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Comparison and Evaluation of Different Types of Vehicles to Transport Containers within an Intermodal Terminal

Case study: Port of Barcelona

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ABSTRACT

Due to globalisation, transport policies have been changing and adapting to increase the demands and the needs of the market. Sea ports have a major role in the economic system in which they coordinate the transport of large volumes of cargo in long distances with a high level of productivity.

The growth of handling cargo has led to increase congestion in roads because roads are the most used method to transport goods between port and its hinterland. This is the reason why many West European ports are working with train terminals as an alternative form of transport.

As part of an intermodal case of study, we have focused on train terminal operations at the port of Barcelona, because currently there is not enough capacity, but it is expected to increase within the next ten years. Moreover, because of the limited geographical area, it is important to take in consideration the method for managing the logistics within the container terminal in Barcelona.

The objective of this study is to develop a model to analyse and evaluate different types of horizontal transport between the yard and the train terminal at the port of Barcelona in order to identify the most suitable transport system. We compare five different transport systems under three scenarios. The results indicate that some horizontal transport systems are more efficient than others.

ACKNOWLEDGEMENTS

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We especially thank our advisor in this research, Dr. Lawrence Henesey, for sharing with us his knowledge in the studied issue and for his kindness and his good sense of humour. In addition, Dr. Jan A. Persson gave us some ideas which helped us in the mode of starting the research.

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To our home university “Escola Tècnica Superior d’Enginyeria Industrial de Barcelona” of the “Universitat Politècnica de Catalunya” that was giving us during last five years the knowledge and the tools for developing this final project.

We appreciate the support of our friends who have taken an interest in our research and have made these months easier.

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1. INTRODUCTION

In last twenty years the global economic system has been changing due to globalisation. New production and transportation policies such as Just-In-Time, which is an inventory strategy implemented to improve the return on investment of a business by reducing in-process inventory and its associated costs, and intermodal transportation combined with out sourcing to countries with low cost have changed logistics patterns. Therefore, the concepts of logistics and transport have been taking a major role within the global market.

One of the main areas where intermodal transportation is performed is in terminals of ports, which function as nodes between links. Containers are used to transport various types of goods and are often handled in container terminals, which have special equipment for handling containers. The transport of containers has been increasing at ten percent each year during last twenty years [1]. So, the number of containers, which are handled in container terminals, has consequently increased to 360 million TEU per year (twenty-foot equivalent unit) [1]. We have decided to focus on this part of sea port due to the management problem to adapt the container terminal capacity to the new situation. A major function of container terminal managers is the efficient allocation of resources in terminal, such as cranes, workers and machines. The problem complexity increases with both the number of handled containers and the size of vessels.

On the one hand, a possibility to adapt container terminals to the demands is extending the terminal, but it is not always possible. Actually, the main ports in Europe have not enough space to extend. For instance, Antwerpen, Hamburg, Le Havre and Rotterdam have utilization rates for their container terminals over than ninety percent [1]. On the other hand, another possibility is improving the efficiency in container terminal, which means to minimize the service time employing the current available resources at the terminal. One method to improve the efficiency is to use automated handling systems like Automated Guided Vehicles (AGVs) and automated quay or yard cranes. But not always it is necessary to work with this type of equipment; sometimes manual vehicles can be useful. It depends on different factors such as cargo volumes, cost policies and social consequences. Of course, the layout of the terminal is also important to have in mind.

Container terminal has to be more flexible and reliable in order to satisfy constant market changes. Therefore, it is necessary to equip the intermodal terminal with dynamically re-configurable facilities. One way of managing container terminals is using Decision Support Systems that include optimisation and simulation tools.

This study is focused on the transport between yard and train terminal within a container terminal, due to the importance of connecting ports and terminals to inland or hinterland areas. Currently, there is a high congestion in roads. Part of this is due to the transport of goods by trucks. It has negative effects such as uncomfortable feeling in road customers and environmental effects. There are two ways to decrease congestion in roads. The first one is increasing transport of goods by train. It is something which Spanish companies are working because until now train transport has not been used so extensively. For instance, only between a two or three percent and no more than five percent of cargo in containers that arrive by ship leaves the port of Barcelona by train. And the last way but not least is the Short-Sea Shipping between main ports to secondary ports in the same geographical area, leading to increase the container traffic in terminals. Despite decreasing the road congestion, both train and Short-Sea Shipping have disadvantages because they are less flexible and require more loading and unloading, which increase costs and times.

Furthermore, in order to do intermodal changes as faster as possible, container terminals must have efficient equipment and managers must plan all the performance in terminal before arrivals of containers.

This study analyses the port of Barcelona [2], which is located in the most dynamic Spanish region for trade because it is considered to be the natural gateway for North-East of Spain (Catalonia).Also, it is a major entry point for all the Iberian Peninsula and the Western Mediterranean, particularly France. The port has been growing significantly in last fifteen years and the amount of cargo handled is increasing annually around ten percent. In year 2006, the port handled 45 million tonnes of cargo, which represents a growth of twelve percent relative to the previous year. Moreover, container traffic was about 2 million TEU, which means an increasing of eight percent relative to the previous year [2]. Currently, it has not enough capacity to satisfy all this demand. Due to that, it has reacted by extending and building a new container terminal of 93 hectares that is called “Prat Pier”. TERCAT [3], which works at the port since 1996 and is the busiest terminal operator of this port with a long and successful history, has recently been awarded the concession by the Barcelona Port Authority to manage the “Prat Pier Container Terminal”. Hutchison Ports Holding [4], which is a world leader in container terminal management, is working with TERCAT in order to develop the port of Barcelona as its principal gateway port in the West Mediterranean. The situation of the port is shown in Appendix 1.

