

HOW TO EFFICIENTLY STORE SEMI-TRAILERS IN INLAND PORTS?

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Introduction and Problem Description

Road transportation is, especially for short-haul distances, an unavoidable and important transport mode for spatial development with high volume capabilities. Around 46 % of the EUs total land freight transport in 2020 was moved by road over less than 300 km (Eurostat 2022). Around 97 % of all trucks run on diesel or petrol, only 0.1 % being electric (Truschkin et al. 2024). Road transportation is in the process of being shifted towards a stronger use of rail and waterway transportation. The European Commission (2011) set a primary goal of shifting 30 % of road freight in the EU travelling more than 300 km to other modes such as rail or waterway by 2030 and more than 50 % by 2050. This measures and development resulted in a continuous intermodal transport growth of around 51 % (in tonne-km) between 2011 and 2021 (UIC 2022). 72 % of the German road transport activity in 2022 was handled by semi-trailers (Truschkin et al. 2024). With an average annual growth rate of 12 % in transportation of unaccompanied semi-trailers between 2005 and 2023 (UIC 2022) they are the most important ILU type for European continental transport. The number of semi-trailers has nearly even tripled between 2013 and 2022 (Truschkin et al. 2024). The growth of intermodal transport and the increased use of rail and waterway modes will put a lot of stress on the critical intermodal handling facilities within the logistical networks, the inland ports and combined transport hubs. These nodes must now accommodate higher throughput volumes and must more frequently handle and store semi-trailers. However, most existing infrastructure was neither designed for the expected volumes nor for the specific handling needs of unaccompanied semi-trailers. Those facilities usually cannot quickly enlarge spatially by building new parking lots, rail tracks and truck gates or by procuring more handling equipment. They need to rely on flexible, affordable, short-term, operational improvements. Efficient storage and turnover of semi-trailers at inland terminals are becoming key bottlenecks in the intermodal logistics chain.

To date, most research and practical solutions in transport logistics have focused on containerized cargo, particularly in (large) seaports. Large seaports and (usually) smaller inland ports differ significantly in scale, digital maturity and operational structures, with inland ports relying more on manual processes. Additionally, inland ports play a regional role and mostly handle small-scale operations with limited storage, having fewer equipment and expansion capacity compared to seaports. Due to their more dynamic environment and constraints, operations and planning software solutions can often not be tailored as well to their needs, which requires a greater focus on internal organizational measures than in seaports (Rodrigue 2016). Container terminals benefit from standardized unit dimensions and handling equipment, from well-established stacking processes, and from decades of experience and research in optimization of (yard) operations. However, semi-trailers differ significantly in type variation, size, weight distribution, structural characteristics, and in the ability to be handled by crane. They require different, specialized handling equipment and cannot be stacked, making the application of container-based storage solutions in inland ports often inapplicable or inefficient. Their operations are highly susceptible to congestion and delays while inefficient handling reduces the terminal performance and environmental impacts are exacerbated through increased emissions from waiting handling equipment and vehicles. These fundamental differences necessitate a reevaluation of how semi-trailers are stored and managed within inland port environments. There is an increasing need for tailored strategies and technologies that address the specific challenges of semi-trailer storage - challenges that are not adequately addressed by existing port management systems. The following sections explore the state of research and academic literature regarding efficient storing of semi-trailer in inland ports and other logistical handling facilities.

Literature review, methodology and research work

In this review paper we investigate the topic of efficient semi-trailer storage strategies for inland ports and logistical handling facilities. Within the work, we focus on the following scope and delimitations. In this work, the expression 'inland ports' is used as an umbrella term for logistical handling facilities which act as regional or continental, bi- or tri-modal interfaces, which provide spatial logistical development to the inland. Those facilities are typically referred to as inland ports, combined transport hubs, dry ports, or transshipment hubs. We distinguish them from seaports which mainly act as the interface between long-distance maritime transport and inland/hinterland transport modes, since those typically operate in a very different high-throughput, technologically supported, standardized and container focused, environment. The (intermodal) loading unit (ILU or LU) in focus are semi-trailers for road transport (rxo 2025). Moreover, we focus our work on actual operational decision problems in the yard (instead of conceptual, strategical or tactical planning tasks). Furthermore, we distinguish between yard (internal) management problems and superior yard allocation problems, which in literature are often used interchangeably or are not clearly differentiated. Based on the set topic and scope delimitations we investigate the following claims:

