Addressing Challenges in Creating Traffic Profiles for Transshipment Hubs in Seaports

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Abstract. Globalization has significantly increased containerized traffic, driven by the rising demand for swift cargo movements at low cost. When creating cost- and time-efficient maritime transport networks, transshipment hubs are of high importance. There, containers are moved from one vessel to another. This enables carriers to design hub-and-spoke networks (where feeder vessels serve the spokes and deep sea vessels interconnect the hubs) as well as connecting deep sea services by interlining. Hubs are often located along major shipping routes and are concentrated near canals and straits. The successful operation of transshipment hubs relies on various socio-economic factors, trade policies, and robust infrastructure. When making strategic decisions, simulation is often used to estimate the impact of each viable option on terminal performance. Such simulation studies heavily depend on suitable synthetic traffic profiles that reflect the workload and yard occupancy of transshipment hubs over a longer time horizon. Past work has shown that for transshipment hubs, the expected average yard occupancy is approximated over the course of several weeks, which increases the runtime of simulation studies. The approach presented in this paper addresses this issue by modifying the code of library ConFlowGen and applying it on three use cases. The results show that the traffic profiles generated with the modified code are more suitable for simulating operations of transshipment hubs. Several traffic profile characteristics are discussed, that are difficult to satisfy at the same time.

Keywords: Container Terminal · Port Planning · Synthetic Data Generation · Maritime Transport · ConFlowGen.

1 Introduction

Globalization has created the need for faster cargo movements while ensuring economic viability for liner services, thus making transshipment operations an essential activity to maintain robust global supply chains (Kavirathna et al., 2018). In this regard, transshipment hubs improve the efficiency of global container logistics by facilitating the exchange and redistribution of goods between different maritime routes. Transshipment accounts for one-third of global port container throughput (Drewry Shipping Consultants, 2012). The significant growth and advancements in container trade has increased the need for transshipment, that typically involves a container flow between the port of loading, one (or several) intermediate port(s), and the port of destination (Rodrigue and Ashar, 2016). Transshipment hubs are also essential for major liner shipping networks to be able to design shipping networks that are optimized in terms of efficient ship utilization, shortened transit times, and increased port coverage. Therefore, there has been a steady growth in the number of pure transshipment hubs since 1990s (Rodrigue and Ashar, 2016). However, the strategic planning of a transshipment hub necessitates an in-depth evaluation of geographic location, infrastructural requisites, and operational complexities to optimize logistics and transportation efficiency. Transshipment hubs require deep-water berths, spacious container yards, and robust container handling equipment to manage high container traffic volumes (Reda et al., 2016). Additionally, socio-economic factors such as regulatory frameworks, government policies on transshipment, manpower shortage etc. also affect the operating efficiency of transshipment hubs (The Logistics Institute - Asia Pacific, 2010). Due to aforementioned factors, transshipment hubs generally require high initial capital investments due to complex infrastructural requirements. Furthermore, such terminals also require high operating costs due to operational complexity (Notteboom et al., 2023). When planning the construction or extension of such a container terminal several investment decisions need to be made, such as the length of the quay wall, the number of ship-to-shore cranes, the size of the yard in combination with the terminal operating system to procure, etc. (Böse, 2020).

It is good practice to evaluate investment decisions by means of simulation studies and assess the expected terminal productivity (Kastner et al., 2020). Simulation is necessary due to the variability in operations: Whenever a large vessel berths and container handling operations commence, there is a peak in workload that needs to be taken into consideration when planning upcoming shifts (Schütt, 2020; Kastner et al., 2024). Moreover, differences in terminal operations between months can be considerable (Vieira et al., 2024), and in a good simulation study, this needs be reflected. In port consulting, e.g., it is therefore good practice to explore the expected yard occupancy by means of various traffic profiles derived from the assumed fleet mix(es) (Schütt, 2020). Édes et al. (2024) show how this can be achieved using the open-source library *ConFlowGen*. It is described as “a generator for synthetic container flows at maritime container terminals with a focus on yard operations” (ConFlowGen developers, 2024). A traffic profile constitutes of virtual containers that pass through a terminal during a given time horizon; every container is associated with a terminal-in and terminal-out event (Kastner et al., 2022; Kastner and Grasse, 2023; Édes et al., 2024). At the terminal-in event, the inbound vehicle has reached the terminal, the container is unloaded, and then stored in the yard; at terminal-out event, the container is retrieved from the yard and loaded onto the vehicle before its departure. Édes et al. (2024) show that the expected yard occupancy based on formulae are aligned well with the yard occupancy derived from synthetic container flows. This works quite well for gateway terminals with a lot of truck traffic but for transshipment hubs, an issue is spotted. While gateway ports with trucks reach their expected yard occupancy quickly, transshipment hubs build up their yard inventory over a much longer time period, making it difficult to create representative traffic profiles with a realistic yard occupancy within short time horizon. To improve the utility of ConFlowGen to create traffic profiles for transshipment hubs, further development is needed. A concept of implementation is shown in the present paper and for three exemplary terminals, the difference between the previous and updated version are shown.

2 Method

In the scope of this study, first the code of *ConFlowGen* is revised and adapted (see Section 2.1). The effect of the modification is then illustrated by creating several traffic profiles with and without the changes for three exemplary terminals (see Section 2.2).

2.1 Revision of the ConFlowGen algorithm

The changes required to reach the desired yard occupancy faster are indicated in Figure 1. These are implemented in the scope of this publication. The process in dark gray is adapted from the ConFlowGen developers (2024). In the present publication, one crucial simplification is made: Only deep sea vessels, feeders, and trucks are considered. Whenever the ConFlowGen documentation mentions large vehicles in the technical description, this jointly refers to deep sea vessels, feeders, trains, and barges. Thus, this does not distinguish between seaside and landside traffic on an algorithmic level. In this publication, however, only trucks are used for import and export flows. This enables the authors to be more precise in naming the process steps. In the left column in light gray, the influencing factors are mentioned. Increasing the speed in which the yard is filled will affect these as Section 3 will show. The down-pointing arrow indicates a terminal-in event and the up-pointing arrow indicates a terminal-out event, which jointly define the container dwell time. In the right column in light gray, each of the algorithmic steps is commented. Moreover, the two revised steps are highlighted. The stars in dark gray indicate an actual change, whereas the light gray star indicates that this is not be modified.