In next chapter the background is explained, which explains the causes that motivate this research. Then, the scope of the research is presented in chapter 3 while the objectives that we want to obtain with this research are explained in chapter 4. Chapter 5 presents the research methodology that has been used in order to work in this study and it is followed by chapter 6 which consists of a literature review about container terminals and ways of working within them. The model description is presented in chapter 7 and in this part the layout of the intermodal terminal of the case of study, the entities in the model and different policies for operating in this terminal are explained. Then, in chapter 8 the design of experiment is described, which includes the presentation of possible scenarios, the method to calculate cycle times of all the equipment used in the analysed terminal, the experiment description to obtain waiting times and productivities of all the involved equipment and the cargo handling time to unload and load each train. Finally, in chapter 8 the performance criteria used in order to evaluate and compare the different studied alternatives in horizontal transport are also presented. Chapter 9 presents the analysis of the results, which is divided in two parts. The first one is the comparative analysis of each type of studied horizontal transport systems and different numbers of equipment in each type have been taken into consideration. And the second one is the comparative analysis of the studied types of horizontal transport, which considers only the most suitable options related to the number of equipment. Chapter 10 presents the costs analysis of these best options. Chapter 11 compares them. And finally, conclusions and future work are explained in chapter 12.

2. BACKGROUND OF THE THESIS

It is known that the demand for transporting goods has been increasing [1]. In long distances, ships are a good way of transport because they allow transporting high volumes of cargo with low cost and low environmental effects. This is the reason why the demand in sea ports is increasing every year.

There are plenty of multinational companies that need different ways of transport for their products because they sell them in different countries from where they have their factories. It leads to increase the demand of transport by ship. Once products arrive at their appropriate port, they have to change the mode of transport in order to arrive at their customers. Therefore, ports have become intermodal hubs, where changes of modes of transport are done.

When cargo arrives to the port, there are three possibilities to bring goods to the costumers. The first one is other type of vessel to another smaller port; this performance is called Short-Sea Shipping. The second one is the transport by road and the third one is to use the train. This choice depends on the type of good, the destination and the cost.

Another point to have in mind is the competitiveness between ports in the same geographical area. Currently, the main ports of West Europe compete each other in quality, efficiency and price because the main cargo ships, which travel on main maritime routes, only berth in ports with the best conditions such as high efficiency and low cost.

At this moment, the way of operating in quays is quite developed, so it means that it is not easy to compete in this aspect with the other ports. Actually, the way of increasing the number of customers, obtaining high benefits and becoming an important port is by improving the conditions in the hinterland. This means to have a complete transport network and efficient handling equipments in order to carry out intermodal changes.

Transport by road has been and is still the most used method to bring products to their costumers. However, at the same time it causes a lot of problems like congestion in roads and negative environmental effects. This is the reason why using trains is a suitable alternative.

The harbour railway enables the railway traffic companies to transport their goods to the vessel or the domestic market quickly and reliably and represents an indispensable element of the port infrastructure as well as a relevant pillar concerning the appeal of the universal port.

Some of the main ports in West Europe are developing the facilities in train terminals and are building an efficient rail network. For instance, the transhipment forecast for the port of Hamburg (Germany) also predicts double-digit growth rates for rail traffic, especially with regard to containers for the year 2015. Currently, 30% of the entire cargo handled at the port arrives or leaves the port by train [5]. Furthermore, in the port of Antwerp (Belgium) this percentage is approximately 15% [6] and in the port of Rotterdam (Holland) the percentage is about 12% [7]. However, in the port of Barcelona this utilisation rate is only 3% [8].

We have focused on the port of Barcelona [2]. Currently, it is difficult to increase the traffic of cargo by train due to the fact that there is not enough capacity to transport cargo and passengers at the same time. There is an important congestion. Furthermore, the transport of passenger is prioritised and considered more important than transport of cargo. So, the time needed to transport goods is quite long. For instance, currently an average number of three or four days are necessary to bring cargo from Barcelona to Madrid while the same route by road takes only about ten hours [8]. Because of the transport by rail is not competitive with the road, at this moment the majority of land transport is done by road.

This situation is expected to be changed in next years because Spanish Government is building a new fast speed rail network (AVE). It will be used only for transporting passenger, so the actual rail network will be more available to transport cargo. Furthermore, the opening in the market of railway sector is being done. With these two facts, an increase of capacity in transport of cargo by rail is expected.

The port of Barcelona is doing a lot of projects with regard to adapt its systems and equipments to this new situation. The capacity of the port is expanding with news areas such as “Prat Pier”. It has a train terminal with high capacity inside. Project managers of TERCAT [3], which is the company that will manage the new pier at the port, expect to increase the transport by train from the current 3% to 15%, or if it is possible 25% [8] in next fifteen or twenty years in relation to the containers that arrive or leave the port by train of the total handled containers within the port.

Figure 2-1 shows the layout of the port of Barcelona and indicates the place where is situated the container terminal called “Prat Pier” and the actual terminal managed by TERCAT.

Figure 2-1: Layout of the Port of Barcelona[1]
Source: http://www.apb.es, “Autoridad Portuaria de Barcelona”.

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[1] Figure 2-1 is enlarged in Appendix 2.

3. SCOPE OF THE RESEARCH

The study is focused on the rail terminal at the port of Barcelona [2]. To be precise, we focus on the transport of containers between rail and yard area in a new container terminal, called “Prat Pier”. It is expected that it will start to operate during year 2009. Therefore, at this moment, managers of the port are planning all the performance of the new terminal.