- I. There currently is no comprehensive academic literature base which identifies, recommends or classifies storage strategies for efficient semi-trailer storing in ports.
- II. In comparison to container stacking, container yard management and container yard allocation problems, semi-trailer storing decision problems only play a tangential role.
- III. Contributing factor: Compared to containers as the ILU type, semi-trailers are generally underrepresented in academic literature.
- IV. Contributing factor: Compared to seaports, inland ports are generally underrepresented in academic literature.

To investigate our claims and to uncover the assumed research gap this scoping review was conducted in a PRISMA-styled approach (Page et al. 2020). The review process, including the used search string is depicted in Figure 1.

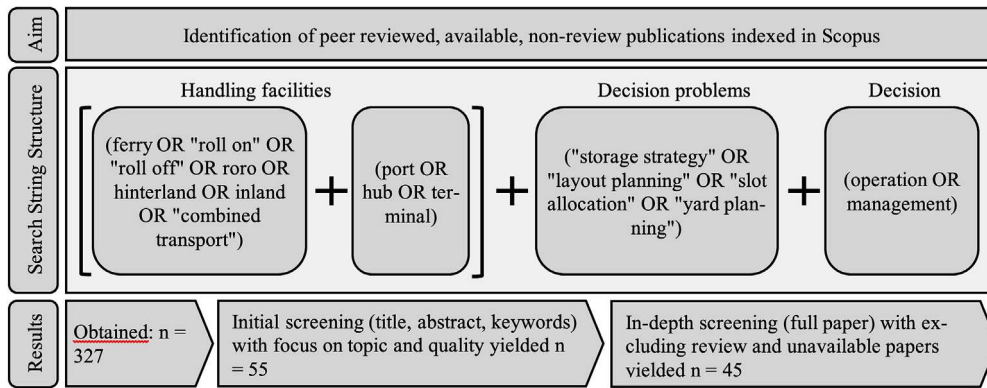


Figure 1: Review process including search string and result overview, own representation.

The applied search string consists of three blocks, embodying to the review scope. The first block filters for in-scope logistical handling facilities, purposefully neglecting seaports. The second block focuses on the investigated decision problems related to storage strategies. The third block ensures a focus on the decision level ensuring results dealing with actually operational tasks. The search was conducted for peer reviewed papers on the search engine Scopus (search date: March 1, 2025) and resulted in 327 papers. An initial (title and key-words) screening yielded 55 relevant results which dealt with yard management in maritime logistics. After another, more in-depth screening 45 publications were finally considered for review, analysis and categorization. Review papers in the results, as well as publicly not accessible papers, were excluded in the screening process.

Results and analysis

In this chapter the review results are presented and analyzed. Within the review process we investigated the following criteria: Time and location of the research work, type of LU (container, trailer, vehicle), type of port (seaport, inland port, combined transport hub), mode of transport and port functional areas (water, rail, road; yard, horizontal transport), as well as the category of the considered decision problem.

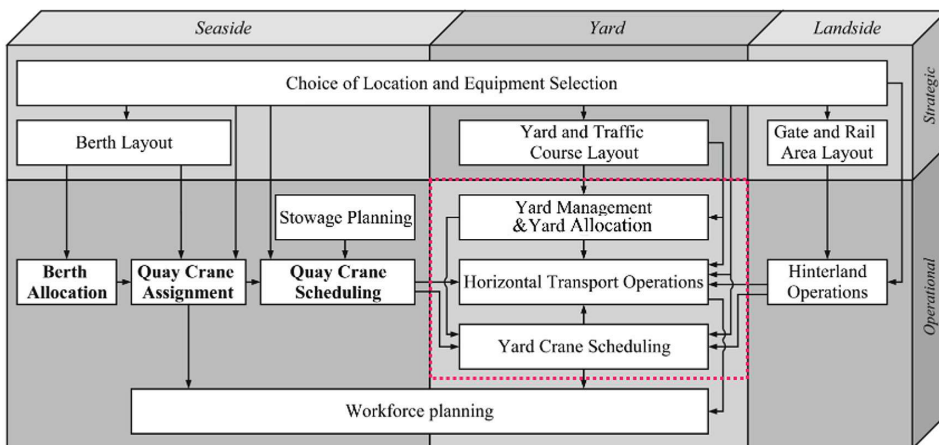


Figure 2: Terminal Planning problems. Edited based on Bierwirth and Meisel (2010).

