland}\right) + Loading\ Time + Unberthing\ Time\ (\mathbf{3b})$$

Lastly in equation 3c, the TT itself refers to a function that combines the length of the trip from Port A to Port B and the speed of the vessel during the trip, which can be written in its most simple form as:

$$Transit\ Time_{xi} = \min(Distance_{xi}, Vessel\ Speed)\ (\mathbf{3c})$$

The last equations introduce how the handling capacity of each port is determined based on the infrastructure and workforce limitations that are often present in ports. Thus, the container handling capacity is given by:

$$HC_A(t) = \min\left(HC_A^{max}, HC_A^{equipment}, HC_A^{operation}\right)\ \ (\boldsymbol{4a})$$

$$HC_B(t) = \min\left(HC_B^{max}, HC_B^{equipment}, HC_B^{operation}\right)\ \ (\boldsymbol{4b})$$

The handling capacity at Port A and B is limited because of two general types of constraints, physical or operational, as seen from equations 4a and 4b. The first type includes scarce resources such as the number of cranes, reach stackers and straddle carriers, while the second type refers to the limiting factors associated with the workforce, like its shift planning, availability or even maintenance. The overall handling capacity at each port is the minimum value that satisfies all three constraints, ensuring that the handling capacity will not exceed the maximum values of the most limiting factor at each instance.

The equation regarding the container demand for the ports can be written as a simple trade gravity equation as it was first introduced by Tinbergen (1962), which states that the bilateral trade is proportional to the total economic volume of the two regions and inversely proportional to the distance between them (equation 5). So, the CD for a port is given by:

$$CD_{xit} = \frac{T_{it}}{D_{xi}^2} \quad \mathbf{(5)}$$

where: CD_{xit}: the container demand between port x and i in period t; T_{it}: the total GDP of port i in period t; D_{xi}: the distance between port x and port i (Zhong et al., 2023).

Feedback Loops

The model for the flow of containers in the simple two liner service scenario can be analysed through the prism of three distinct feedback loops, such as (1) the container flow, (2) the inventory of containers and, ultimately, (3) the container handling operations. The interrelations of all the parameters of the feedback loops are depicted in figure II.

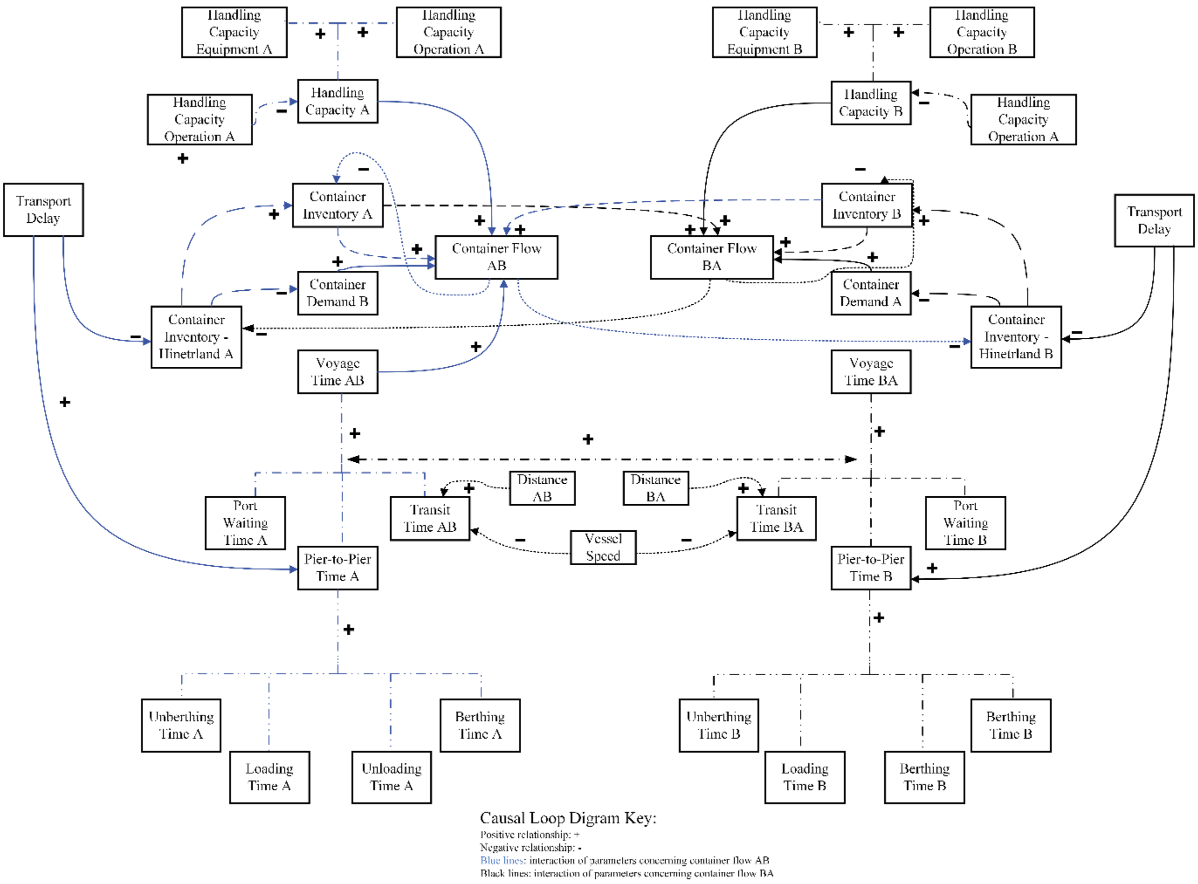

Figure II. Interrelations of model parameters.

Notes: The figure was constructed using Microsoft Visio software, the relationships between the parameters were assigned based on equations 1a through 5.

Firstly, the container flow feedback loop depicts the relation of the flows between the two ports (CF_{AB} & CF_{BA}) and the container inventory at each port (CI_A & CI_B), as it can be deducted from equations 1a through 4b. Specifically, the container inventory levels at Ports A and B depend on the transportation process of the containers from one to another. The higher container flows reduce the inventory level of the loading port and increase that at the discharge port. Both parameters are heavily affected by the given container demand at each port (Assumptions 4 & 6). Since this is a dynamic system, the changing container inventory feeds back into equations 1a, 1b, 2a, and 2b affecting the succeeding container flows. The handling capacity of each port and the voyage time act as balancing forces in the loop, whereas the demand and the container inventory reinforce it.