We have focused on the link between rail terminal and yard for two reasons:

- The first one is that an increase in the transportation of cargo by train is expected in Spain. Currently, rail transport is not common but it is necessary in order to improve the transport of goods taking in consideration the fact that there is a concern of the congestion in Spanish roads, especially near the main cities such as Madrid and Barcelona.

- A lot of research has been done regarding ways of unloading cargo from vessels and different types of transport between quay and yard. Currently, most of West-European ports are working in improving the productivity of equipment and resources used in rail terminal in order to find the most efficient way to unload and load trains and to transport all containers between yard and rail terminal.

This research is focused on the port of Barcelona because it has been growing significantly in the last fifteen years, and it is forecasted that this growth will continue for the next fifteen or twenty years. This is the reason why this port is increasing its capacity building a new terminal.

4. OBJECTIVE OF THE RESEARCH

The objective of this study is to analyse and compare the performance of different methods to transport containers between rail terminal and yard in the new container terminal “Prat Pier” at the port of Barcelona.

It is our aim to model and represent the process of selecting terminal equipments for the transport between rail terminal and yard including the choice of the type of vehicle and the number of vehicles used in the studied area.

The study presents five possible options in the horizontal transport in the studied area:

1. Truck.
2. Automated Guided Vehicle (AGV).
3. Shuttle Carrier (SC).
4. Truck and Cassette.
5. Automated Guided Vehicle and Cassette.

We compare the performance of the different transport equipment explained above by considering some parameters such as productivity and cost of all equipments involved in the studied area (rail crane, yard crane and vehicle). Also, the necessary time to unload and load a train is considered. The goal is to choose the most suitable equipment to transport containers with a high efficiency.

5. RESEARCH METHODOLOGY

In order to analyse the performance of the container terminal at the port of Barcelona, we have followed a strategy employing three different methods. These methods are explained as follow:

5.1. Literature Review

This method consists of doing a review of journals, periodicals, specialized books, conference papers and other research publications related to the subject area. At the beginning of this research, the literature review was the best way to understand the performance and the way of working in a container terminal within a sea port. We analysed the-state-of-the-art of the optimisation and simulation tools used to planning the performance and resources allocation in an intermodal terminal with a high level of efficiency. This review helped us to understand how all the equipments employed in a container terminal work and the different ways to model, optimise and simulate the performance of all these equipments.

5.2. Interviews

This method consists of discussing about the subject area with the staff at the port, leading us to have feedback from people experienced in that area. In the case of this study, it was necessary to get some specific data related to the port, such as forecasted demands, lay-out of the terminal, work timetable, cargo characteristics, ways of operating in the terminal and costs. We obtained most of this data from Jorge Moreno, a project manager of TERCAT at the port of Barcelona.

5.3. Modelling

First of all, three different scenarios have been considered in the study and we have calculated the threshold time to unload and load a train for each scenario. Considering the most suitable policy for operating, this method consists of making a model in order to obtain cycle times, waiting times, productivities of cranes and vehicles as well as cargo handling time to unload and load a train. Then, we have done a cost analysis. Finally, it is possible to analyse and compare the results of the different transport systems in order to help to choose the most suitable option for the horizontal transport between the rail terminal and the yard of “Prat Pier” at the port of Barcelona. The tool which has been used to do all calculations is an Excel worksheet.

6. LITERATURE REVIEW

First of all, we have initially contacted the port of Barcelona due to the fact that our study is placed there. In the port of Barcelona web page [2] there are a lot of information such as the container traffic, the type of handling equipment used in container terminals, the statistics and the results of the last year 2006. Another documents to take into account are the related to forecasts the demands and the container terminal enlargement.

Additionally, we have surveyed several reports and scientific articles about logistics in sea ports and intermodal terminals, and various ways of improving productivity and capacity using simulation and optimisation tools without employing additional resources. We present our literature review in this section.

Henesey [1] describes multi-agent systems for container terminal management in his PhD thesis. He introduces the subject of container terminals by explaining the actual growth in container traffic in sea ports and its negative effects, like congestion. On the one hand, he proposes to extend the container terminal area and on the other hand, he proposes to increase the productivity in container terminal using a computer-based support for management decision making as well as automation. Then, he reviews the current documents about the thesis subject. He develops a simulation model capable to represent the real behaviour of container terminal, which is called Simport. Finally, he uses this model to compare and evaluate two Automated Guided Vehicle Systems (AGVs) in a container terminal. One of them is a traditional AGV and the other is an AGV which works with cassette.

An anonymous person from the World Trade [9] published an article about how make America’s blue water ports more efficient. It is focused on transport system in intermodal terminals to get more productivity and to continue the economic prosperity. The growth of productivity in these terminals is important for decreasing the congestion in roads, and its negative environmental effects. Some ideas to increase the productivity in sea ports are: making harbour trucking a profitable business, operating ports during extended hours and developing methods to collect cargo information and sharing it with all the customers in the terminal.

Mbiydzenyuy [10] developed an optimisation model for sea port equipment configuration. In his Master thesis, he explains the information and communication technology used in port terminals, the different categorisations of handling systems and finally, a description of some handling equipments (automated and non-automated). With the information and communication system, terminal managers can obtain the inputs to run optimisation and simulation programs. The outputs are the resources allocation, including handling systems and the movement planning in a container terminal.