The number of inbound containers belonging to import and transshipment flows is decreased during the ramp-down period of 7 days by 90 %, achieved by placing only 10 % of the containers on each vessel that calls the terminal in this phase. The number of outbound transshipment containers during the ramp-up period of 7 days is reduced by artificially decreasing the transport capacity of each vessel during this phase by 90 %. The container dwell times used as input in ConFlowGen (cf. also Figure 1) are displayed in Table 2. Only standard and empty containers are taken into consideration. The dwell times of empty containers are all longer than 10 days while the laden containers remain on the terminal for always less than 10 days. Especially trucks are fast to pick up containers with approx. 3 days dwell time, whereas transshipment containers occupy valuable space in the yard for 8 to 9 days on average.

2.2 Creation of the traffic profiles

Before initiating data generation with ConFlowGen, the input data are retrieved using a systematic methodology. This involves the selection of three ports and one exemplary container terminal each, chosen based on its transshipment incidence and geographical location. The selection criteria ensure that each port has a transshipment incidence greater than 50 % and that they are geographically distributed to cover key maritime nodes. The three selected container terminals are:

- The Salalah Container Terminal in Oman is a key transshipment hub on the major East-West shipping lane. Its strategic location enhances connectivity between the Middle East, the Indian Subcontinent, and East Africa. The terminal has an annual capacity of 5 million Twenty-foot Equivalent Units (TEUs) (Salalah Terminal, 2023) and a high transshipment incidence of 87 % (Salalah Port, 2024).
- APM Terminals Valencia in the Port of Valencia, a transshipment hub on Spain's Western Mediterranean coast, serves the Western Mediterranean and the West Coast of Africa. It has an annual capacity of 1.34 million TEUs (APM Terminal Valencia, 2024) and a transshipment incidence of approximately 62 % (Valencia port, 2023).
- Colombo International Container Terminal (ICT) in the Port of Colombo in Sri Lanka is a key transshipment hub in South Asia. It has an annual capacity of 2.4 million TEUs (SLPA, 2022b) and a transshipment incidence of approximately 79.2 % (SLPA, 2022a).

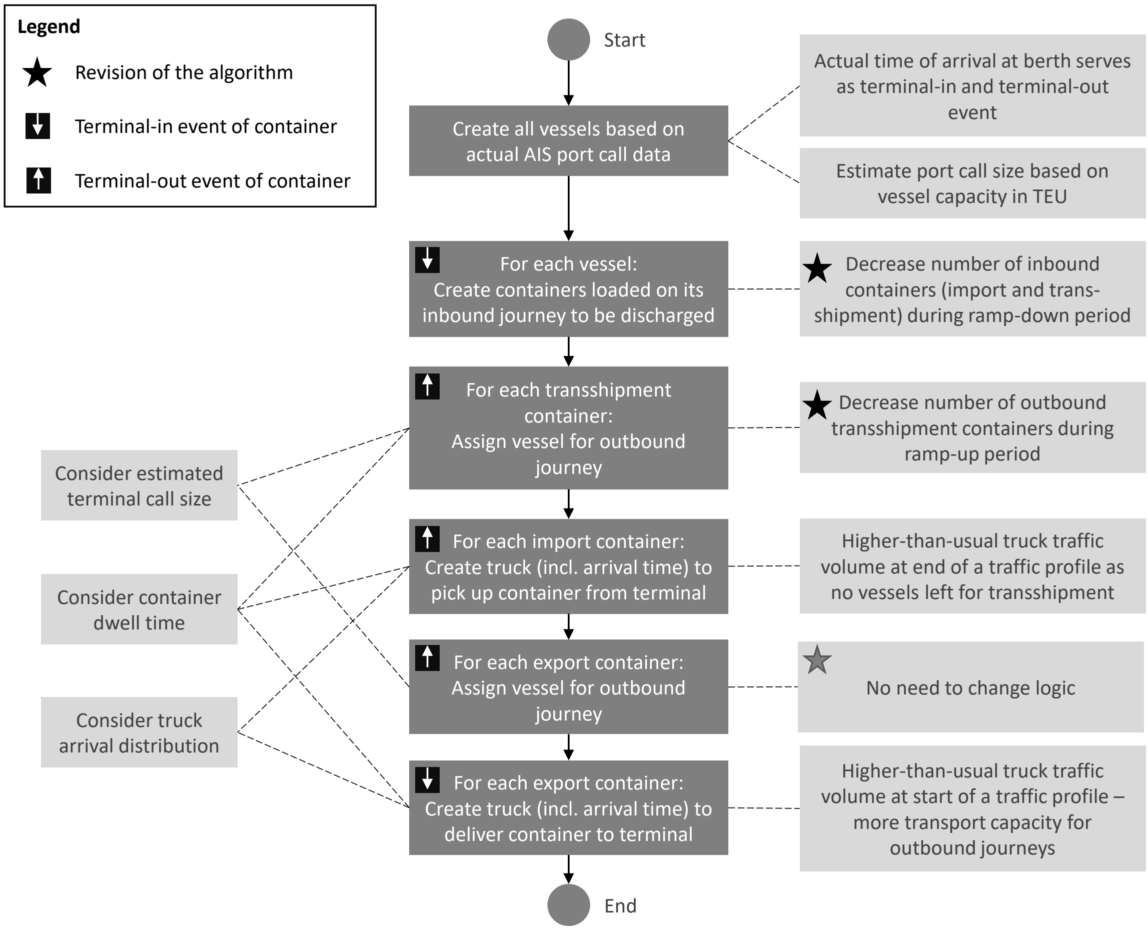


Fig. 1: Revision of the ConFlowGen algorithm

In a first step, sailing lists for all aforementioned container terminals are obtained from MarineTraffic, covering the period from 17th April 2024 till 15th May 2024. Then, all vessels below the capacity of 3000 TEU are classified as feeder vessels and the rest as deep sea vessels (cf. PIANC, 2014; UNCTAD, 2022).