The second feedback loop, which analyses the container inventory levels of the two ports in the model involves each port's inventory level (CI_A & CI_B) and the required voyage times (VT_{AB} & VT_{BA}). Specifically, the container inventory level at each port may influence the transfer times between ports A and B since high levels could cause delays due to limited resources, and ultimately congestion. In such a case, the longer transfer times will cause a reduction in the container flows between the ports, leading to lower inventory levels, which if occurring sequentially causes dynamic adjustments in the transfer times and the inventory levels. The hinterland flow of empty/ full containers and the container inflows from port to port are the reinforcing parameters, while voyage times and the container outflows from port to port are the balancing parameters of the loop.

The third feedback loop refers to the container handling capacities that are available at the two ports (HC_A & HC_B), which also affect the container flows between one another (CF_{AB} & CF_{BA}). The handling capacities act as a constraint for the container flows, since reaching the limited capacity may lead to port congestion. Additional consequences of exceeding the container handling capacity at each port are reduced service quality and inefficiencies in the handling operations.

These are the principal feedback loops that highlight the interdependencies between the parameters of the model, which with their dynamic interactions set the stage for the emergence of the liner service system. The structure of the model enables the understanding of the impact of certain parameters on the container flows in a two-port liner service.

V. Scenario Analysis

A scenario analysis is provided in this section, consisting of the benchmark case in scenario 1 and additional scenarios examining the effectiveness of the system under different conditions. In essence, there are three stages: (1) the analysis phase shown in the benchmark scenario and its comparison to the rest, (2) the discussion regarding the importance of the alternative cases, and (3) the assessment of the system (Brauers & Weber, 1988). The system is evaluated based on its reaction on the change of endogenous and exogenous parameters that affect the container flows between Port A and Port B. The scenarios are in ascending order in terms of realism. Specifically, the last scenario will examine the effectiveness of the proposed model in simulating a liner service with unequal demand between the two ports, unequal handling capacity and unequal efficiency in the container circulation.

The scenario analysis constitutes the preferred method of evaluating the proposed model, because it can clearly depict how the model operates in the simplest of cases, like in the benchmark scenario, and contrast it when its evolved using more complex settings and differentiated parameter levels. The parameters that are of the greatest importance in this analysis are the scheduling deviation of ships and the delays occurring in the hinterlands' container circulation. In principle, the model must be effective in simulating in a realistic manner, at least, the scenario which involves concurrent delays for both aforementioned parameters. Additional explanatory capabilities regarding the effect of other parameters in the system, such as distance and container handling capacities, are welcomed but not necessary, as they are beyond the principal scope of this paper.

Scenario 1 acts as the benchmark, depicting the container flows between to completely symmetrical ports that face no delays during the entire liner service. Scenario 2 introduces a delay occurring during sailing, analysing the behaviour of the system when there is only one parameter of interest changed. Scenario 3 provides similar insights, but regarding the influence of proportional delays of the circulation of containers in the hinterland of A and B respectively. Scenario 4 examines the system when both parameters of interest are in place concurrently, to establish which one has more dominant effect. Lastly, scenario 5 checks how other factors affect the system, such as container demand and handling capacities of Port A and Port B.

The model has been adjusted to portray relatively similar characteristics with the Europe-Asia liner shipping route. The distance between the two ports is similar, for scenarios 1 to 4, and the life expectancy of the liner service is chosen based on the average duration of services of this route. However, the simulation is conducted using solely hypothetical values, especially regarding the supply of containers and the handling capacities of ports. To validate the effectiveness of the proposed SD model further investigation is necessary, offering a sensitivity analysis as well based on the deviation of the simulated results from the real-world data. To successfully determine this, the model must incorporate real-life values for its parameters for specific ports, and not just average aggregate data values of the entire route. This analysis, though, aims at evaluating if such a procedure is necessary for the proposed model beforehand. Examining the simulation results and comparing them with the expectations of the model based on the theory, may offer insights that would constitute such research in the liner shipping industry useful for the future.

Scenario 1- Results

In this base case scenario, all parameters that may lead to a possible delay are set to 0, whilst the system operates under full efficiency conditions for the entire duration of the liner service (120 days). The container flows for both routes (AB & BA) are constant and overlapping throughout the period, indicating a seamless transfer of containers between the ports. This is presented in figure III.

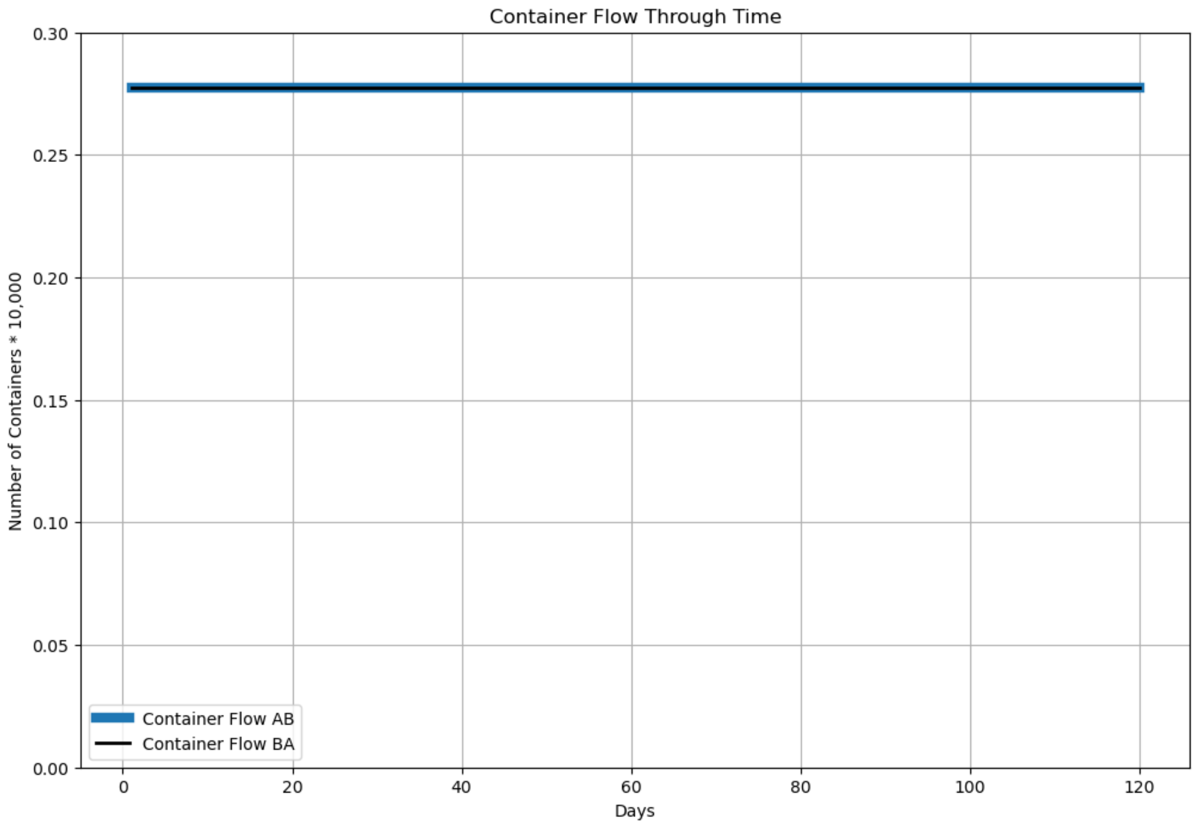

Figure III. Container flows between Port A & Port B, in case of full efficiency.