Kosowski and Persson [11] investigated in their Master thesis the development and evaluation of dispatching strategies for the IPSI ^{TM} AGV system. They improve the current programs including the use of cassettes. They classify AGVs and explain their way of operating. Then, they describe the dispatching problem with the flow path layout and the vehicle requirements in order to minimize the cost related to the time, distance and priority. And finally, they explain the simulation model used and the results obtained with it.

Degano et al. [12] worked in the modelling automated material handling in intermodal terminals. They emphasize that globalisation have caused new tends in the actual economic system like Just in Time and intermodal transportation. To execute these new policies, transport takes an important role in the logistics chain. To increase the productivity in the intermodal terminal, it is important to plan all the movements and actions, so they have modelled the transport system within the terminal to obtain a flexible and reactive system. They propose a Petri-net model in order to regulate the terminal behaviour in both regular and faulty situations. In the case of faulty situations, they highlight the importance of the timeliness in all the process, this is the reason why they develop a system to detect disturbances of the “nominal” functioning (the functioning planned with Petri-net) and apply regulation policies to minimize the delay propagation and the cost associated with.

Vis [13] analysed the performance of two types of container storage and retrieval system, such as manned straddle carriers and automated stacking cranes, at a container terminal. Simulation and analytical tools have been used in order to do this analysis.

Vis et al. [14] developed a liner algorithm that it is used to minimize the number of transport equipment required to move containers between stacks and quay crane.

Corry and Kozan [15] wrote an article about an assignment model for dynamic load planning of intermodal trains. This model minimizes the double handling of containers, the excess of travel in order to load the train and optimises the weight distribution in the train. First of all, a dynamic model is used to solve the Load Planning Problem (LPP) with the arrivals randomly generated. Then, this model is simulated with a simplified version and within more realistic scenario. Finally, a static model with these simulated results as inputs is used to find the optimal solution.

Gambardella et al. [16] show the use of optimisation and simulation as a decision support tools in the management of a real world intermodal terminal. It is focused on the problem of the allocation of resources. It was examined as a part of a case studied in a port of Italy, La Spezia, where the lack of space in the yard is a critical issue. In this model, the arrivals by statistical distributions were known in advance.

Parola and Sciomachen [17] wrote a report about the intermodal container flow in a port system network. They analyse the possible growths via simulation models of two ports: Genoa and La Spezia, both of them in Italy. Three different scenarios were simulated with WITNESS 2000 by assuming the traffic growth in the time period 2002-2012. They compare the percentage of containers that leave the port by train and by road.

Rida et al. [18] wrote a report about calibration and validation of container terminal simulation. Simulation tools are suitable to improve the management of container terminal helping the managers to evaluate alternatives management policies. Before using a simulator, it is necessary to calibrate and validate this one to be sure that the model is able to represent the container terminals behaviour. This study presents a process to do this calibration, which consists on executing the simulator with the policies used at the moment with real variables as inputs, and checking that the simulator outputs are close to the reality.

Finally, in order to develop the model, which represents the behaviour of the equipment used in the studied intermodal terminal, it has been used queuing theories that Amaia Lusa [19] from ETSEIB (Universitat Politècnica de Catalunya) has provided us.

7. MODEL DESCRIPTION

The objective of this analytical model is to compare the performance of different types of horizontal transport systems in a container terminal. In addition, this study analyzes advantages and disadvantages of using cassettes with some of these vehicles.

Three types of vehicles without cassettes are studied:

1. Truck
2. AGV
3. Shuttle carrier

And two types of vehicles with cassettes are studied:

1. Truck with cassette
2. AGV with cassette

The explanation about model description is organized as follow. First, we present the layout of the "Prat Pier". Second, the equipments involved in the studied process are explained. Third, four different possible policies for operating in the intermodal terminal are presented.

7.1. Layout of the Intermodal Terminal

The intermodal terminal consists of rail, yard and connection area. This scenario is represented in Figure 7-1.

At the same time, the rail area is composed of eight rails of Iberian width (1676mm), one to three Rail Mounted Gantry cranes (RMG rail cranes), a stacked area next to the rails, which is used to store the prepared cargo, and the area behind the crane where vehicles arrive to be loaded or unloaded by rail cranes.

The yard area consists of a group of yard stacks, each of them with a Rail Mounted Gantry crane (RMG yard crane), and a transfer point, where vehicles arrive and are unloaded or loaded by the crane.

The layout of intermodal terminal in the "Prat Pier" at the port of Barcelona is enclosed in Appendix 3.