For the categories, an overview of planning seaside transshipment operations was proposed by Bierwirth and Meisel (2010), providing guidance and structure to the domain's different decision problems (see Figure 2). We conducted the categorization as an adaptation of this valuable base. Since this work focusses on operational decisions regarding non-stackable ILUs in the yard, the focus area was limited to the marked area (Figure 2). The resulting categorization, as well as the scope differentiation are shown in Tables 2 and 3.

Time and location

The temporal distribution over the years is depicted in Figure 3. Time data indicates, that research work related to the applied search string started to gain popularity in 2017 with peaks in 2021 and 2024. A positive trend until today can be seen (data from March 2025). The continuous increase of publications in the scope proves the increasing popularity and importance of the topic. Given that the number of overall findings in this specific topic is rather low, compared to various other maritime logistics fields, a research gap can reasonably be assumed.

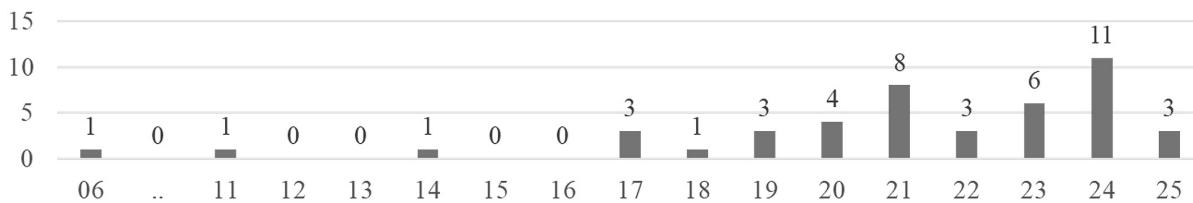


Figure 3: Temporal distribution of reviewed research works, own representation.

Geographic data (Figure 4) shows, that authors from Asia and Europe appear to be most active in the research area (left). Regarding the handling facility locations, Asia and Europe also seem to be relevant application areas for the scope of the topic (right). It has to be mentioned, that a large amount of publications were not mentioning actual application locations and were therefore not classifiable. Two papers did state to focus on certain transport routes, rather than on handling facilities.

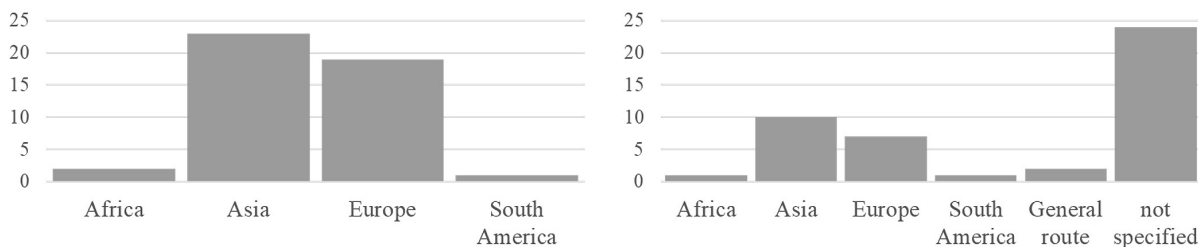


Figure 4: Geographic distribution of reviewed research works, by first author location (left) and by stated handling facilities in focus (right), own representation.

Loading unit types

Around 93 % of the reviewed publications (42) mentioned containers as the LU in focus. Two papers focused on car terminals, whose goods are rather specialized break bulk (vehicles) instead of on ILUs. One paper did not state any specific LU in their research. Only 4 % of the reviewed publications (2) actually mentioned semi-trailers (Szczepa ski et al. 2021; Ozawa et al. 2025) as one of the investigated LU types (in combination with containers). The very large proportion of containers in the results, although we have reduced the weighting of seaports in the first block of the search string, demonstrates the comprehensive dominance of the container not only in practice but also in research.