Notes: The figure presents the number of containers flowing from Port A to Port B through the life-service of the container liner service, set at 120 days. The y-axis shows the number of containers, and the x-axis the timeframe in days. The figure was constructed using values from the simulation with the ships' scheduling deviation and the delay factors at each port all set to 0. The simulation was conducted using a Python algorithm at a Jupyter Notebook environment. For more information regarding the code and the parameters setting refer to the Appendices.

Scenario 2 – Results

In scenario 2, the external shock introduced increased the deviation on the ships' scheduled arrivals from 0 to 5 days. This led to a sharp decrease of the intercept and a negative slope, at a similar rate for both curves. In fact, the intercept has approximately decreased at half the level of the base case scenario, while the negative rate leads to container flows of less than 500 containers by the end of the service's life, for both routes AB and BA. The lowered intercept suggests that delayed arrival of ships has a significant impact on the container flows, especially at the initial stage. The decreasing negative slope on the other hand showcases that despite the delays are carried over from one port to another, the delay reduces over time suggesting that time is gained during the sailing trip for CF_{AB} (blue curve) and CF_{BA} (black curve). This is shown in figure IV.

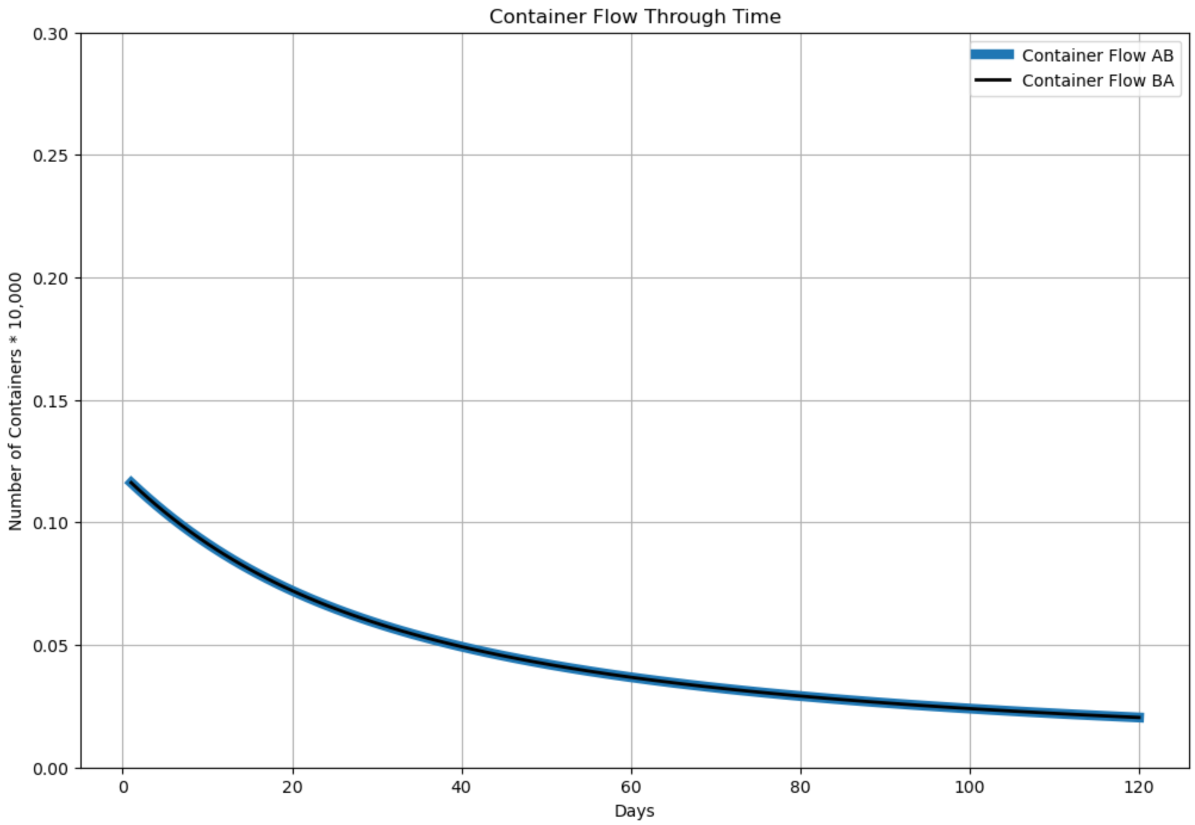

Figure IV. Container flows between Port A & Port B, delayed vessels' arrival.

Notes: The figure presents the number of containers flowing from Port A to Port B through the life-service of the container liner service, set at 120 days. The y-axis shows the number of containers, and the x-axis the timeframe in days. The ships' scheduling deviation is set at 5 days, and the delay factors at each port were all set to 0.

Scenario 3 – Results

In this scenario, the delay factor at each port was raised from 0 to 2 days, indicating a delay caused by the container circulation in the hinterland. This disruption reflects an internal shock introduced in the model, negatively affecting the two curves compared to the base case scenario. Although, the intercept has remained the same for both flows as in the base case scenario, after approximately the 20-days mark the flows experience and sudden drop. When the liner service reaches the middle of its life-expectancy, the curves start declining at slower rate. Both curves react in the same way when increasing proportionately the delay in the hinterland connection for both ports. This is showcased in figure V.

