Analysis and simulation of the operational capacity of a Rail Motorway Terminal.

This work aims to analyze the factors that influence the operational time at a railway-motorway intermodal terminal, with a specific focus on the loading and unloading of trains with semi-trailers. This operation is commonly referred to as a rail motorway intermodal process. The terminal under analysis is the Zaragoza-PLAZA intermodal terminal, located in Zaragoza, Spain. Using AnyLogic® PLE, a discrete event and block-based logic simulation software, a model is developed to realistically simulate the terminal's operations, offering potential improvements. The model enables observation of the terminal's behavior by modifying certain parameters. The results obtained can be directly applied to the existing terminal for performance enhancements. Finally, a sensitivity analysis of the model is conducted, allowing us to assess how various factors influence the terminal's operations.

Keywords: Rail Motorway Terminal; simulation; intermodality.

1. Introduction.

This section discusses the factors affecting the operational capacity of a rail highway terminal. The implementation of rail motorways is a growing reality in Europe, particularly in peripheral countries where long distances need to be covered by road freight. The reduction in fuel consumption and emissions achieved through this intermodal transport system is significant, making it an attractive alternative to road transport. However, a bottleneck exists in the intermodal operations between railways and transport trucks, specifically at intermodal railway terminals. Therefore, it is crucial to analyze the loading and unloading processes of semi-trailers onto trains to ensure these operations are time-efficient and competitive.

Simulating these processes using tools, like those applied in this study, allows for determining not only the optimal size of the transfer yards but also the necessary equipment and its specifications to make these operations viable. Currently, most rail motorway systems utilize pre-existing terminals originally designed for container transport. The possibility of developing a terminal specifically for rail motorway use, as proposed in this case study, is innovative. It allows the terminal spaces to be accurately dimensioned, organized, and equipped for this purpose.

The issue of optimizing the loading and unloading operations of containers in intermodal freight trains has been investigated in previous studies, primarily to determine the optimal distribution of areas covered by cranes (Boysen, 2010). Most studies focus on the operation within the available space in the transshipment yard, concentrating on train-to-train operations, and analyzing the inefficiencies of certain operations through simulations (Abourraja, 2018). More sophisticated models employing generation algorithms combine the activities of the main agents involved in the loading and unloading operations of a railway terminal, aiming to enhance equipment coordination and operational efficiency (Chang, 2019).

However, the present study demonstrates several notable differences from previous research. In addition to considering the interaction of work teams and simulating operational times to improve effectiveness (Muravev, 2021; Sadeghi, 2021), this research analyzes the specific case of a rail-highway intermodal terminal, where semitrailers are mounted on train wagons. In this terminal, semitrailers must utilize an additional platform-like support structure for elevation, and fixed structures are required within the transshipment yard for securing these supports during operations. Consequently, an additional complication arises, involving the determination of the number of auxiliary platforms needed, the placement of the corresponding fixed structures within the transshipment yard, and the allocation of work zones based on the number of cranes required to meet daily operational objectives.

This work, therefore, aims to simulate as realistically as possible the loading and unloading of semi-trailers at an intermodal railway terminal, with the goal of measuring key factors influencing its efficiency, such as the number and positioning of cranes and the time required for the operations.

A rail motorway involves the use of trains to transport road semi-trailers on flat wagons, particularly over long distances, thereby reducing energy consumption, environmental emissions (López-Navarro, 2014), and highway congestion (Camarero, 2022). The loading process occurs at specially designed railway terminals that accommodate these operations, which require larger spaces. Some terminals allow the tractor unit to drive the semi-trailer onto the train via a specially designed ramp (Modalhor System), while others use various types of cranes (reach stackers or gantry cranes) to load the semi-trailers. These cranes lift the semi-trailers by gripping their lower frame and placing them onto the train (Chebotareva, 2022).

Certain semi-trailers are reinforced to allow cranes to lift them without additional equipment. However, since most current semi-trailers lack such reinforcements, support platforms are used. The semi-trailers are positioned on these platforms, which are then lifted by the crane, preventing deformation of the trailers. To enable the tractor unit to place the semi-trailers on these platforms, auxiliary structures fixed to the ground, equipped with a small ramp, are used. These structures help the tractor unit position the semi-trailer accurately onto the lifting platforms. Therefore, to optimize the loading and unloading operations, along with vehicle movement in and out of the terminal, it is essential to analyze the best placement and distribution of these auxiliary structures within the terminal, ensuring the overall process time is minimized (Carboni, 2018).

This study aims to examine the factors influencing terminal operations and their impact on the total time required for the train loading and unloading process. The goal is to determine the maximum number of semi-trailers that can be handled at the terminal within the available time frame to support a daily rail service (Hamimiche, 1998; Higginson, 1997).

One of the key factors is the time required for each operation performed by the various devices within the terminal. This includes the time taken by cranes to load and unload semi-trailers onto the train wagons, the time for coupling and uncoupling the semi-trailers from the tractor unit, and positioning them on the auxiliary structure for lifting. Additionally, the travel time of cranes, from placing semi-trailers on the wagons to returning to the auxiliary structures, is another critical factor. The number of cranes in operation (Tănăsuică, 2021) and the number and positioning of auxiliary structures throughout the terminal also affect crane travel distances and are directly related to train length.

Finally, the event sequencing logic that prioritizes specific actions over subsequent ones is another factor influencing the fluidity of terminal operations. This sequencing can vary based on the specific circumstances at any given time (Vida, 2023).