Port types

About 73 % of the reviewed publications (33 of 45) mentioned seaports as the considered handling facility while 20 % of the reviewed papers (9) mentioned inland ports. 24 % (11) stated to focus on combined transport hubs. Only 18 % (8) of the reviewed publications mentioned more than one port type. The combination of 'inland port' and 'combined transport hub' appeared five times, there were two combinations of 'seaport' and 'combined transport hub' and one mention of 'seaport' and 'inland port'. Since we purposefully did not reference seaports in our search, their proportion is still very large which gives

another hint of their academic relevance in comparison to the other handling facility types. The isolated mentioning of only one port type in most of the findings indicate, that authors (although implicitly) do often clearly differentiate between sea and inland ports even though clear definitions or precise demarcations between both are very scarce in scientific literature.

Transport modes

Within the reviewed publications, all combinations of transport modes were found. The shares and distributions are depicted in Table 1.

Table 1: Combination of Transport modes in the findings, own representation.

	Water (total)	Rail (total)	Road (total)	Water (excl.)	Rail (excl.)	Road (excl.)	Water-Road	Water-Rail	Rail-Road	Trimodal
#	28	19	22	8	1	2	3	1	7	10
%	62 %	42 %	49 %	18 %	2 %	4 %	7 %	2 %	16 %	22 %

Functional areas

From the perspective of a logistical handling facility, the transport modes water, rail and road represent corresponding functional areas within the facilities. Moreover, there are other functional areas of relevance namely the yard and horizontal transport. Within the data, 82 % of the reviewed publications (37) stated to focus their work on the yard area, whereas 58 % (26) considered horizontal transport as their scope.

Decision problem areas

The reviewed publications were assigned to the decision problems given in Table 2. About 56 % (25) of the publications conducted their research on one isolated decision problem. 31 % (14) publications considered a combination of two combined decision problems, one paper approached even three decision problems collectively.

Around 24 % (11) of the publications unambiguously dealt with the yard management problem as defined in the review scope. Based on Figure 2, approaches of yard allocation, truck allocation and crane scheduling also meet the scope, which results in 37 hits (82 %) and confirms the search string to be reasonable on point. The comparably low proportion of in-scope publications which used the 'yard management' term indicates a lack of a unified decision problem naming convention and shows blurring boundaries between the different decision areas.

Decision problem	Operational leading question	#	%	Scope
Yard allocation	When to use which yard block/area?	15	33	Y
Yard management	How to position/stack/ reshuffle/prioritize LUs?	11	24	Y
Layout planning	How to spatially structure the functional areas?	8	18	N
Truck allocation	Where to put the trucks at which time?	7	16	Y
Stowage planning	Where to put the freight on the vessel?	5	11	N
Berth allocation	Where to put the vessel?	4	9	N
Crane scheduling	What to lift with which crane in which order?	4	9	Y
Train scheduling	How to load/unload/turn around the train?	1	2	N
Other/no decision	-	4	9	N

Table 2: Considered decision problems of the reviewed research works, own representation.

Five publications looked into the yard management problem as an isolated problem, one publication combined it with a crane scheduling problem and five publications investigated the yard management problem together with the yard allocation problem. The latter indicates a strong entanglement between the yard allocation and yard management problem but could again also indicate a lack of a precise demarcation or a clear naming scheme for different decision problems in yards.

Intersecting results

There are only two reviewed publications which at all considered semi-trailers: Ozawa et al. (2025) focus on strategic collaboration approaches with an organizational perspective. Szczepanski et al. (2021) proposed decision support for terminal layout designs. Focusing the analysis on the 14 publications which mentioned inland ports and combined transport hubs, it becomes clear that they all consider containers as ILU. Three of those publications also focused on seaports and six dealt with decision problems in scope, whereas in five of them, storage strategies were given and at least briefly described (see Table 3).

Table 3: Overview and intersectional analysis of reviewed papers which focus on inland ports or combined transport hubs, own representation.