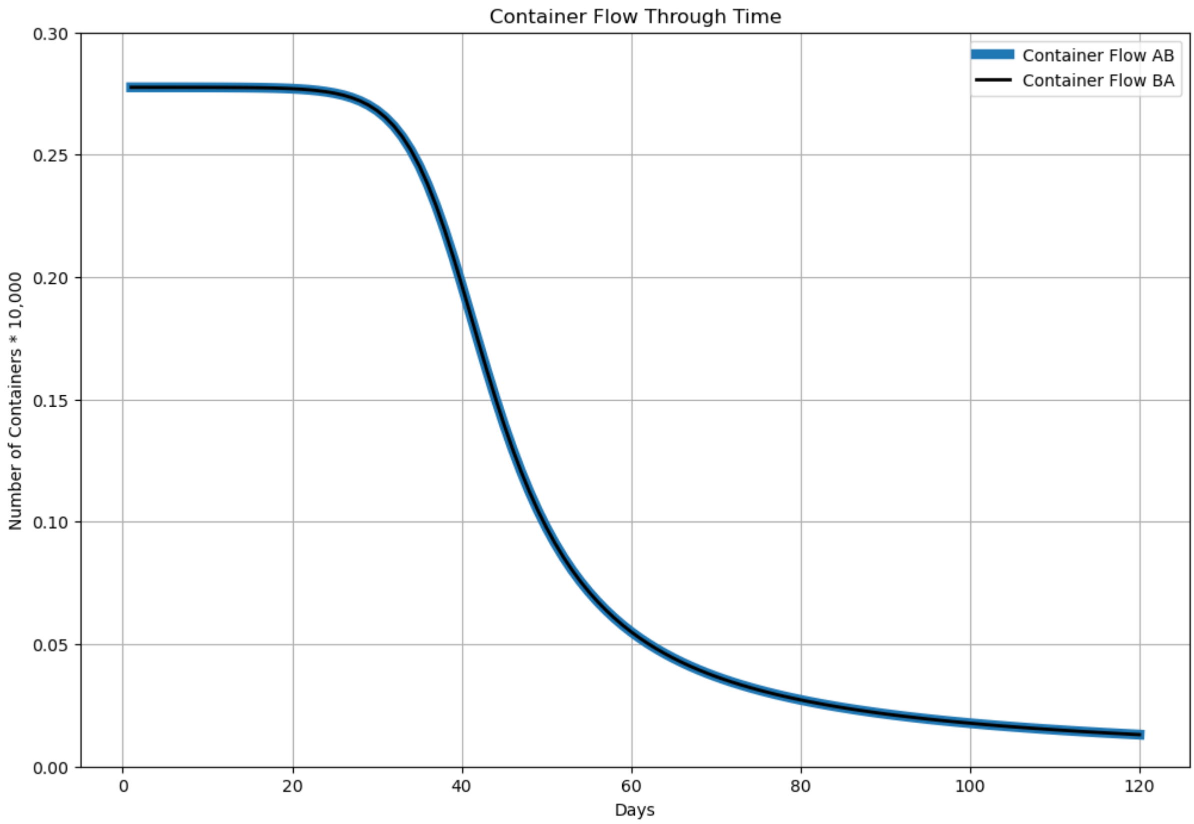

Figure V. Container flows between Port A & Port B, delays in container movements in hinterland.

Notes: The figure presents the number of containers flowing from Port A to Port B through the life-service of the container liner service, set 120 days. The y-axis shows the number of containers, and the x-axis the timeframe in days. The ships' scheduling deviation is set at 0, and the delay factor at each port are 2 days.

To establish a better understanding of how the system operates under a more realistic scenario, a second case is provided below in figure VI. In this case the delays occurring in the container circulation at each hinterland are unequal. It assesses how the model reacts in a differentiated time efficiency in the container circulation in each hinterland and in the handling operations at each port. In the case explored in figure VI Port A faces a five-times higher container circulation delay than Port B, representing a 5-times more efficient port compared to Port A. The two container flows react in a similar fashion as in the case of figure V, but with a different magnitude, which is expected. It is worthwhile mentioning, however, that CF_{AB} reaches a level of 0 containers transferred from Port A to Port B after the 60-days mark. Based on the theoretical framework of liner shipping operations and the assumptions of the proposed model, such behaviour is not expected. This suggests that no containers are transferred from Port A to Port B, not even the ones that are needed to have the CF_{BA} level observed in figure VI. According to this figure CF_{BA} runs after the 60-days mark solely with the container inventory at hinterland B, which however seems unlikely upon further examination of the inputs in the model. Thus, the proposed model fails to take correctly into consideration the transfer of containers from A to B in cases of extreme differences between the efficiency of the container circulation in each hinterland.

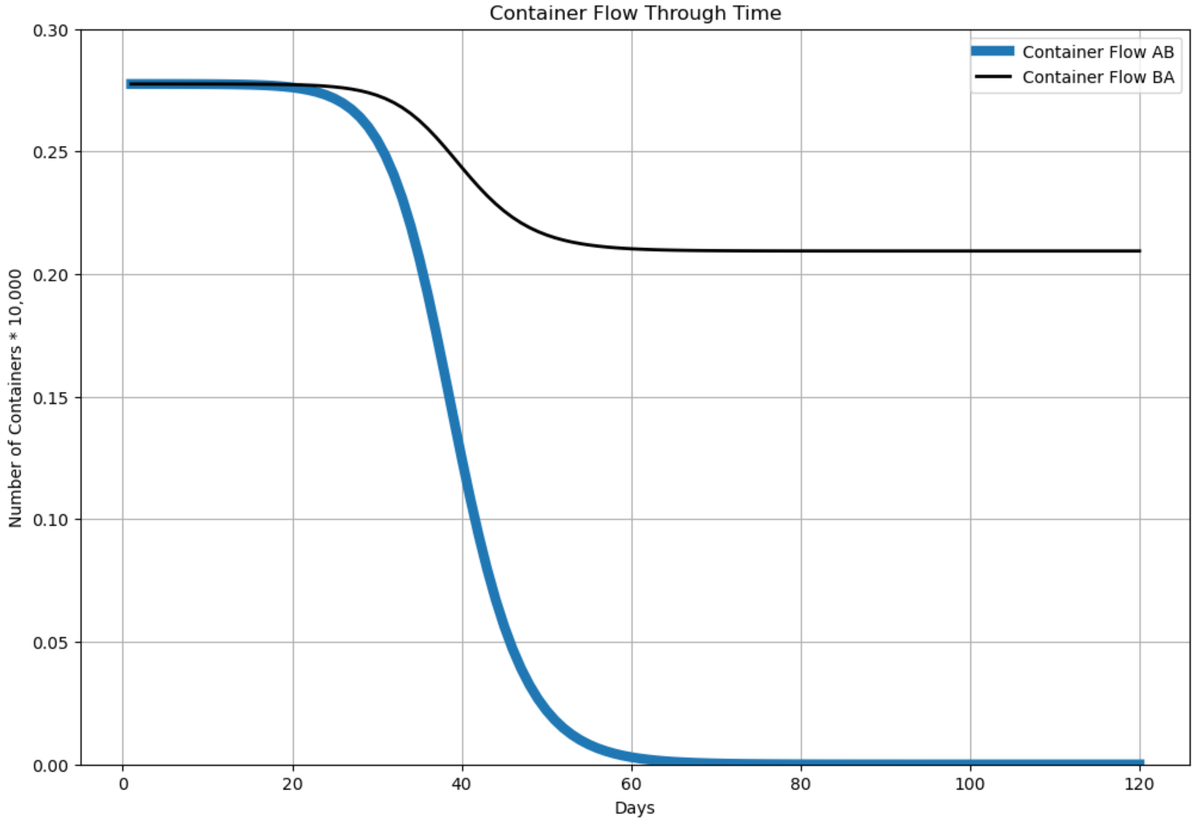

Figure VI. Container flows between Port A & Port B, unequal delays in container movements in hinterland.