The aim of this work is to determine the optimal number of cranes, and consequently the maximum number of platforms that can be handled simultaneously, as well as their ideal positioning along the length of the train.

2. Factors Affecting Terminal Operation.

In a railway terminal, various vehicles interact, including cranes (reach stackers), trucks, and trains, each with distinct speed and maneuverability characteristics. These vehicles are influenced by different factors that shape the overall terminal operations (Woxenius, 2011). In the following subsections, we analyze the impact of these factors on the terminal's efficiency.

2.1 Terminal equipment speed.

For accurate simulation results, the speeds of all equipment and vehicles operating in the terminal must be precisely adjusted, as even small changes in speed can significantly affect the total process time (Bartulović, 2022). In this case study, the speeds of trains and trucks have been carefully calibrated for both the delivery and collection of loads. Additionally, the speed of the cranes has been differentiated based on whether they are carrying a semi-trailer, as the added weight prevents them from moving as quickly as when they are operating without a load.

2.2 Semi-trailer coupling and uncoupling times

The time required to couple and uncouple semi-trailers impacts both cranes and trucks, as both are involved in this process. Similar to vehicle speeds, extended coupling and uncoupling times can negatively affect the overall operational efficiency of the terminal. For cranes, this time includes the process of loading or unloading semi-trailers from the wagons and placing them in the interchange areas with the trucks. For trucks, it refers to the time truck drivers spend coupling and un coupling the semi-trailers to and from the tractor units.

2.3 Use of adapted or standard semi-trailers.

The chassis of most standard semi-trailers is not designed to be lifted, especially when loaded, necessitating alternative solutions for handling. One option is to use specially adapted semi-trailers, which feature reinforced chassis and strategically placed openings to allow cranes to lift them more easily. However, these adapted semi-trailers are uncommon, so it becomes more practical to find a solution that allows for the use of standard semi-trailers on intermodal trains.

One such solution involves using external auxiliary platforms placed beneath the semi-trailers. These platforms support the semi-trailers during lifting, maintaining their structural integrity and preventing damage. Cranes can lift these platforms by attaching to hitches at the ends, allowing for safe placement of the semi-trailers onto the train wagons. Since the semi-trailers need to be positioned on these platforms, it is essential to install fixed structures in the terminal's transfer yard to facilitate the process. Determining the optimal placement of these fixed structures is part of the study presented in this work.

3. Zaragoza-PLAZA case study: new rail motorway terminal.

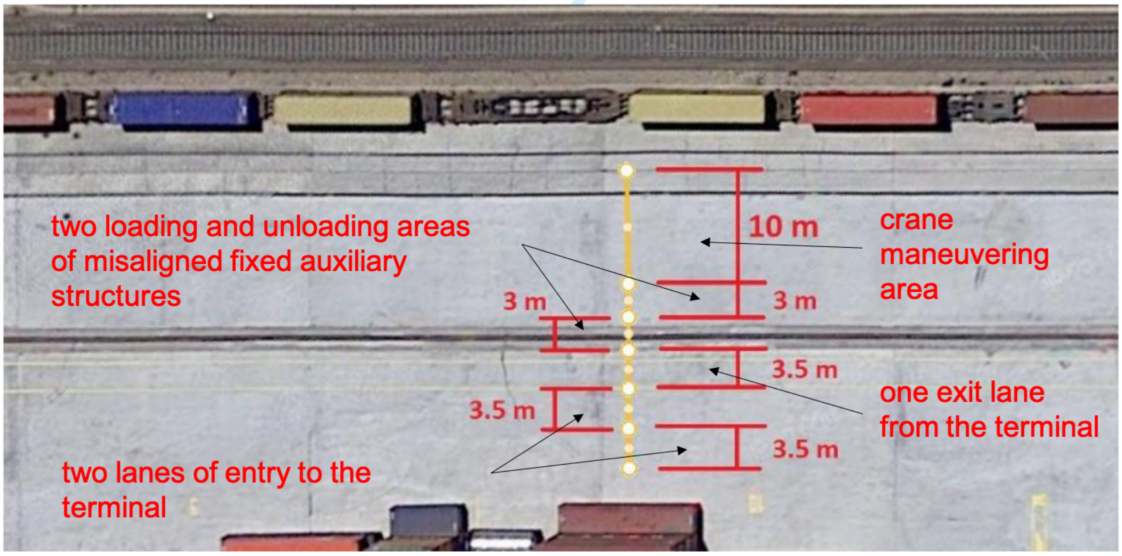
This study examines the factors influencing the loading and unloading operations of trains dedicated to rail motorways at the Zaragoza-PLAZA railway terminal, with the goal of determining the total process time. The terminal includes a dedicated area for intermodal freight handling, where rail motorway train operations take place (Escobar, 2021). The intermodal terminal is equipped with five tracks, each 750 meters long, and features an adjacent concrete platform covering 37,000 m². This platform serves as a transshipment area, a temporary storage yard, and a loading/unloading zone. Within this zone, the following areas will be located:

- The movement area for the stacker cranes.
- The load exchange area, where the auxiliary structures are positioned.
- Two traffic lanes for truck movement (entry and exit).

Figure 1. Aerial view of the Plaza terminal, including the loading/unloading tracks and the transhipment yard.