Paper of:	ILU: Container	Port Type: Seaport	Decision Problem: Yard management	Storage strategies:	Strategy applicability to trailer storing?
Hu et al. (2021)	Y	Y	yard allocation	“adjacent yard space sharing strategy”	
Jachimowski et al. (2018)	Y	N	yard management	“random”, “by category”, “dedicated”, “consolidated”, “housekeeping”	partially applicable
Kaidabettu et al. (2021)	Y	N	yard management & train scheduling	no	
Kłodawski et al. (2024)	Y	N	train scheduling	no	
Kostrzewski und Kostrzewski (2019)	Y	N	other	no	
Ozawa et al. (2025)	Y	N	other	no	
Rozić et al. (2022)	Y	N	yard management & allocation	“potentials & parameter ranking”	partially applicable
Szczepański et al. (2021)	Y	N	layout planning	no	
Tao et al. (2023)	Y	N	yard & truck allocation	no	
Wiercx et al. (2019)	Y	N	truck allocation & train scheduling	no	
Yan and Xu (2023)	Y	Y	layout planning	no	
Zajęc (2021)	Y	Y	yard management	“greedy”, “FIFO”, “load distribution”	
Zajęc et al. (2023a)	Y	N	yard management & allocation	“greedy”, “stack by weight”	
Zajęc et al. (2023b)	Y	N	yard management	no	

None of the analyzed literature does fully comply to the set review scope. It can therefore be concluded, that the assumed research gap in academic literature (claim I) is clearly existent. From the analyzed literature containing storage strategies, Hu et al. (2021) and Zajęc et al. (2023b) do not contain applicable strategies for semi-trailers, since they focus on stackability (container yard management) and load balancing between locations (container yard area allocation). In the publications of Jachimowski et al. (2018) and Rozić et al. (2022), storage strategies are partially applicable to semi-trailers, since (in addition to stacking approaches) they also propose approaches which build up on classifications and rankings without the need to stack. The publication of Zajęc (2021), while still focusing on containers in seaports, does provide storage strategies which are applicable to semi-trailers.

The vast majority of publications in the resulting analysis (93 %), as well as in the approx. 280 rejected papers, considered container stacking, container yard allocation and container yard management problems, although containers themselves were not part of the structured search. This clearly shows the overwhelming impact and domination of the container as ILU across the board of decision problem categories. On the other hand, decision problems related to semi-trailer storing (with only two publications mentioning them), are heavily underrepresented, which therefore confirms our second claim as well as the contributing factors.

Discussion and conclusion

Improper allocation of semi-trailers or excessive truck workloads for loading and unloading operations (as organizational flaws) can lead to significant traffic congestion within handling facilities. This results in waiting times, increased energy consumption and elevated carbon emissions. Although strategic truck assignment and appointment systems have been shown to be effective in mitigating these issues, algorithmic solutions developed are usually designed for large container terminals in seaports. Mathematical models for optimizing operations (as operational or tactical decision support - e.g. as storage strategies) are usually designed with seaport operations in mind, so it is often challenging or not possible to apply them directly to inland terminals, which are characterized by lower volumes and complex multi-agent interactions. From a market and customer perspective, the freight forwarder-oriented nature of inland terminals, driven by competitive pressures, makes it difficult to implement pricing mechanisms such as penalties or auctions, which are an established measure in seaports. This furthermore necessitates more flexible and adaptable modelling approaches (Abril et al. 2024). While most existing studies focus on optimizing storage strategies tailored to specific terminal layouts and facility types, the methodologies and tools available for inland terminals have significant limitations. This can hinder the development of universally applicable modelling or simulation approaches that can be easily adapted to real-world operational environments (Zajac et al. 2023). Those circumstances clearly depict the challenges of applying existing solutions to smaller handling facilities due to their differences in structure, technologies, capacity, and operational paradigms. Our research indicates that existing literature predominantly focuses on container storage strategies within seaports, with considerably less attention given to inland ports and semi-trailers. As a result, proposed strategies often fail to align with the specific operational requirements and handling processes of semi-trailers, even though they play a vital role in logistical development. Unlike the advanced technical strategies and mathematical models developed for container terminal storing, applicable semi-trailer storage strategies in the literature generally cover only basic principles such as customer-oriented storing or 'first-in, first-out'.

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