Notes: The figure presents the number of containers flowing from Port A to Port B through the life-service of the container liner service, set at 120 days. The y-axis shows the number of containers, and the x-axis the timeframe in days. The ships' scheduling deviation is set at 0, and the delay factor at port A is 5 days, while at port B is 1 day.

Scenario 4 - Results

In this scenario the behaviour of the proposed model is examined when there are simultaneous delays both during the sailing leg and in hinterland container circulation. The vessel's delayed arrival is set to 1 day, as is the delay in Port A, while the delay at port B is at 5 days. Figure VII presents a similar picture to figure IV, with both curves following the same trajectory, even though Port B faces a significantly higher delay in total. This suggests that in the proposed model a vessel's delayed arrival has a significantly larger impact on the container flow. Such a dominant scheduling deviation effect is not expected, highlighting a need for further research on this connection. It must be mentioned that similar results were found in case of proportional changes to all delay factors, suggesting that under this model structure the scheduling deviation is always the dominant parameter.

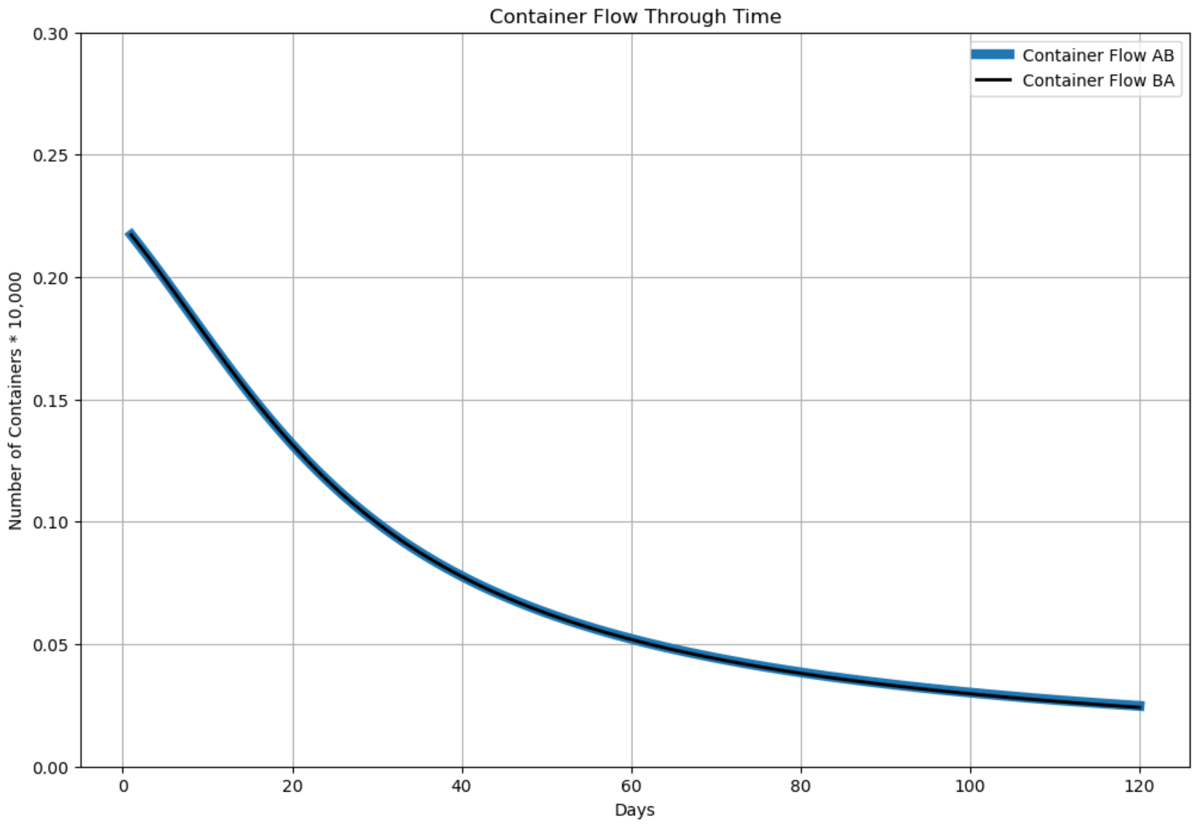

Figure VII. Container flows between Port A & Port B, simultaneous delays in container movements in hinterland and sailing leg.

Notes: The figure presents the number of containers flowing from Port A to Port B through the life-service of the container liner service, set at 120 days. The y-axis shows the number of containers, and the x-axis the timeframe in days. The ships' scheduling deviation is set at 1 day, and the delay factor at port A is 5 days, while at port B is 1 day.

Scenario 5 - Results

This final scenario examined the reaction of the proposed model under the most realistic set up of the two-port liner service. In this case, all parameters regarding the delays were set to 1 day each, with the addition of unequal container demand through a considerable change for the distance of the route AB, which was set 3 times higher than the respective distance of the BA route. Although such unequal route distance is not realistic on its own, under the proposed model it was the only way to set a scenario of different container demands between the ports, given equation 5 and assumption 1.

Under this scenario the results are like scenario 4, with CF_{AB} and CF_{BA} progressing at the same declining level throughout the liner's service life. This behaviour should not be exhibited since the AB route has a much higher distance, the demand for containers towards Port B should be much lower than the demand for Port A, meaning that the container flow of this route should have been much lower as a result. This suggests that the proposed model fails to successfully integrate a change in distance in the system, highlighting the need for further examination on the direct positional arguments used on the calculation of the voyage time and the role of the container demand. This is shown in figure VIII.