This analysis focuses exclusively on the two tracks closest to the interchange platform and the operation of reach stacker cranes. The cranes will be assumed to move at a speed of 10 km/h when carrying a load and 20 km/h when unloaded. Trucks, on the other hand, can travel at a maximum speed of 30 km/h within the platform. Additionally, trucks must arrive at the station's parking lot at least one hour prior to the unloading of their semi-trailers from the wagons. Importantly, only a number of trucks equal to the number of operational cranes can access the exchange platform simultaneously.

Figure 2. Main dimensions between the tracks and the dockyard.



To operate trains with semi-trailers at this terminal, several modifications and operating rules must be implemented. First, fixed auxiliary structures need to be installed to support the semi-trailers as they are lifted onto auxiliary platforms by the cranes. This setup allows the cranes to either mount the semi-trailers onto each railway car or retrieve the semi-trailer along with the auxiliary platform from the railway car and place it onto the fixed structures at the terminal.

Additionally, clearly marked entry and exit lanes for trucks accessing the terminal are essential. It is also important to establish a designated area within the transshipment yard, located between the railway tracks and the fixed auxiliary structures, to provide ample space for crane operations during the loading and unloading processes.

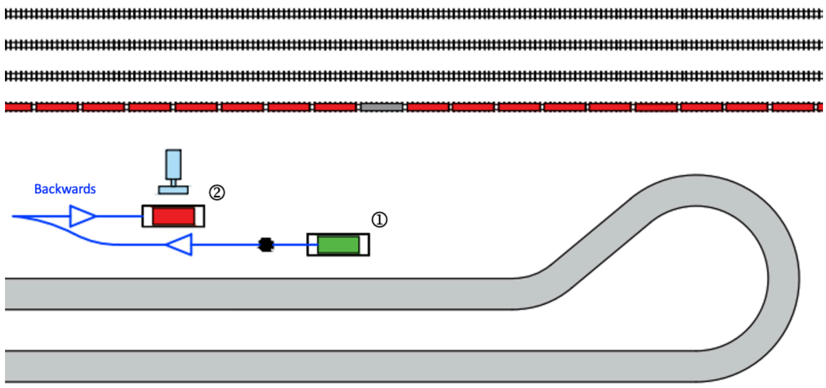
3.1- Distribution of fixed auxiliary structures within the terminal.

The layout and positioning of the fixed auxiliary structures within the terminal significantly affect the overall time required for loading and unloading. Among the alternatives evaluated, the configuration illustrated in Figure 1 was selected. This design features two structures positioned at a distance apart but misaligned to facilitate the reverse maneuvers of trucks with semi-trailers.

The arrangement of these platforms throughout the terminal effectively divides the transshipment yard into as many zones as there are cranes, enabling efficient operations. In each zone, two fixed auxiliary structures are placed alternately, facilitating operations for receiving semi-trailers delivered by trucks and those unloaded from trains.

As depicted in Figure 3, the truck first leaves its semi-trailer on the initial fixed platform, uncouples the tractor unit, and then proceeds to the second fixed structure to retrieve the semi-trailer that the crane has placed. These fixed structures are crucial, as they serve as the bases for the lifting platforms, ensuring that the semi-trailers are raised properly for safe crane operation without causing damage.

Figure 3. Maneuver to align the truck with the auxiliary fixed structure.



3.2- Monitoring System Iterations.

In the various iterations of the system simulation, a specific movement requires careful modeling. It is essential to recognize that the auxiliary platform is utilized to lift the semi-trailer onto the train. Therefore, when a truck approaches to deposit a semi-trailer, it must be placed on a fixed structure equipped with an auxiliary platform. This setup allows the crane to subsequently raise the semi-trailer above the auxiliary platform.

Conversely, when a semi-trailer is unloaded from the train—along with the auxiliary platform used for lifting—it must be deposited on a fixed structure that does not have an auxiliary platform. Thus, fixed auxiliary structures 1 and 2 must alternate their functions: receiving semi-trailers from trucks when equipped with an auxiliary platform, and receiving from cranes when the platform is absent.

As a result, in each iteration, the position of the auxiliary platform alternates between fixed structures 1 and 2, ensuring efficient operations and proper handling of the semi-trailers.

4. Development of the Simulation Model.

The simulation was conducted using AnyLogic® software, which is based on block logic and discrete event systems. Through decision conditions and the integration of various agents' blocks, the operation of the terminal is effectively represented within the software. Key parameters include the previously defined speed values, crane loading and unloading times (estimated to be between 6 and 8 minutes), and truck coupling and uncoupling times (estimated between 4 and 6 minutes).

The model is constructed using specific physical variables of the terminal, such as lengths, distances, and the existing auxiliary structures, as well as the state variables of the vehicles, including speeds and dimensions. Subsequently, the behavior logic of different agents is implemented in the model. This includes programming the operations of trains accessing the station, the sequence of loading and unloading semi-trailers, the simultaneous operation of cranes, and the movement of trucks as they approach the terminal and position themselves at the auxiliary structures for coupling and uncoupling the semi-trailers.

It is crucial to establish the starting functional parameters related to operating times. The most significant parameters that can affect the total process time include:

1. Travel times of the cranes between wagons and the interchange area.
2. Loading and unloading times of the cranes.
3. Truck coupling and uncoupling times.

To enhance the first parameter, a study of the fixed structures' locations within the terminal is necessary to determine the optimal distribution that minimizes the total processing time. For the other two parameters, a sensitivity analysis will be conducted, varying each parameter to assess its influence on the overall system.