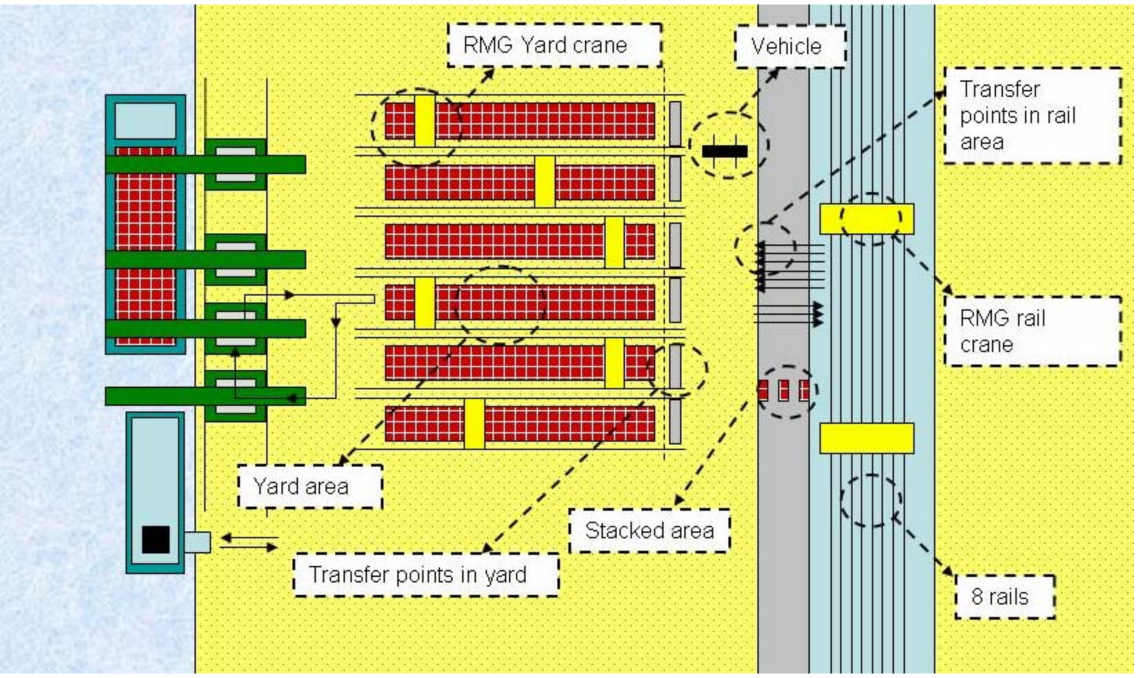

Figure 7-1: Model of Intermodal Terminal
Source: Modified from PhD of L. Henesey, “Multi-Agent Systems for Container Terminal Management”.

7.2. Entities in the Model

The modelled entities are the following:

- *Train:* containers arrive or leave port by train in the intermodal terminal. Each train contains 60 TEU, which 45% are containers of 20’ and 55% are containers of 40’ [8].

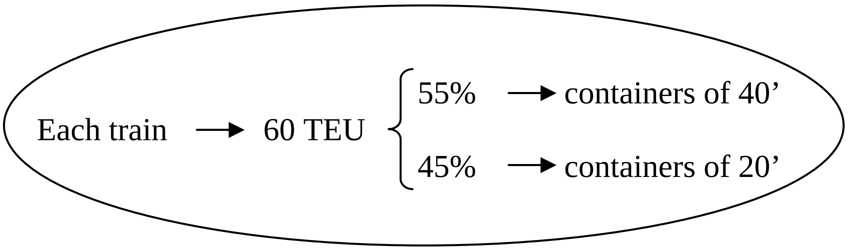

Figure 7-2: Proportion of Containers of 20’ and 40’ in each Train

- *RMG rail crane:* its function is to unload and load containers in a train terminal. An example of RMG rail crane is shown in Figure 7-3. The characteristics of RMG rail crane used in the studied intermodal terminal are the followings:

    1. Total length = 27 m
    2. Combined load handling area = 15 m (five containers in parallel)
    3. Total height = 24,6 m

4. Lifting height = 12 m
5. Weight ~ 500 t
6. Gantry travel speed = 2 m/s
7. Trolley travel speed = 2 m/s
8. Lifting speed = 1 m/s

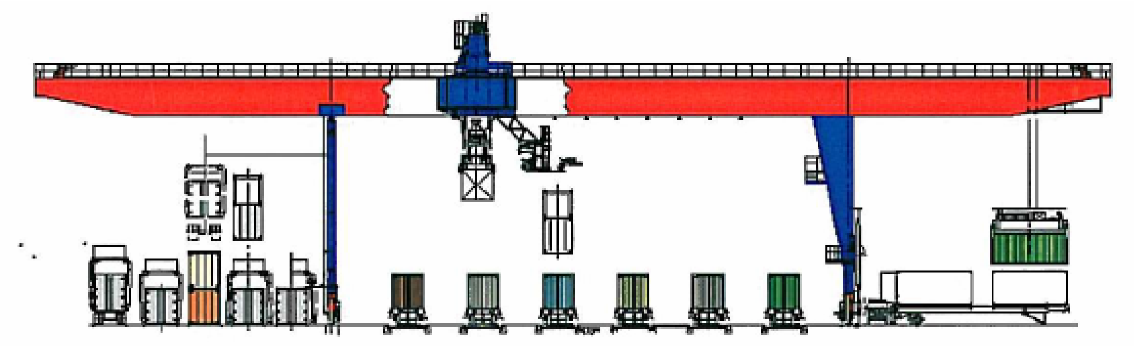

Figure 7-3: RMG Rail Crane
Source: Jorge Moreno, TERCAT.

- *Yard:* is the part of intermodal terminal where all handled containers are stored between their arrival and their leaving time. As follow, an example of yard area is shown.

Figure 7-4: Yard Area in an Intermodal Terminal
Source: http://www.jwdgroup.com, "JWD Group".