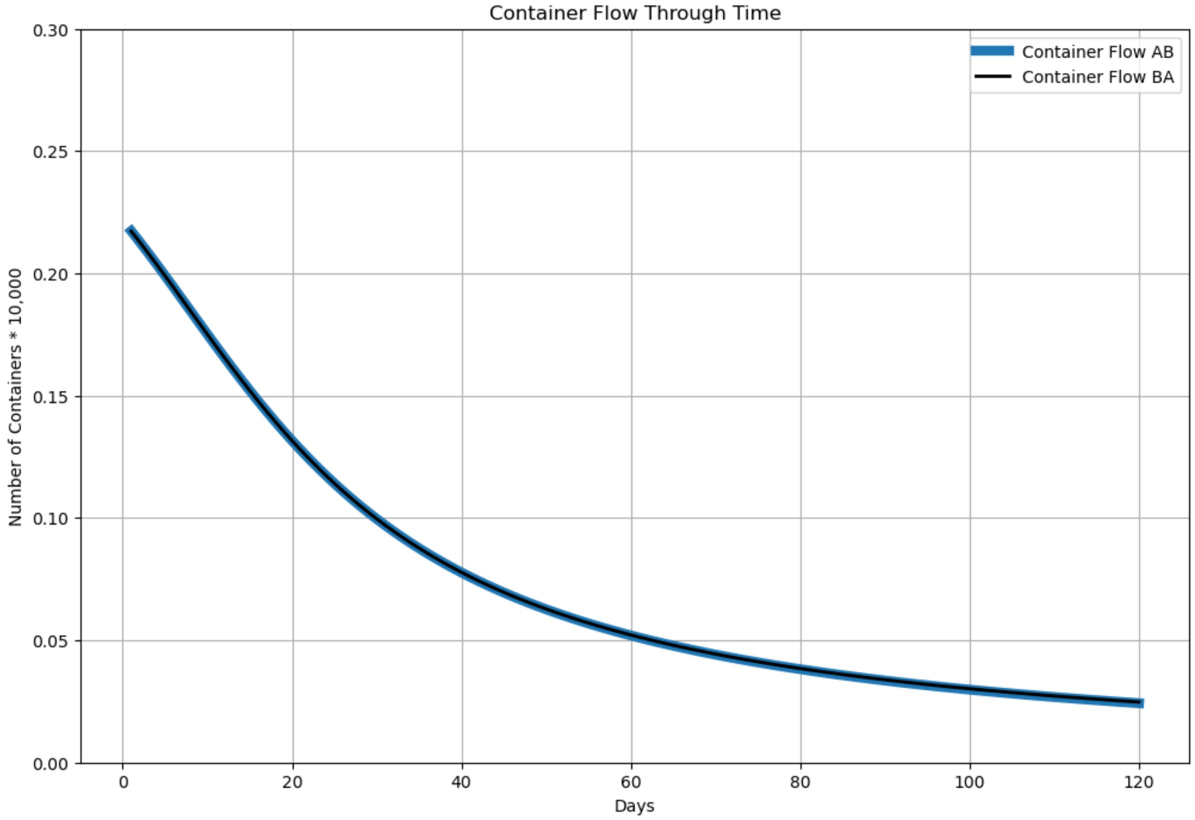

Figure VIII. Container flows between Port A & Port B, simultaneous delays in container movements in hinterland and sailing leg with unequal container demand between the two ports.

Notes: The figure presents the number of containers flowing from Port A to Port B through the life-service of the container liner service, set at 120 days. The y-axis shows the number of containers, and the x-axis the timeframe in days. The parameters regarding possible delays are identical to scenario 4. The demand is adjusted through an unrealistic increase of the distance of the AB route, given assumption 1 and equation 5, from 11,000 km to 33,000 km. The distance of the BA route remains at 11,000 km.

VI. Discussion

Considering that the results of Scenario 1 are the benchmark case, it is shown that the model reacts differently in external shocks (Scenario 2) compared to internal shocks (Scenario 3). An increased deviation in the vessel's scheduled arrival, representing a delay occurring during the sailing leg, affects similarly both routes by shifting their container flow intercept significantly downwards, and then experiencing modest but steady negative slopes (figure IV).

Increasing the delay factor on both ports by the same amount, however, creates a different setting. There is no initial shift of the intercept, but there a rapid decrease of the container flows after a short period, that flattens out as time passes (figure V). This suggests that the delays caused by the container circulation problem affect the container flows with a time lag. Furthermore, the rapid decrease may be caused by the appearance of port congestion in the system, significantly deteriorating the efficiency and container flows in the short term. After time progresses, though, the system balances, suggesting that the cause of these delays in the container circulation have been corrected internally in the model.

However, the second case examined in scenario three highlighted a weakness of the proposed model to effectively simulate the transfer of necessary containers from AB that would maintain the high flow levels of flow BA. Given assumption 2, this behaviour is probable only if the container inventory at hinterland B is large enough to accommodate the trade on its own for 60 days in total. Based on the inputs, though, this an unlikely case. Thus, the model is at least partly problematic in maintaining the overall container demand stable over time, violating assumption 1 in cases of extreme differences in the efficiency of the hinterland circulation of containers and their connection to the port.

Scenario 4 offers the most useful insights regarding the ability of the SD model to integrate both factors of interest. Figure VII showcases that vessels' delays affect the system at higher degree compared to delays in container circulation. Although this may be the actual effect, it seems that the proposed SD model magnifies the effect of the scheduling deviation relative to the circulation delays. One possible cause is that the scheduling deviation is introduced in the equations of the model as a direct positional argument, whereas the circulation affects the flows indirectly by holding up the container inventory at the port. Moreover, when vessel delays occur concurrently with hinterland delays it may be the case that they act as balancing factor, meaning that containers reach the port before the vessel arrives and thus the reduction on the container flows is ultimately affected solely by the delayed ships' arrival. However, more research should be conducted to establish the exact relationship between these two factors.

Considering the similarities of figures VII and VIII it must be pointed that the model fails to effectively take into account changes to balancing factors other than delayed ships' arrival and container circulation in hinterlands. Neither changes in handling capacities nor changes in route distance had the effect it was assumed based on theory. This behaviour signifies either that the effect of such factors is limited, or that the model fails to effectively measure it. In addition to the results of scenario 4, it is reasonable to assume that the model overestimates the influence of scheduling deviations on container flows. To be certain, though, a sensitivity analysis must be conducted to check whether any real-world data would support these findings. Without such research it can only be assumed that the model has an inherent weakness by overestimating the influence of scheduling deviations over other factors.