The primary objective of this simulation is to analyze the operational capacity of an intermodal railway freight terminal for the exchange of semi-trailers, focusing specifically on the loading and unloading processes. Factors affecting operating times will be examined, including the placement of fixed structures within the terminal, loading and unloading times for semi-trailers on train wagons, coupling and uncoupling times between semi-trailers and tractor units, crane travel durations from train wagons to fixed structures, the simultaneous operation of multiple cranes, and vehicle approach times to the fixed structures.

To streamline the analysis, we established that two fixed structures are required for each crane—one for unloading from the train and another for collection from the truck. Initially, we simulated whether the fixed structures for unloading should be positioned together or alternated with those for collection, assuming three cranes in operation. The results indicated that it is more efficient for each crane to have its designated work area with both types of fixed structures positioned together, albeit misaligned to facilitate truck maneuvering.

Subsequently, we compared operating times for different numbers of cranes, ranging from one crane with two fixed structures to four cranes with eight fixed structures. Finally, to refine the solution, simulations were conducted to assess the impact of various parameters on total operating time, such as the coupling and uncoupling time of the tractor unit from the semi-trailer and the loading and unloading maneuvering times for the crane, considering three different time intervals for both the crane and the truck.

5. Simulation Results for Different Work Strategies

5.1- Parameters Used in the Simulations.

Several parameters significantly influence the simulation results, necessitating their precise definition:

- **Number of Trains:** Two trains are utilized in this analysis, with the potential to increase this number if needed.

- **Number of Wagons:** Each train comprises 42 cars, ensuring that the total length does not exceed the maximum allowable track length of 750 meters.
- **Number of Cranes:** The simulations consider the operation of 1 to 4 cranes.
- **Number of Fixed Structures:** Two fixed structures are assigned per crane, resulting in a total of two structures for each crane included in the simulation.
- **Loading and Unloading Order:** The sequence of loading and unloading the wagons is determined randomly. This order is input into the system using data provided in a spreadsheet format.
- **Break Time for Operators:** Crane operators are required to take breaks throughout their shifts. A break of 15 minutes is scheduled every 2 hours of work, and this time is added directly to the total time at the end of the simulation.

Table 1. Resources Used in the Simulations.

Resources	Parameters		Values
Trains	Number of wagons		42 wagons
	Number of cranes		1-4 cranes
Cranes	Speed	loaded	10 km/h
		unloaded	20 km/h
	Time	load/unload	6-8 minutes
Trucks	Number of trucks		1 per crane
	Average speed		30 km/h
	Time	coupling/uncoupling	4-6 minutes
Fixed Structures	Number of structures		2 per crane

Operators	Break time/total	15 minutes/2 hours

5.2- Loading and Unloading Process.

The loading and unloading process can be summarized as follows: first, the trains are simulated as they enter the tracks. Once they come to a stop, the loading and unloading of the wagons begins. A crane moves to the first wagon on the unloading list, which has been pre-organized according to the order of each truck, selected randomly in the simulation.

Simultaneously, the assigned truck enters the terminal and proceeds to one of the fixed structures equipped with a lifting platform.

After these initial movements, the crane unloads the semi-trailer from the wagon, removing it from the train. At the same time, the truck driver places his semi-trailer on the fixed structure above the lifting platform and uncouples the semi-trailer's traction unit, making it ready for the crane to lift.

The subsequent movements involve repositioning: while the loaded crane moves to the nearest empty fixed structure, the truck driver positions his tractor unit on the same structure the crane is heading towards.

At this fixed structure, the crane deposits the semi-trailer it unloaded from the train. Once deposited, the truck driver couples his tractor unit to the semi-trailer. Meanwhile, the crane moves to the other fixed structure where the semi-trailer that the truck had previously uncoupled is located, and begins to load it.

Once the truck driver completes the coupling task, he exits the terminal. Concurrently, the crane, after picking up the semi-trailer using the lifting platform, transports it to the corresponding train wagon from the unloading list and loads it onto that wagon.

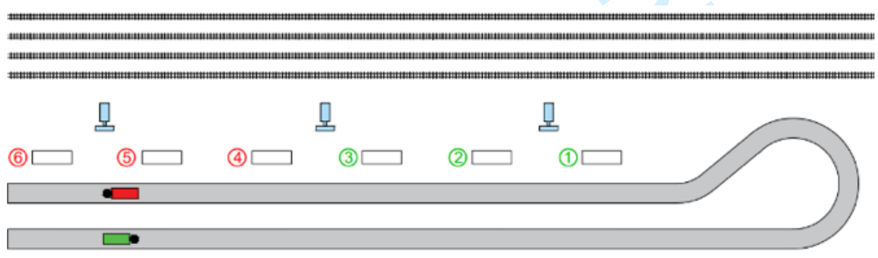
It is important to note that a new truck cannot access the terminal until the crane has commenced its next task, specifically after the semi-trailer has been deposited in the wagon and the crane is en route to the next loaded wagon.

5.3- Total Times Obtained from the Simulation and Selection of Best Configuration.

During the simulation process, various configurations for the fixed exchange structures were tested throughout the terminal to minimize total simulation time and streamline the loading and unloading process. Two primary configurations were considered:

(1) **Aligned Distribution**: In this configuration, the fixed structures are arranged in a straight line along the terminal. The number of structures corresponds to the number of cranes in operation. For instance, if three cranes are utilized, six fixed exchange structures are required: the first three will be designated for receiving semi-trailers from the trucks, while the remaining three will be for receiving semi-trailers unloaded from the train by the cranes.