Figure 2 presents the fleet mix histograms for vessels arriving at the selected three container terminals, illustrating the distribution of vessel capacities and the type of maritime traffic at each port. The histogram for the Salalah terminal indicates a higher concentration of vessels with TEU capacities up to 8500. The frequency of vessels decreases with increasing TEU capacity, dropping to zero above 13500 TEU. The histogram for APM Terminals Valencia shows a more diverse distribution of vessel capacities. While there is a higher concentration of vessels with capacities up to 8500 TEU, some vessels exceed this capacity, indicating the terminal's ability to accommodate a variety of vessel sizes. The histogram for Colombo ICT shows a significant number of vessels with capacities above 8500 TEU, the highest among the three terminals studied. Vessels with capacities below 5000 TEU are underrepresented, suggesting that Colombo ICT primarily handles large-scale shipping operations compared to the other two terminals.

Figure 3 illustrates the distribution of terminal call sizes for both feeder vessels and deep sea vessels for all three container terminals. Colombo ICT consistently receives the highest number of terminal calls, compared to the other two terminals. APM Terminals Valencia shows a moderate number of terminal calls, while Salalah experiences the lowest number of terminal calls. A common observation among all three terminals is that the number of deep sea vessels calling at the terminals is significantly lower on weekends than on weekdays.

Figure 4 depicts the inbound to outbound traffic flows for all three terminals. The diagrams are created using the berthing data retrieved from MarineTraffic and the estimated transshipment incidence percentages that help estimate the number of outbound TEUs transitioning between different modes of tranpsort. For simplicity, it is assumed that the inbound and outbound traffic volumes for each mode of transport are approximately equal.

The traffic profiles are generated using the approach described below:

1. For each sailing list retrieved from MarineTraffic, the terminal call sizes are randomly chosen based on the percentages mentioned in Table 1, resulting in 30 terminal call scenarios per terminal, i.e., 90 in total.
2. Transshipment incidences for all three ports are derived from the aforementioned annual reports.
3. For each terminal and scenario, ConFlowGen is run once with and once without the ramp-up and ramp-down modification illustrated in Figure 1, resulting in 180 traffic profiles total.

3 Results and Discussion

In the first part of the analysis, the number of loaded and discharged containers for each vessel calling the terminals is examined in Figure 5. At all three terminals, the first terminal call takes place on 17th April and the last on 15th May. Figure 5a, Figure 5b, and Figure 5c each depict all 30 synthetically generated traffic profiles, first with a ramp-up and ramp-down period and then without, as indicated by the respective title. Whenever a ramp-up and ramp-down period is used, this uses the modification of ConFlowGen as proposed in this paper; the version without any ramp-up and ramp-down corresponds to the previously known behavior of ConFlowGen as reported by (Édes et al., 2024). For every vessel that actually called the terminal according to the MarineTraffic