- *RMG yard crane:* its function is to unload and load containers in the transfer point of the storage area. An example of RMG yard crane is shown in Figure 7-5. The characteristics of RMG yard crane used in the studied intermodal terminal are the followings:

1. Total length = 320 m
2. 5 containers in height, which are stacked one upon the other
3. 10 containers wide
4. Gantry travel speed = 1,833 m/s
5. Lifting speed = 1 m/s

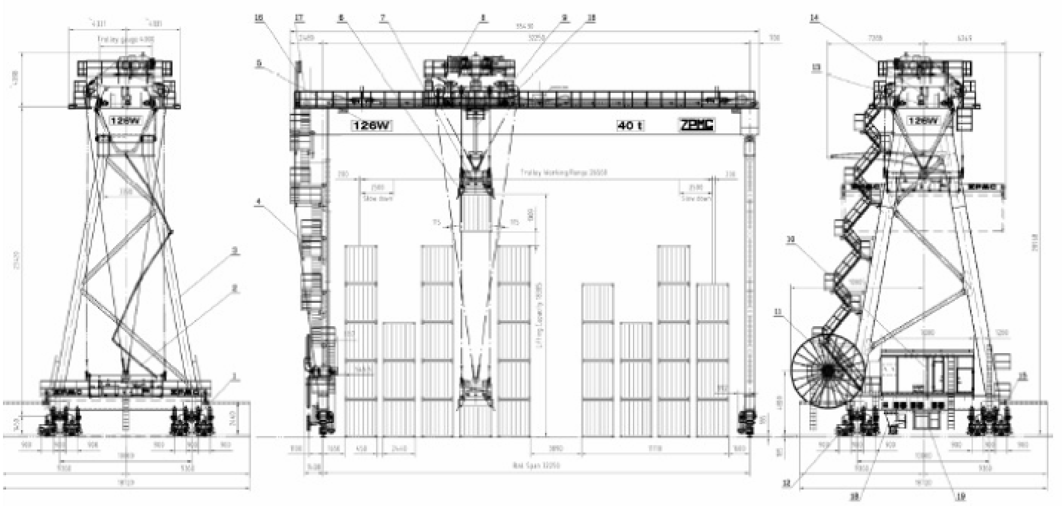

Figure 7-5: RMG Yard Crane
Source: Jorge Moreno, TERCAT.

- *Truck:* is the first analysed option as horizontal transport between rail and yard area. It is assumed that its average speed is 30km/h. They can use cassettes to transport containers. An example of trucks with trailer, which are loaded with containers, is shown in Figure 7-6.

Figure 7-6: Truck with Trailer
Source: http://www.tts-marine.no, “TTS Group”.

- *Automated Guided Vehicle (AGV):* is the second analysed option as horizontal transport. It is assumed that its average speed is 6 m/s. In addition, they can use cassettes to transport containers. An example of AGV is shown in Figure 7-7.

Figure 7-7: T-AGV
Source: http://www.tts-marine.no, "TTS Group".

In relation to the number of containers loaded onto vehicles two options have been considered. The first one is that only one container can be loaded onto each vehicle and the second is that each vehicle can transport one container of 40' or two containers of 20'.

- *Shuttle carrier (SC):* is the third analysed option as horizontal transport. An example of SC is shown in Figure 7-8. It is assumed that its average speed is 30km/h. It can transport two container of 20' or 40'.

Figure 7-8: Shuttle Carrier
Source: http://www.jwdgroup.com, "JWD Group".

- *Cassette:* the fourth option analysed in this study is a system that consists of a truck with a cassette and the fifth one consists of an AGV with a cassette. The cassette improves the transport system because it can store the containers that have been transported to yard or to rail area while they are waiting to be handled by cranes.

Figure 7-9: Cassette
Source: http://www.tts-marine.no, "TTS Group".

The necessary times to connect and disconnect a vehicle from its cassette are the followings:

1. Time to connect = 10 s
2. Time to lift the cassette = 15 s
3. Time to descend the cassette = 9 s
4. Time to disconnect = 10 s

Two options have been considered for the number of containers that are loaded onto cassettes. The first one is that only one container is loaded onto each cassette and, the second one is that the cassette can be loaded with two containers of 40' or with four containers of 20'.

An example of truck with cassette is shown in Figure 7-10 and an example of AGV with cassette is shown in Figure 7-11.

Figure 7-10: Truck with Cassette with Two Containers of 40’ One upon the Other
Source: http://www.tts-marine.no, “TTS Group”.

Figure 7-11: IPSI AGV with Cassette with Two Containers of 40’ One upon the Other
Source: http://www.tts-marine.no, “TTS Group”.

- *Containers:* is the method to consolidate goods that are stored inside to be handled in a container terminal. There are two standard sizes of containers, which are 20’ and 40’. As follow, the dimensions of the standard containers are presented.

    1. Container width = 8’ or 2,44 m
    2. Container height = 8,49’ or 2,59 m
    3. Container length (20’) = 20’ or 6,096 m
    4. Container length (40’) = 40’ or 12,192 m

7.3. Policies for Operating

There are four options for managing the logistics in the new intermodal terminal called "Prat Pier" at the port of Barcelona. The choice of the best option depends on the criteria of managers, which refers to the relevant factors for them such as cost, productivity, efficiency or available space. However, the best study includes all these factors at the same time, in order to find a suitable option. It is important to decide the necessary number of equipments in order to minimize both waiting times and cost.

In this case, four options are possible [8]. Each of them refers to different methods of unloading and loading. These options are presented as follow.

1. *Loading and unloading when train arrives*: this policy does not prepare containers in the platform next to the railway before the train arrives, otherwise when a vehicle, which is loaded with a container from the yard, arrives to the combined load handling area the rail crane picks up the container and places it onto the ground. Then, the available vehicle is loaded with a container from the train by rail crane and travels to a transfer point in the yard. There, the yard crane picks up the container from the vehicle and places it into the suitable position in the yard. After that, the vehicle is loaded with a container from the yard and travels to the combined load handling area again. Therefore, the vehicle travels always loaded with a container. On the other hand, rail crane prioritises unloading of the train, if there is an available vehicle in the cargo handling area, instead of loading train with containers from the ground. So, rail crane choose in each moment the suitable operation of loading or unloading the train. This is the reason why important equipment is necessary in order to minimize waiting times and avoiding problems. This policy could be the best according to minimize cycle times in case of all equipments work correctly. Even so, it requires a major number of equipment and a higher level of coordination between them than the others policies. So, the investment in the terminal could be higher than in the other options.