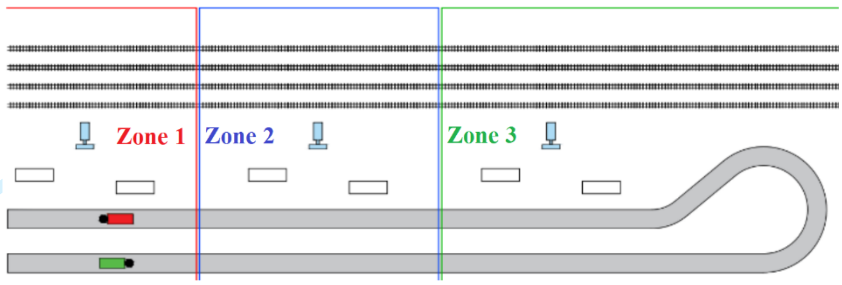
Figure 4. Illustration of the Aligned Distribution of Fixed Structures.



(2) **Zonal Distribution:** This configuration, described in section 2.2, divides the terminal into zones equal to the number of cranes in operation, with two

fixed structures placed at the center of each zone. All zones provide access to the same number of train cars.

Figure 5. Illustration of the Zonal Distribution of Fixed Structures.



The next step involves simulating both configurations to determine which one minimizes the unloading time for two complete trains. The following table presents the total times for both configurations using three cranes in the simulation.

Table 2. Time Spent Depending on the Location of the Fixed Platforms.

	Total Time (s)	Total Time (h)
(1) Aligned	52,905.83	**14.69**
(2) Zonal Distribution	49,193.32	**13.66**

As indicated in the table 2, the zonal distribution significantly reduces the total loading and unloading time for the two trains by approximately one hour. This improvement is attributed to the shorter travel distances for the cranes during the loading and unloading processes. Consequently, the zonal distribution configuration is selected for subsequent analyses.

Further simulations were conducted with varying numbers of cranes, with total times calculated including the estimated break time for workers—15 minutes for every two hours of operation.

Table 3. Time Spent Depending on the Number of Cranes.

[Number of trains = 2; Number of wagons per train = 42]

Number of cranes	**1**	**2**	**3**	**4**
Number of fixed structures	2	4	6	8
Total time without breaks (s):	43.44	20.72	13.66	10.16
Break time (h):	5.25	2.50	1.50	1.25
Total time with breaks (h):	**48.69**	**23.22**	**15.16**	**11.41**

After calculating the total time, it is essential to determine the number of worker shifts required for each alternative, based on the number of cranes in use. **Table 4** presents the results, indicating that the alternatives utilizing 2 and 3 cranes necessitate the fewest employee shifts, assuming each shift lasts 8 hours.

$$Total\ number\ of\ work\ shifts = \frac{crane\ operating\ time\ (h)}{time\ of\ a\ shift\ (h)} \cdot number\ of\ cranes$$

Table 4. Number of Work Shifts Required Based on the Number of Cranes. [Shift duration = 8 h]

Number of cranes	1	2	3	4
Total time per crane (h)	48.69	23.22	15.16	11.41
Total number of work shifts	**7**	**6**	**6**	**8**

To choose the optimal option, it's essential to consider the expected daily demand for trains, ensuring that the operation of two fully-loaded trains does not exceed 24 hours. Additionally, the transportation of semi-trailers on rail motorways must remain competitive with road transport, meaning the total operation time (including loading/unloading and travel time) should be comparable to road alternatives.

Operational constraints also affect the return paths of the trains, requiring that the entire loading/unloading process for both trains be completed within a 16-hour window, as indicated in the figure.

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Figure 6. Total Times as a Function of the Number of Cranes.

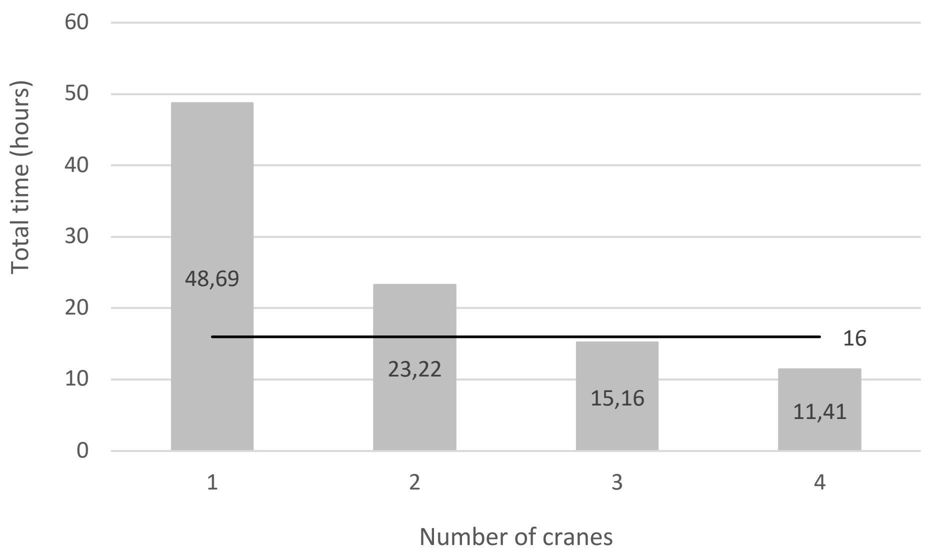


Figure 6 illustrates that the option which minimizes loading and unloading time, complies with the terminal's operational requirements, and reduces the number of worker shifts is the alternative employing three cranes.