In general, it seems that the model is incapable of simulating effectively a container liner service when the level of realism in the parameters increases. This may be due to the rigid, and to a second degree unrealistic, assumptions that were made initially. Specifically, the fixed overall demand assumption seems to be the prime cause for all the unexpected results, which limits the explanatory ability of the model. Upon further reflection, it would be suggested that the container demand is formulated independently for each port, following the principle of equation 5. This change should correct the stagnant output of scenario 5, at least in part. Additionally, raising the number of ports in the system would raise the levels of realism of the proposed model and eliminate any inconsistencies between the theory and the model's output, as additional ports could act as reinforcing factors in the system. Still, though, reevaluating assumption 1 and creating a dynamic demand setting should be the priority when revisiting the model.

VII. Conclusion

The proposed model offers a comprehensive map of how parameters of a liner service interact with each other, offering a fairly realistic depiction of the system as a whole. It is unavoidable and necessary, though, to reduce the complexity of the model when attempting to examine the effect of few parameters on the whole system. The proposed SD model has also proved to be effective in analysing the relationships between the various interrelated parameters leading to port congestion at a theoretical level. However, the results of scenarios 4 and 5 indicate that in practice the model fails to accommodate secondary parameters to its analysis successfully, like the increase in distance and the differentiated handling capacities for each port.

The delays caused during the sailing stage are depicted in scenario 2, suggesting that the overall container flow reduces as expected from theory. Similar conclusions could be drawn when looking into scenario 3 as well. Yet, scenario 4 points towards a complete domination effect of delays during sailing over other explanatory parameters, which does not follow neither the theory nor the current view in the literature. These results indicate that either further research should be considered or a re-evaluation of certain parameters in the proposed model. The model must be reviewed with caution so as to correct the parameters that cause such output and enable the model to simulate effectively a liner service under more realistic conditions. Even though, this correction can and should be made it must be mentioned that the model cannot resemble an actual liner service under a two-port framework.

Overall, the proposed model offers an effective method in integrating the ships' scheduling with the container circulation problem, and attempting to analyse their effect on the container trade flows between two hypothetical ports in simplified conditions. So, regarding the research question:

How to integrate the ships' scheduling with the container circulation problem to manage congestion in ports?

the answer is the use of SD modelling. Of course, the model can be further improved, but even at this stage it offers useful insights on how these two parameters are interrelated with each other and affected by external factors, which can be used to explain arising port congestion. Managing this congestion can also be examined using an SD modelling approach, yet further research should be undertaken introducing potential solutions in the proposed SD model and measuring their effect on the container flows.

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Appendices

Appendix A

The python code used to for Scenario 1, which is the base case scenario, is given below:

```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt

days = 120
container_supply = 30000 #TEUS

limit_op_A = 10000 #TEUS
limit_eq_A = 11000 #TEUS
hc_A_max = min(limit_op_A, limit_eq_A)
pwt_A = 1 #Days
p_hint_A_delay = 0.2
delay_factor_A = 0 #Days


limit_eq_B = 15000
limit_op_B = 16000
hc_B_max = min(limit_op_B, limit_eq_B)
pwt_B = 1 #Days
p_hint_B_delay = 0.2
delay_factor_B = 0 #Days

berthing_time = 0.2 #Days
unloading_time = 0.2 #Days
loading_time = 0.2 #Days
unberthing_time = 0.2 #Days
scheduling_dev = 0 #Days

AB_distance = 22000 #km
BA_distance = 11000 #km

def voyage_time_AB (ci_hint_A, scheduling_dev):
  delay_A =(p_hint_A_delay * (ci_hint_A / container_supply)) * delay_factor_A
  pp_time_A = berthing_time + unloading_time + loading_time + unberthing_time + delay_A
  pp_time_B = berthing_time + unloading_time + loading_time + unberthing_time
  tt_AB = min(AB_distance, speed_A / AB_distance)
  voyage_time_AB = pwt_A + pp_time_A + tt_AB + pwt_B + pp_time_B + scheduling_dev
  return voyage_time_AB

def voyage_time_BA (ci_hint_B, scheduling_dev):
  delay_B =(p_hint_B_delay * (ci_hint_B / container_supply)) * delay_factor_B
  pp_time_A = berthing_time + unloading_time + loading_time + unberthing_time
  pp_time_B = berthing_time + unloading_time + loading_time + unberthing_time + delay_B
  tt_BA = min(BA_distance, speed_B / BA_distance)
  voyage_time_BA = pwt_A + pp_time_A + tt_BA + pwt_B + pp_time_B + scheduling_dev
  return voyage_time_BA

ci_A_0 = 15000
ci_B_0 = 15000
ci_hint_A_0 = 0
ci_hint_B_0 = 0
speed_A = 30 #knots
speed_B = 30 #knots
cd_A_0 = 20000
cd_B_0 = 10000
cf_AB = min(cd_B_0, hc_A_max,ci_A_0, 1 / voyage_time_AB(ci_hint_A_0, AB_distance,
scheduling_dev))
cf_BA = min(cd_A_0, hc_B_max,ci_B_0, 1 / voyage_time_BA(ci_hint_B_0, BA_distance,
scheduling_dev))
trade_volume_AB = min(cd_B_0, cf_AB)  #At the starting point of the liner service
trade_volume_BA = min(cd_A_0, cf_BA) #At the starting point of the liner service
t = np.linspace(0, days, days + 1)

cf_AB_time_series = []
cf_BA_time_series = []

past_trade_volume_AB = trade_volume_AB
past_trade_volume_BA = trade_volume_BA
past_delay_factor_A = delay_factor_A
past_delay_factor_B = delay_factor_B
past_scheduling_dev = scheduling_dev
```

```
for i in range(1, len(t)):
   cd_A = trade_volume_BA / BA_distance
   cd_B = trade_volume_AB / AB_distance
   cf_AB = min(cd_B_0, hc_A_max,ci_A_0, 1 / voyage_time_AB(ci_hint_A_0, AB_distance,
scheduling_dev))
   cf_BA = min(cd_A_0, hc_B_max,ci_B_0, 1 / voyage_time_BA(ci_hint_B_0, BA_distance,
scheduling_dev))

   ci_hint_A = (0.5 + 0.3 + 0.2) * (-cd_B + cf_BA)
   ci_A_change = cf_BA - cf_AB + ci_hint_A
   ci_hint_B = (0.5 + 0.3 + 0.2) * (-cd_A + cf_AB)
   ci_B_change = cf_AB - cf_BA + ci_hint_B
   ci_A_0 = ci_A_0 + ci_A_change
   ci_B_0 = ci_B_0 + ci_B_change
   ci_hint_A_0 = ci_hint_A_0 + ci_hint_A
   ci_hint_B_0 = ci_hint_B_0 + ci_hint_B

   trade_volume_AB = past_trade_volume_AB
   trade_volume_BA = past_trade_volume_BA

   delay_factor_A = past_delay_factor_A * (1 + ci_hint_A)
   delay_factor_B = past_delay_factor_B * (1 + ci_hint_B)
   past_delay_factor_A = delay_factor_A
   past_delay_factor_B = delay_factor_B
   scheduling_dev = past_scheduling_dev / (1 - (0.2 * (cf_AB + cf_BA)))
   past_scheduling_dev = scheduling_dev

plt.figure(figsize=(12, 8))
ax = plt.subplot(111)
ax.plot(t[1:], cf_AB_time_series, linewidth = 6, label='Container Flow AB')
ax.plot(t[1:], cf_BA_time_series, color ='black', linewidth = 2, alpha= 1, label='Container Flow BA')
plt.xlabel('Days')
plt.ylabel('Number of Containers * 10,000')
plt.legend()
plt.grid(True)
plt.title('Container Flow Through Time')
plt.ylim([0, 0.3])
plt.show()
```