2. *Preparation of cargo on the ground, unloading when the train arrives directly onto a vehicle and then loading cargo onto the train*: this policy consists of preparing containers on the ground in the combined load handling area next to the railway before the train arrives. First, all containers from the train are unloaded onto vehicles and then train is loaded with containers that were prepared on the ground. Therefore, vehicles only are used for preparing cargo and for unloading train. So, each vehicle travels loaded with a container along one direction and with no container in the other direction. This policy could be suitable when there is enough time to prepare containers next to the railway before the train arrives in order to minimize waiting time for this train. In this case, the decision of the necessary number of vehicles is very important.

3. *Unloading onto the ground and loading when the train arrives directly from a vehicle*: this policy is the opposite of the one described above. It means vehicles are used only for loading trains and for transferring containers to the yard. So, each vehicle also travels loaded with a container along one direction and with no container in the other. First of all, rail crane unloads train by placing containers onto the ground. As in the policy described previously, is suitable if there is enough time

for vehicles to transfer all containers, which are unloaded onto the ground, to the yard. In this policy, it is also important to decide the number of vehicles.

4. *Preparation of cargo on the ground, unloading onto the ground and loading onto the train*: this policy consists of preparing all containers on the ground before the train arrives and unloading containers from the train onto the ground when train arrives. Therefore, in this case no vehicle is used when the train is in the intermodal terminal. Clearly, this policy requires large space in combined load handling area next to the railway and it is not always possible. Moreover, it could cause problems when more than one train arrives at the same time in case of lack of space.

In this study, all calculations are done considering the second policy but the results can be used in the third policy as well due to the fact that the third policy is the opposite of the second. Furthermore, the first policy is not studied in this research because on the one hand, it is suitable for a high level of demand. Despite that the demand in the rail terminal at the port of Barcelona is increasing, it is not expected to achieve so high level until twenty years. On the other hand, it is necessary a good coordination and high technological equipments in order to work in this way and all these equipments lead to an increase of the investment. Related to the fourth policy, it has not been included in this research because it requires large amount of space next to the railway area to temporarily store all containers that will be loaded on the train and the containers that have been unloaded from the train. In addition, we consider it is not a good policy because the vehicles do not work when the train is in the terminal, so more time is needed to do all these processes.

8. DESIGN OF EXPERIMENT

The explanation about the design of experiment is organized as follow. First, we identify three possible scenarios considering different levels of demand in the terminal. Second, we explain how we have calculated cycle times of all systems involved in the process. Finally, the performance criteria that are used to evaluate and compare the different analyzed options are presented.

8.1. Possible Scenarios

As it is explained before, the objective of this research is to evaluate the use of different horizontal transport systems in the new intermodal terminal of the port of Barcelona in order to help managers to choose the most suitable system to do the horizontal transport between rail and yard area. It is necessary to evaluate the different options in real scenarios in order to obtain these results.

In this case, the studied terminal "Prat Pier" has not started to work yet. It is forecasted that it will start to work during year 2009. Therefore, the studied scenarios are based on different forecasts that have been done by managers of the port of Barcelona.

Three different scenarios have been considered. The first one is related to a low utilisation, the second one is related to middle utilisation and the last one is related to a high utilisation. Each of them refers to different periods of time in the terminal because it is expected an increase of cargo that arrives or leaves the port by train in the next years. Therefore, the scenario with low utilisation refers to the first years of operation and the scenario with high utilisation refers to a period of time when the terminal will be working at its maximum capacity. The second scenario refers to a period of time between the beginning and the maximum stability.

The assumptions that have been considered in order to calculate the suitable number of rail cranes and the cargo handling time for each train (considering load and unload) are:

- All trains, which come to terminal, unload and load containers.
- Each train transports 60 TEU.
- The terminal works 365 days per year and 24 hours per day.
- It is possible to have one, two or three RMG rail cranes.

It is expected that total demand in the "Prat Pier" will be about 3 million TEU per year [8]. With this data and the forecast regarding the growth of the port, the next options are considered as possible scenarios:

- *Low utilisation*: it assumes that 5% of total demand in the "Prat Pier" arrives or leaves the port by train. Therefore, the demand in the intermodal terminal will be 150.000 TEU per year or 417 TEU per day. It means three or four trains arrive and leave the terminal every day. The results of the threshold time are shown in Table 8-2.

- *Middle utilisation*: it assumes that 15% of total demand in the "Prat Pier" arrives or leaves the port by train. Therefore, the demand in the intermodal terminal will be 450.000 TEU per year or 1.250 TEU per day. It means ten or eleven trains arrive and leave the terminal every day. The results of the threshold time are shown in Table 8-2.

- *High utilisation*: it assumes that 25% of total demand in the "Prat Pier" arrives or leaves the port by train. Therefore, the demand in the intermodal terminal will be 750.000 TEU per year or 2.083 TEU per day. It means seventeen or eighteen trains arrive and leave the terminal every day. The results of the threshold time are shown in Table 8-2.