6. Variation of Parameters.

After determining the most suitable solution based on operational and cost criteria, we will examine how variations in certain initially established parameters affect the simulation results. The two parameters with the most significant impact on the simulation are the coupling and uncoupling times for both trucks and cranes. This includes the duration required for hooking and unhooking semi-trailers from trucks, as well as the time needed to load and unload the semi-trailers and their auxiliary platforms from the train and onto the terminal's fixed structures.

6.1 Variation in the Coupling/Uncoupling Times of Semi-Trailers with Trucks.

This analysis explores how variations in the coupling and uncoupling times of semi-trailers with trucks affect the total operation time, while keeping all other factors constant. By isolating the impact of these specific maneuvers, the study provides deeper insights into overall operational efficiency. Three simulations were conducted, each considering different time intervals for the truck maneuvers: 2-4 minutes, 6-8 minutes, and 11-13 minutes. In each test, the crane maneuvering time was held constant. The time values for the maneuvers followed a normal probability distribution, with boundary values reflecting the specified time ranges.

This approach, implemented using AnyLogic® software, leverages probability distributions to account for real-world variability, enhancing the accuracy and reliability of the simulation results.

Table 5. Operating Times Assigned to Trucks for a Fixed Crane Time in Each Test. [crane load/unload: 6 - 8 minutes]

	Test 1	Test 2	Test 3
Truck coupling/uncoupling time (min)	2 - 4	6 - 8	11 - 13

After adjusting the truck maneuver times, simulations were rerun for all configurations (ranging from 1 to 4 cranes), with the results factoring in worker break times.

Table 6. Total Operation Time in Each Test.

		Total time (hours)		
Cranes	Break time (h)	Test 1	Test 2	Test 3
1	5.25	48.69	48.69	48.75

2	2.50	23.22	23.22	23.37
3	1.50	15.16	15.16	15.28
4	1.25	11.41	11.41	11.46

When analyzing these results, it becomes clear that Tests 1 and 2 produce identical values, while Test 3 yields slightly longer times. A closer examination suggests that when truck maneuvering times fall below a certain threshold, the crane itself becomes the limiting factor for the total operation time, effectively preventing further reductions.

To better understand this process, the steps performed by each system agent (crane and truck) are outlined below:

- Crane Operations (the time used by the "Grua" agent for each movement is the total of the following events):
  1. Empty travel time from the crane's current position to the assigned train wagon.
  2. Unloading the semi-trailer from the train wagon.
  3. Loaded travel time with the semi-trailer from the train to the designated fixed structure in the terminal.
  4. Unloading the semi-trailer onto the fixed structure and releasing it.
  5. Empty travel time from the current fixed structure to the next one.
  6. Hooking and loading the semi-trailer from the second fixed structure.
  7. Loaded travel time with the semi-trailer to the designated train wagon.
  8. Loading the semi-trailer onto the assigned train wagon.
- Truck Operations (the time used by the truck agent for each movement is the total of the following events):

1. Travel time with the semi-trailer attached from the terminal entrance to the fixed structure (based on truck speed and platform location).
2. Uncoupling the semi-trailer from the truck.
3. Waiting time until the crane completes its task.
4. Empty travel time from the current fixed structure to the next one.
5. Coupling the semi-trailer to the truck.
6. Travel time with the semi-trailer attached from the fixed structure to the terminal exit.

Figure 7 present a schematic overview of the total time required for all maneuvers to unload and load a semi-trailer (for the crane) and to hook and unhook the semi-trailer (for the truck), considering the worst-case times.

In the first scenario, when both the crane and truck take between 6 to 8 minutes for their respective maneuvers, the crane proves to be the slower component, setting the overall pace. In the second scenario, assuming the crane still takes 6 to 8 minutes while truck maneuvers take 11 to 13 minutes, the truck becomes the limiting factor. However, the crane's time remains the critical value because minimizing crane idle time is essential for smooth terminal operations.

For optimal performance, truck times must be managed to ensure the crane does not experience delays, as the crane dictates the overall unloading rate. Additionally, truck operations should be timed carefully to prevent congestion at the terminal entrance, ensuring smooth traffic flow.

Figure 7. Schematic Representation of Time Used by Cranes and Trucks (6-8 min. for both crane and truck)

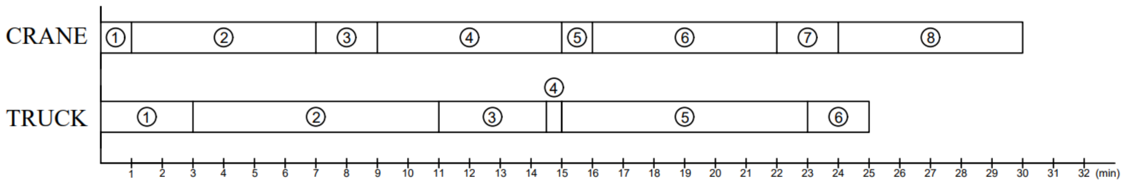
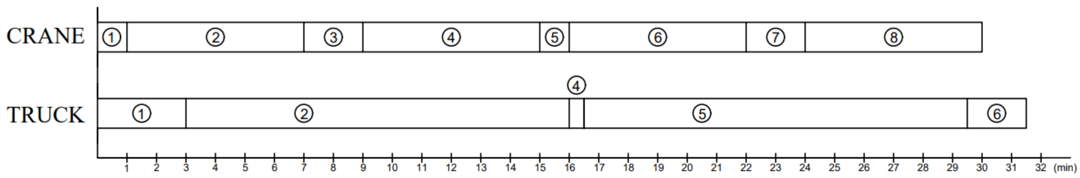


Figure 8. Schematic Representation of Time Used by Cranes and Trucks (6-8 min. crane, 11-13 min. truck).