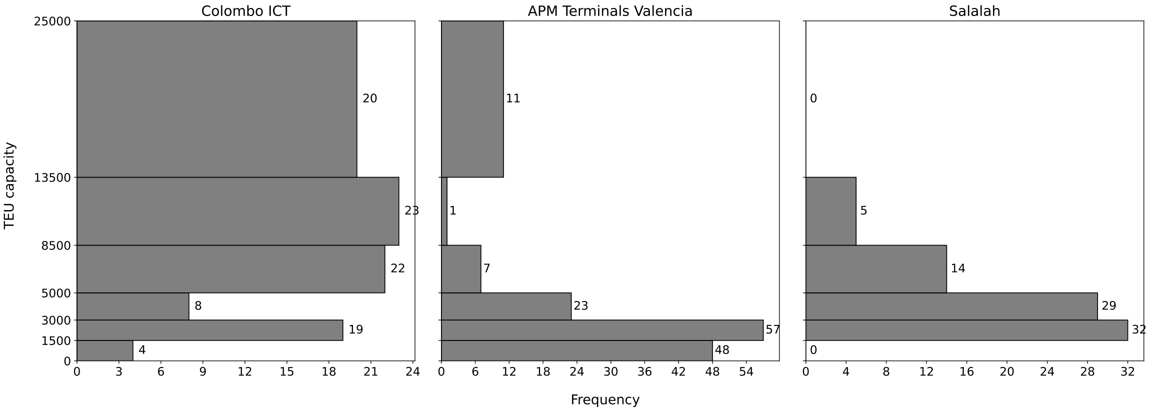


Fig. 2: Fleet mix histograms

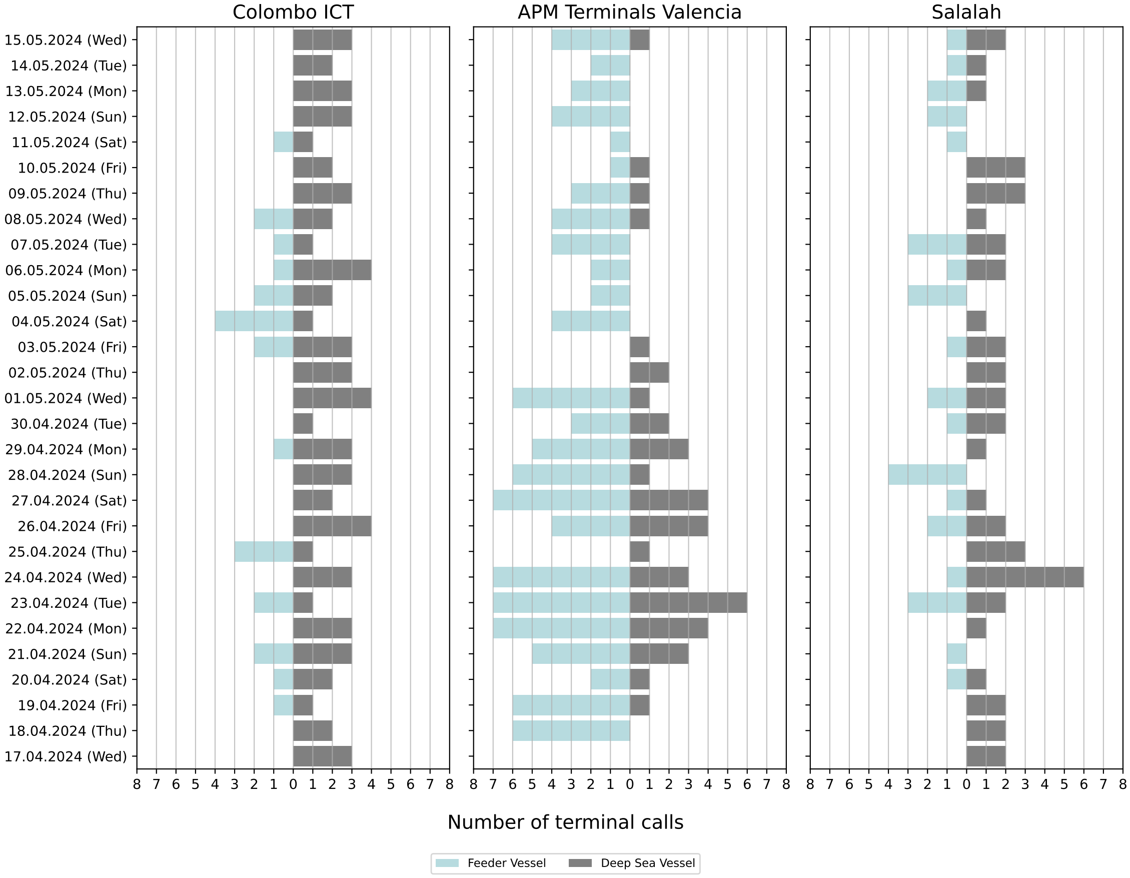
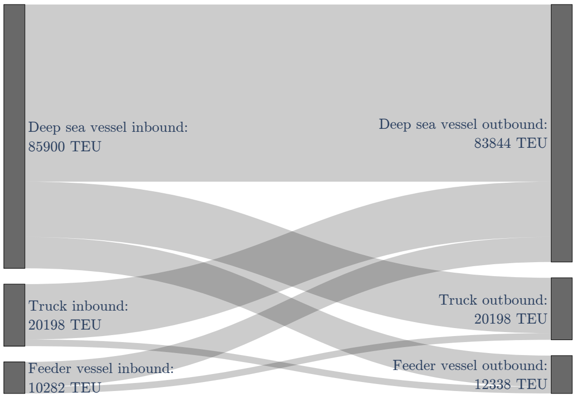
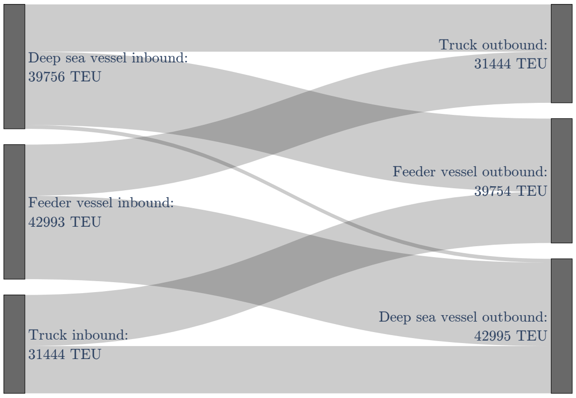


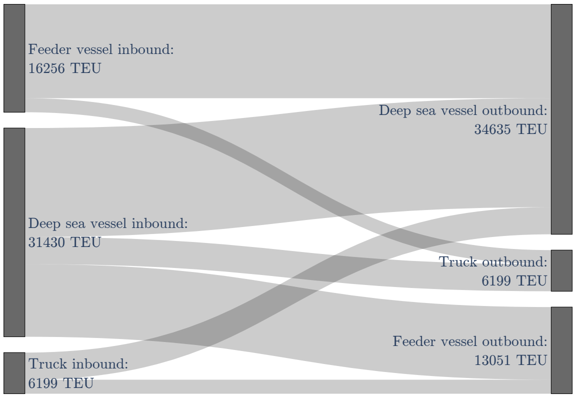
Fig. 3: Vessel arrivals-Bi-directional bar plot



(a) Colombo ICT



(b) APM Terminals Valencia



(c) Salalah

Fig. 4: TEU flows from inbound vehicle types to outbound vehicle types

Table 1: Terminal call sizes as reported by International Bank for Reconstruction and Development / International Development Association or The World Bank (2023)

Ship size (TEU)	Terminal call size									
	<250	251–500	501–1000	1001–1500	1501–2000	2001–2500	2501–3000	3001–4000	4001–6000	>6000
<1,500	23.0%	36.2%	33.9%	6.0%	0.5%	0.2%	0.1%	0.1%	0.0%	0.0%
1,501-5,000	6.3%	20.1%	35.4%	20.2%	10.1%	4.5%	1.8%	1.4%	0.2%	0.0%
5,001-8,500	1.3%	5.5%	22.0%	23.7%	18.0%	11.9%	7.4%	6.9%	2.7%	0.6%
8,501-13,500	0.6%	3.7%	13.4%	16.0%	14.7%	13.7%	11.1%	14.7%	9.2%	3.1%
>13,500	0.2%	0.4%	3.0%	5.7%	8.3%	9.9%	9.8%	20.0%	28.3%	14.4%