Appendix B

The code that was used to generate Scenario 5 is given below:

```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt

days = 120
container_supply = 30000 #TEUS

limit_op_A = 30000 #TEUS
limit_eq_A = 25000 #TEUS
hc_A_max = min(limit_op_A, limit_eq_A)

pwt_A = 1 #Days
p_hint_A_delay = 0.2
delay_factor_A = 1 #Days

limit_eq_B = 5000
limit_op_B = 5000
hc_B_max = min(limit_op_B, limit_eq_B)
pwt_B = 1 #Days
p_hint_B_delay = 0.2
delay_factor_B = 1 #Days

berthing_time = 0.2 #Days
unloading_time = 0.2 #Days
loading_time = 0.2 #Days
unberthing_time = 0.2 #Days
scheduling_dev = 1 #Days

AB_distance = 33000 #km
BA_distance = 11000 #km

def voyage_time_AB (ci_hint_A, AB_distance, scheduling_dev):
  delay_A =(p_hint_A_delay * (ci_hint_A / container_supply)) * delay_factor_A
  pp_time_A = berthing_time + unloading_time + loading_time + unberthing_time + delay_A
  pp_time_B = berthing_time + unloading_time + loading_time + unberthing_time
  tt_AB = speed_A / AB_distance
  voyage_time_AB = pwt_A + pp_time_A + tt_AB + pwt_B + pp_time_B + scheduling_dev
  return voyage_time_AB

def voyage_time_BA (ci_hint_B, BA_distance, scheduling_dev):
  delay_B =(p_hint_B_delay * (ci_hint_B / container_supply)) * delay_factor_B
  pp_time_A = berthing_time + unloading_time + loading_time + unberthing_time
  pp_time_B = berthing_time + unloading_time + loading_time + unberthing_time + delay_B
  tt_BA = speed_B / BA_distance
  voyage_time_BA = pwt_A + pp_time_A + tt_BA + pwt_B + pp_time_B + scheduling_dev
  return voyage_time_BA


ci_A_0 = 15000
ci_B_0 = 15000
ci_hint_A_0 = 0
ci_hint_B_0 = 0
speed_A = 30 #knots
speed_B = 30 #knots
cd_A_0 = 20000
cd_B_0 = 10000
AB_distance = 33000 #km
BA_distance = 11000 #km
cf_AB = min(cd_B_0, hc_A_max,ci_A_0, 1 / voyage_time_AB(ci_hint_A_0, AB_distance, scheduling_dev))
cf_BA = min(cd_A_0, hc_B_max,ci_B_0, 1 / voyage_time_BA(ci_hint_B_0, BA_distance, scheduling_dev))
trade_volume_AB = min(cd_B_0, cf_AB)  #At the starting point of the liner service
trade_volume_BA = min(cd_A_0, cf_BA) #At the starting point of the liner service
t = np.linspace(0, days, days + 1)

cf_AB_time_series = []
cf_BA_time_series = []

past_trade_volume_AB = trade_volume_AB
past_trade_volume_BA = trade_volume_BA
past_delay_factor_A = delay_factor_A
past_delay_factor_B = delay_factor_B
past_scheduling_dev = scheduling_dev
```

```
for i in range(1, len(t)):
  cd_A = trade_volume_BA / BA_distance
  cd_B = trade_volume_AB / AB_distance
  cf_AB = min(cd_B_0, hc_A_max,ci_A_0, 1 / voyage_time_AB(ci_hint_A_0, AB_distance, scheduling_dev))
  cf_BA = min(cd_A_0, hc_B_max,ci_B_0, 1 / voyage_time_BA(ci_hint_B_0, BA_distance, scheduling_dev))

  ci_hint_A = (0.5 + 0.3 + 0.2) * (-cd_B + cf_BA)
  ci_A_change = cf_BA - cf_AB + ci_hint_A
  ci_hint_B = (0.5 + 0.3 + 0.2) * (-cd_A + cf_AB)
  ci_B_change = cf_AB - cf_BA + ci_hint_B
  ci_A_0 = ci_A_0 + ci_A_change
  ci_B_0 = ci_B_0 + ci_B_change
  ci_hint_A_0 = ci_hint_A_0 + ci_hint_A
  ci_hint_B_0 = ci_hint_B_0 + ci_hint_B

  trade_volume_AB = past_trade_volume_AB
  trade_volume_BA = past_trade_volume_BA

  delay_factor_A = past_delay_factor_A * (1 + ci_hint_A)
  delay_factor_B = past_delay_factor_B * (1 + ci_hint_B)
  past_delay_factor_A = delay_factor_A
  past_delay_factor_B = delay_factor_B
  scheduling_dev = past_scheduling_dev / (1 - (0.2 * (cf_AB + cf_BA)))
  past_scheduling_dev = scheduling_dev

  cf_AB_time_series.append(cf_AB)
  cf_BA_time_series.append(cf_BA)


plt.figure(figsize=(12, 8))
ax = plt.subplot(111)
ax.plot(t[1:], cf_AB_time_series, linewidth = 6, label='Container Flow AB')
ax.plot(t[1:], cf_BA_time_series, color ='black', linewidth = 2, alpha= 1, label='Container Flow BA')
plt.xlabel('Days')
plt.ylabel('Number of Containers * 10,000')
plt.legend()
plt.grid(True)
plt.title('Container Flow Through Time')
plt.ylim([0, 0.3])
plt.show()
```