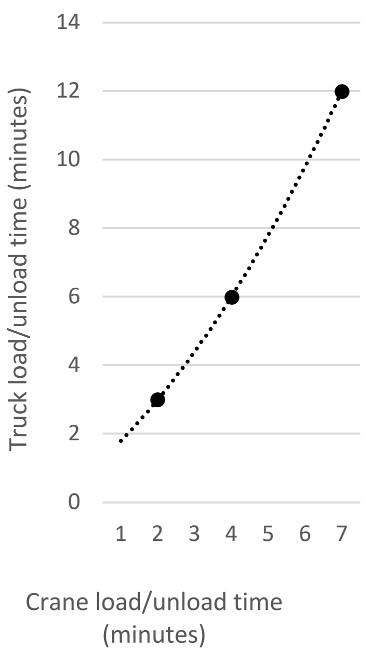


In the second scenario, the increased time spent by the trucks makes this the least favorable case. Since the truck's operations take longer than the crane's, it causes delays in each cycle—cranes are unable to unload semi-trailers until the trucks retrieve them. This prolongs the overall operation time and decreases efficiency.

With this in mind, we can now determine the time limits trucks must adhere to in their operations, relative to the time spent by the cranes, to ensure the total process time does not increase. For crane maneuver times of 2, 4, and 7 minutes, the maximum allowable time for truck maneuvers is 3, 6, and 12 minutes, respectively.

By graphically representing these results, we can estimate the maximum truck operation times as a function of the crane times.

Figure 9. Operation Time Comparison Between Cranes and Trucks.



In conclusion, the total operation time at the terminal will be dictated by the crane operations, provided that the trucks do not exceed the time limits shown in the graph.

6.2 Variation in Crane Loading/Unloading Times.

Following the same approach as in the previous section, several operational time ranges for the cranes are defined: 3-5 minutes, 6-8 minutes, and 9-11 minutes. The truck maneuvering time remains constant at 4-6 minutes, resulting in three distinct test cases.

Table 7. Operating Time Assigned to Cranes, with Fixed Truck Times (truck coupling/uncoupling: 4-6 min).

	Test 1	Test 2	Test 3
Crane load/unload time (min)	3 - 5	6 - 8	9 - 11

The results from the simulations are presented in the following table.

Table 8. Total Operation Time for Each Test.

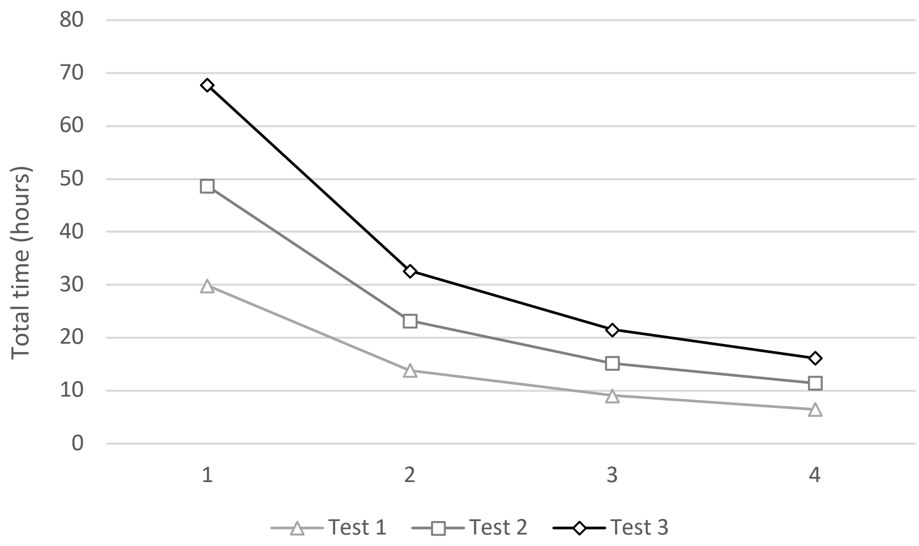
		Total time (hours)		
Cranes	Break time (h)	Test 1	Test 2	Test 3

1	5.25	29.89	48.69	67.74
2	2.50	13.88	23.22	32.62
3	1.50	9.09	15.16	21.52
4	1.25	6.46	11.41	16.12

As expected, the total operation time increases as the crane's maneuvering time range increases. The results align with projections, showing a proportional increase in total time as crane operation times grow.

The graph below compares the total operation times across the three tests, based on the number of cranes used. It highlights the expected proportional increase in total time as crane operation times lengthen.

Figure 10. Comparison of Total Operation Time Across the Tests.



7. Conclusion

This study focused on analyzing and simulating the operations of a rail-road intermodal terminal, specifically the loading and unloading of semi-trailers onto railway platforms. The primary objective was to examine the key parameters that influence these operations when the terminal is utilized as part of a rail motorway system.