Table 2: Assumed average container dwell times in days based on the default values of ConFlowGen (ConFlowGen developers, 2024)

	To					
	Laden Container			Empty Container		
From	deep sea vessel	feeder	truck	deep sea vessel	feeder	truck
deep sea vessel	9.3	4.3	3.0	27.7	14.0	12.2
feeder	8.3	3.8	3.1	14.6	10.6	13.6
truck	6.5	3.6	7.1	13.4	13.0	18.8

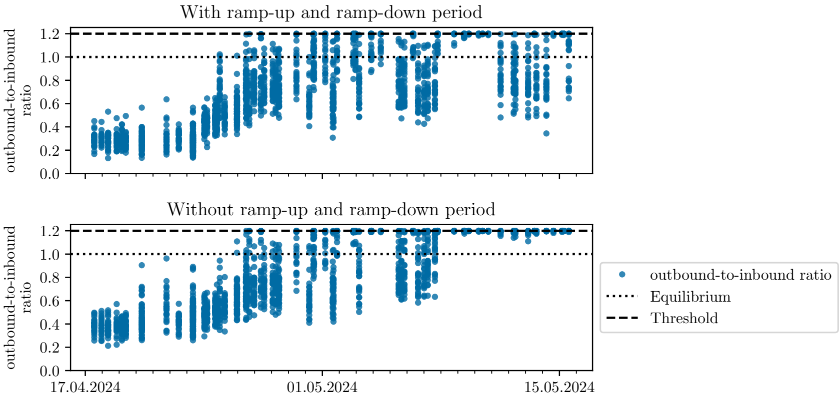
berthing data as reported in Figure 3, therefore 30 values are denoted in the respective diagram – one for each synthetically generated traffic profile. For better comprehensibility, the terminal calls of different sizes (typically measured in TEU) are normalized by computing the ratio of discharged containers on the inbound journey of a vessel and the loaded containers on the outbound journey. The terms inbound and outbound are used relative to the terminal. An outbound-to-inbound ratio of 1 means that the amount of discharged containers is identical with the number of loaded containers; this is referred to as equilibrium. A ratio of 1.2 means that 20 % more containers are loaded onto the vessel than discharged from the vessel. ConFlowGen contains a hard capacity constraint and does not allow more than that to be loaded onto a vessel (Kastner et al., 2022).

For all three terminals, the ramp-up and ramp-down period have created a positive impact. In Figure 5a, on 25th May, a ratio greater than 1 is reached for the first time. This is exactly after the ramp-up period of 7 days has ended. As discussed in the previous section, the proposed modifications reduces the number of transshipment containers loaded onto vessels during the ramp-up period; and a reduction of outbound containers is observed here. Similarly, the ramp-down period of 7 days is clearly visible. Without the ramp-down phase, during the last week all vessels are loaded at their maximum capacity as defined by ConFlowGen following (Hartmann, 2004). If there are no vehicles of one type left, ConFlowGen is forced to switch the mode of transport on the outbound journey of the remaining containers: These are then re-assigned to another mode of transport with remaining capacity or trucks (ConFlowGen developers, 2024). In consequence, a transshipment container might be changed to an import container if no vessel is left that can carry the container. This situation can be repeatedly seen when no ramp-down period is given. When, however, a ramp-down period of 7 days is used, in some cases the ratio even drops below 0.5. This leads to enough free space on the vessels so that transshipment containers can be loaded onto vessels even at the last days of a traffic profile. In Figure 5b, the ratio is much higher around 1st May. This is explained by the large number of terminal calls before that day (cf. Figure 3). The vessels are discharged at the terminal, and those containers are then stacked in the yard, awaiting transshipment. Thus, after a spike in terminal calls, the number of containers loaded onto vessels is larger than the number of discharged containers. In Figure 5c, the modifications in the code show the least effect: Both with and without a ramp-up and ramp-down period, the equilibrium is approximated very slowly. This is explained by the long container dwell time in interlining of close to 28 days (cf. Table 2). Here, lower assumed container dwell times will alleviate the situation. A positive effect, however, is still visible. When a ramp-up and ramp-down period are used, this leads to a lower ratio during the ramp-up period and the free space in the vessels at the end.

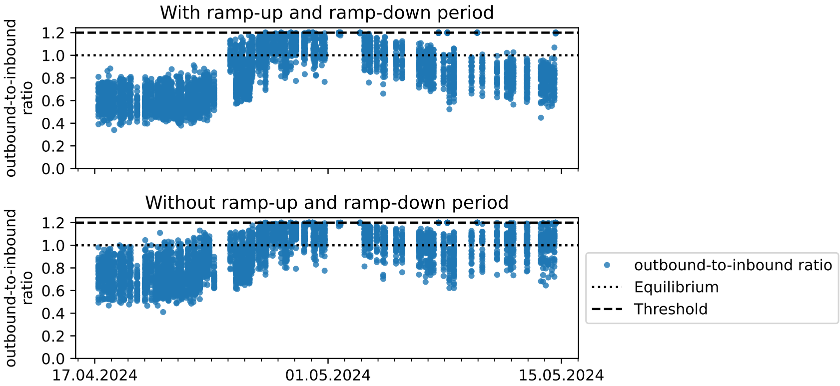
In the second part of the analysis, the shift over time of transshipment, import, and export container volumes is examined. This provides a better understanding of the characteristics of the generated container flows beyond the utilized vessel capacity. The results are depicted in Figure 6, Figure 7, and Figure 8. Each figure consists of six subfigures: In the left column, the 30 traffic scenarios that used a ramp-up and ramp-down period are shown. In the right column, 30 traffic scenarios without a ramp-up and ramp-down period are displayed for reference. In each column, first the number of terminal-in events is shown, then the number of terminal-out events, and then the yard occupancy measured in TEU. The number of terminal-in and terminal-out events are summarized over 84 hours, which corresponds to 3 ½ days, and then up-scaled to one week by multiplying it by 2. This temporal resolution provides a good level of detail over time and highlights the dynamics in place, especially as terminal calls are represented as discrete events. During the ramp-up phase, in all three cases the number of terminal-out events for transshipment containers is decreased, and during the ramp-down phase, the number of terminal-in events for all three kinds is decreased. Both are a direct effect of the intended modification of the code. In addition, the number of import and export containers are less. This is explained by the reassignment logic used when there is a lack of stowage space on vessels: When transshipment containers cannot be loaded because all vessels are full, then the container will be picked up by a truck instead. This in turn leads to more exports containers, too, since ConFlowGen keeps the number of truck arrivals for import and export containers in balance. Given a ramp-down period with throttled inbound traffic, this situation is avoided. This leads to a much better approximation of the desired transshipment incidence: For Salalah, it increases from an average of 81 % (min. 79 %, max. 83 %) to an average of 85 % (min. 83 %, max. 87 %), given an input transshipment incidence of 87 %; for APM Terminals Valencia, it shifts from an average of 54 % (min. 50 %, max 57 %) to an average of 58 % (min. 54 %, max. 60 %), given an input transshipment incidence of 62 %; and for Colombo ICT, it shifts from an average of 74 % (min. 73 %, max. 75 %) to an average of 79 % (min. 78 %, max. 79 %), given an input transshipment incidence of 79 %. It remains to be examined whether longer ramp-down period could help to better approximate the input transshipment incidence in the traffic profile.

Especially in Figure 6, the yard occupancy reaches a stable plateau when ramp-up and ramp-down phases are used. A much faster filling of the yard is visible in Figure 7 and Figure 8. Even though the transported container volumes are reduced, overall a similar yard occupancy is reached. This can be explained by the larger overall transshipment incident in the synthetically generated traffic profiles in combination with the longer container dwell times of transshipment containers. In other terms, the data produced by ConFlowGen when ramp-up and ramp-down periods are used is usually more suitable for further usage, i.e., in the scope of simulation studies.

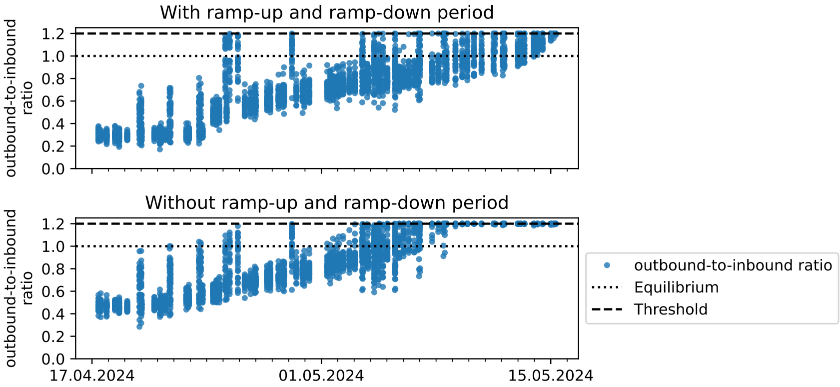
The results of the analyses actually highlight an issue that goes far beyond the usage of ConFlowGen: Generating traffic profiles for simulation studies for transshipment hubs is inherently



(a) Outbound-to-inbound ratio for Salalah traffic profiles



(b) Outbound-to-inbound ratio for APM Terminals Valencia traffic profiles



(c) Outbound-to-inbound ratio for Colombo ICT traffic profiles

Fig. 5: Ratio of loaded and discharged containers for each vessel over all traffic profiles