The simulation model was built using AnyLogic® software, which relies on a discrete-event system and agent-based simulation. The model was constructed using real data, including terminal infrastructure, equipment characteristics, and operational procedures. This realistic foundation allowed the results to be compared directly with actual terminal operations, supporting more informed decision-making.

After validating the simulation model, various analyses were conducted by adjusting the most critical operational parameters. The insights gained from these simulations provided a deeper understanding of how the system responds to disturbances or adverse conditions, helping improve forecasting and mitigate the risk of long-term operational issues.

The primary conclusion is that the overall process time is primarily determined by the crane loading and unloading times. This is because truck maneuvers, including coupling and uncoupling, are completed faster than the crane operations. Even if truck times were to increase unfavorably, it would not impact the total operation time as long as they remain within a certain threshold. This threshold is indicated by the trend line in Figure 8, which is based on the average time cranes take to load and unload semi-trailers in the specific scenario.

The main challenge encountered during the simulation was accurately representing real-world behaviors in a sequence of interconnected events. The variability in operation times and decision-making at each step—especially when conditions are similar—required the development of logic systems to resolve unforeseen situations and prevent system stalls. The terminal's large dimensions made it difficult to visually track every operation within the three-dimensional simulation, which was used to observe system behavior. Additionally, modeling unexpected disruptions or actions not initially accounted for in the simulation proved difficult, as the model operates under the assumption of ideal continuous behavior, albeit based on real-world conditions.

Future research will focus on refining the simulation models to account for potential disturbances and random events that may occur in reality. Incorporating these variables would produce a more accurate and reliable representation of real-world terminal operations.

8. References

1. Abourraja MN, Oudani M, Samiri MY, et al. (2018). "An improving agent-based engineering strategy for minimizing unproductive situations of cranes in a rail–rail transshipment yard". Simulation, 94(8), pp. 681–705 DOI: 10.1177/0037549717733050
2. Bartulović, D., Abramović, B., Brnjac, N., & Steiner, S. (2022). “Role of air freight transport in intermodal supply chains.” *Transportation Research Procedia*, 64: 119-127.
3. Boysen, N., Fliedner, M. y Kellner, M. (2010). "Determining fixed crane areas in rail–rail transshipment yards". Transportation Research Part E: Logistics and Transportation Review, 46(6), pp. 1005–1016 DOI: 10.1016/j.tre.2010.05.004
4. Camarero Orive, A., Parra Santiago, J. I., Díaz Gutiérrez, D., & De Manuel López, F. (2022). “Strategies to Develop the Use of 4R Intermodality as a Combination of Rail Motorways and Motorways of the Sea.” *Journal of Marine Science and Engineering*, 10 (7): 972.
5. Carboni, A., & Dalla Chiara, B. (2018). “Range of technical-economic competitiveness of rail-road combined transport.” *European Transport Research Review*, 10: 1-17.

6. Chang, Y., Zhu, X., Yan, B., & Wang, L. (2017). Integrated scheduling of handling operations in railway container terminals. Transportation Letters, 11(7), 402–412. https://doi.org/10.1080/19427867.2017.1374500

7. Chebotareva, E., Solop, I., Kurenkov, P., & Astafyev, A. (2022). "Development of the container transportation segment on the network Russian railways." *Transportation Research Procedia*, 63: 1708-1716.

8. Escobar, J., & Larrodé, E. (2021). "Analysis of the technical and operational capacity of a combined semi-trailer rail transport service between the port of Algeciras and Zaragoza." *Transportation Research Procedia*, 58: 377-384.

9. Hamimiche, S. (1998). "Consistency in rail investment choices the case of French "rail-motorway" socio-economic returns." *International Journal of Transport Economics / Rivista Internazionale Di Economia Dei Trasporti*, 25(3): 337-351.

10. Higginson, J., Hogan, T., & Weil, M. (1997). "Evaluating the demand for supergauge trucks-on-trains services in western Europe." *European Journal of Operational Research*, 97 (2): 293-307.

11. López-Navarro, M. Á. (2014). "Environmental factors and intermodal freight transportation: Analysis of the decision bases in the case of Spanish motorways of the Sea." *Sustainability*, 6 (3): 1544-1566.

12. Muravev, D., Hu, H., Rakhmangulov, A. y Mishkurov, P. (2021). "Multi-agent optimization of the intermodal terminal main parameters by using AnyLogic simulation platform: Case study on the Ningbo-Zhoushan Port". International Journal of Information Management, 57, pp. 102133 DOI: 10.1016/j.ijinfomgt.2020.102133

13. Vida, D. L., Illés, P. B., & Bányainé-Tóth, D. Á. (2023). "Logistics 4.0 in intermodal freight transport." *Procedia Computer Science*, 217: 31-40.

14. Woxenius, J., & Bergqvist, R. (2011). "Comparing maritime containers and semi-trailers in the context of hinterland transport by rail." *Journal of Transport Geography*, 19 (4): 680-688.

15. Sadeghi, M., Bagheri, M. y Mir, S.P. (2021). "Evaluation of rail terminals in container ports using simulation: A case study". Simulation, 97(12), pp. 809–820 DOI: 10.1177/00375497211024731

16. Tănăsuică, N. M. (2021). "Issues regarding the rolling highways." *Trans Motauto World*, 6(3): 96-103.