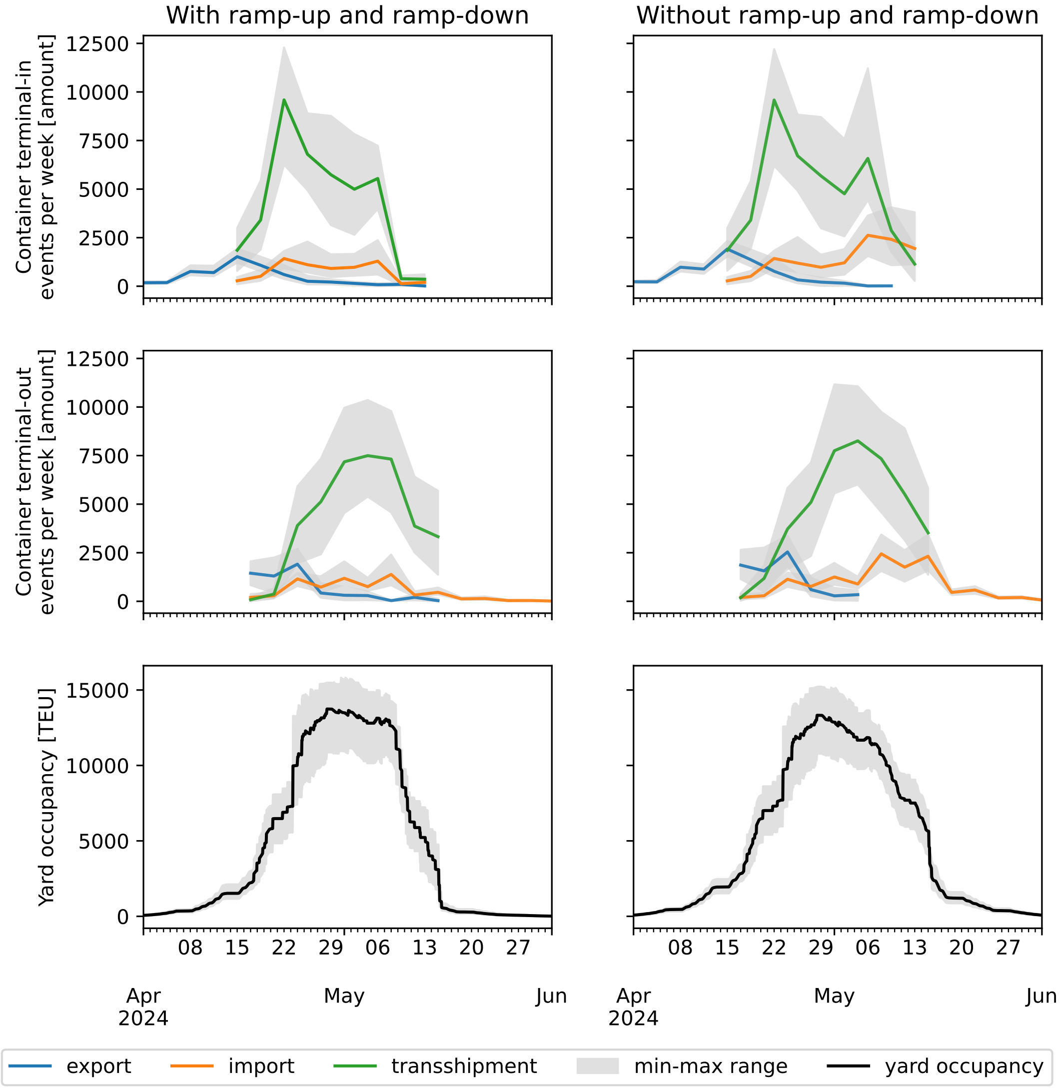


Fig. 6: Transshipment, import, and export volumes over time for Salalah traffic profiles

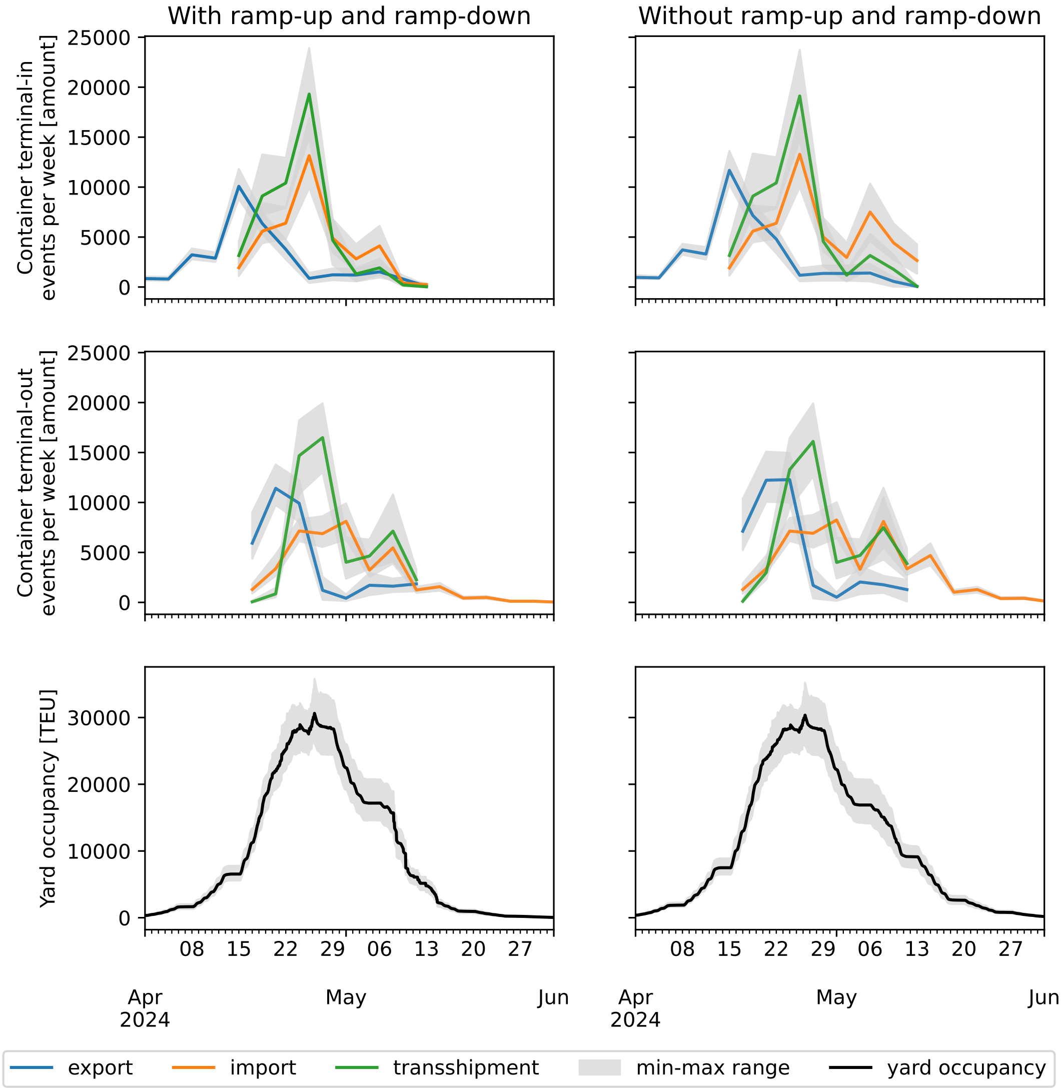


Fig. 7: Transshipment, import, and export volumes over time for APM Terminals Valencia traffic profiles

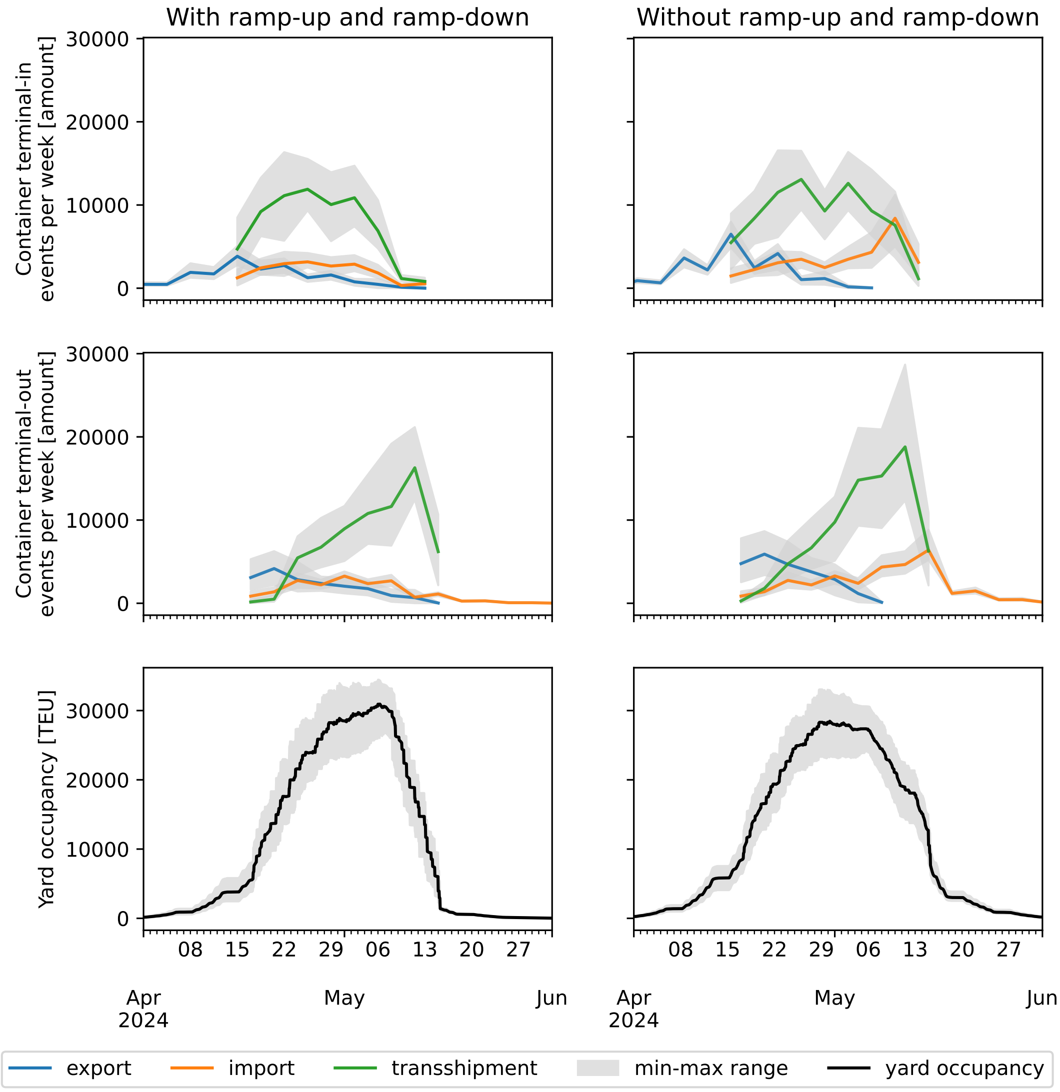


Fig. 8: Transshipment, import, and export volumes over time for Colombo ICT traffic profiles

challenging. When the yard is examined in the scope of a simulation study, the traffic profiles should show several characteristics:

1. The generated terminal call size needs to consider the overall capacity of a vessel. The vessel capacity shall not be exceeded, neither on its inbound nor its outbound journey. This is a precondition to keep the number of handling operations related to a vessel in a realistic range.
2. The generated terminal call size should approximately constitute of the same number of discharge and loading moves, at least as long as no additional assumptions can be made (cf. Édes et al., 2024). As long as the number of loaded containers is lower or approximately equal to the number of discharged containers, it is more likely that realistic stowage plans can be designed for the outbound journey. Thus, those traffic profiles can be combined with post-processing steps (e.g., to create stowage plans) with less additional efforts.
3. Each container shall be assigned to an inbound and an outbound vehicle in a way that the expected average container dwell times are approximated well. The container dwell time is the time difference between the terminal-in and terminal-out event. This traffic profile characteristic is required to have a realistic yard occupancy. When containers are stacked, a higher overall yard occupancy leads to a higher average stacking height. When a specific container needs to be retrieved, these higher stacks increase the risk of reshuffling movements, which lowers the average productivity of the yard (Tang et al., 2015). Thus, traffic profiles which approximate the average container dwell time well are more suitable for simulation studies that focus on the yard of CTs.
4. When a container is assigned a slot in the yard, both the terminal-in and terminal-out event are important. The operational situation at the time of slot allocation at terminal-in is considered for workload balancing between yard cranes when online heuristics are in place; when implementing loading-optimization, the containers also should be placed in proximity of the truck gate or planned berth of the vessel the container is booked for, which requires the information related to the terminal-out event (see, e.g., Voß et al., 2016). When every container is associated with a terminal-in and a terminal-out event, then traffic profiles start and end with an empty yard, and pre-filling the yard with containers that by definition lack this information is not an option.

When a traffic profile seeks to satisfy all the previously named characteristics, the yard of a transshipment hub can only be filled over a long time range, as shown by Édes et al. (2024). When in the scope of a simulation study a faster filling of the yard is required, some of the listed characteristics need to be relaxed during the ramp-up period of traffic profile. In the present publication, longer container dwell times are accepted in the first seven days of the traffic profile, and less inbound containers during the last seven days. The effect of differently-sized ramp-up and ramp-down periods in terms of days as well as different scaling factors (in this study, a reduction by 90 % was chosen) need to be explored in future work. Moreover, alternative approaches to create synthetic transshipment traffic might enrich the scientific discussion.

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