Table 8-1: Information about Scenarios

Scenarios	Percentage of demand	Demand in intermodal terminal (TEU/year)	Demand in intermodal terminal (TEU/day)
1. Low utilisation	5%	150.000	417
2. Middle utilisation	15%	450.000	1.250
3. High utilisation	25%	750.000	2.083

Table 8-2: Threshold Time according to the Number of Trains Handled every Day

Scenarios	Number of trains handled per day	Probability	Threshold time (hours)
1. Low utilisation	3	52,778%	8
	4	47,222%	6
2. Middle utilisation	10	58,333%	2,400
	11	41,667%	2,182
3. High utilisation	17	63,889%	1,412
	18	36,111%	1,333

8.2. Cycle Times

The first step to analyse the performance of the different equipments within the studied intermodal terminal is to calculate the cycle times of all the equipments involved in it. In this case, we have studied two types of cranes. The first one is a rail crane and the second one is a yard crane. We have considered five options as horizontal transport. They are truck, AGV, shuttle carrier, truck with cassette and AGV with cassette.

Calculations have been done with the assumptions of the second policy presented in point 7.3. of this report.

Furthermore, it is assumed that all cranes and vehicles move with constant speed. Therefore, any kind of acceleration is not considered.

Now, the method that has been used to obtain the cycle times of all these systems is presented.

8.2.1. RMG Rail Crane

For RMG rail crane, next actions are considered as a cycle time:

1. *Gantry travel*: rail crane travels from a container to the next suitable container on the train to handle it. In order to calculate the mean value and the standard deviation, seven options are considered for the gantry travel, which are shown in Table 8-3. The second column of it represents the initial position of rail crane on the train, the third column is the next position and the last column indicates if movement is between containers of the same or next wagon. Only the next wagon is considered because the train is unloaded from first wagon to the last one. It is assumed that a 45% of containers are of 20’ and a 55% are of 40’ in trains [8].

   Table 8-3: Possible Movements of Gantry Travel

Option	From	To	Wagon
1	20'	20'	Same wagon
2	20'	20'	Different wagon
3	20'	40'	Same wagon
4	20 '	40'	Different wagon
5	40'	20'	Same wagon
6	40'	20'	Different wagon
7	40'	40'	Different wagon

2. *Lifting time*: rail crane picks up a container from a train. This time is a constant value because lifting height is constant as well. Therefore, the standard deviation is zero.

3. *Trolley travel*: rail crane loaded with a container moves to the combined load handling area in order to unload the container. The mean value and the standard deviation have been calculated considering on the one hand, five possible parallel positions in combined handling area next to the railway with the same probability and on the other hand, eight rails, with the assumption of giving more importance to four rails near to the combined handling area.

4. *Lifting time*: rail crane unloads the container on a horizontal transport system. This time is a constant value because lifting height is constant as well.

5. *Trolley travel*: crane comes back to train without any container. The values of mean and standard deviation are the same than in trolley travel with container (point 3).

Table 8-4: Values of RMG Rail Crane Cycle Time

Operation	Mean value (s)	Standard deviation (s)
1. Gantry travel	4,668	0,987
2. Lifting time (unload train)	16,820	0,000
3. Trolley travel (with a container)	9,150	5,585
4. Lifting time (load on a vehicle)	17,820	0,000
5. Trolley travel (without a container)	9,150	5,585
TOTAL	57,608	12,157

8.2.2. RMG Yard Crane

Next actions are considered in RMG yard crane cycle time:

1. *Lifting time*: yard crane picks up a container from a horizontal transport system.

2. *Travel from transfer point to the yard*: yard crane, which has picked the container, moves to a suitable position in the yard in order to unload the container and stack it. The mean value and the standard deviation have been calculated considering the same probability in unloading a container in each possible position in the first half of yard. It is assumed that the second half does not stack containers that have been transported by train or have to be transported by train.

3. *Lifting time*: yard crane unloads the container in a suitable position in the yard. In order to calculate the mean value and the standard deviation, it is considered the same probability in unloading a container in each possible position in the stack.

4. *Travel to transfer point*: yard crane comes back to transfer point without any container. The values of mean and standard deviation are the same as in travel with a container (point 2).

Table 8-5: Values of RMG Yard Crane Cycle Time

Operation	Mean value (s)	Standard deviation (s)
1. Lifting time (unload vehicle)	21,447	0,000
2. Travel from transfer point to yard	43,636	24,911
3. Lifting time (unload in yard)	12,087	7,326
4. Travel to transfer point	43,636	24,911
TOTAL	120,806	57,148

One observes that there is an important difference between rail crane and yard crane cycle times. In calculation of yard crane cycle time, the trolley travel is not considered due to the fact that this time is shorter than gantry travel time. Trolley travel distance is quite shorter, so it is assumed that yard crane can do both travels at the same time. This is the reason why only the longest travel time is considered in yard crane cycle time.

8.2.3. Vehicles without Cassette (Truck and AGV)

The vehicles included in this section are truck and AGV. Containers are loaded directly onto a vehicle without using a cassette. The speed of these types of vehicles is listed in Table 8-6.

Table 8-6: Values of Speed that are Used to Calculate Cycle Times

	Speed (m/s)
Truck	8,333
AGV	6,000

In order to obtain the cycle time for each vehicle, the following actions are considered:

1. *Load vehicle*: a container from a train is loaded onto a vehicle by rail crane. It means that the vehicle has to wait to be loaded while the spreader of rail crane is descending. Therefore, one constant lifting time of rail crane is considered in case that vehicle is loaded with one container of 40’ or of 20’. In case that the vehicle is loaded with more than one container, the cycle time of rail crane is also added because the vehicle has to wait the second container. Calculations have been done considering both possibilities. These values are shown in Tables 8-8, 8-9, 8-10 and 8-11.

2. *Travel from the rail area to the yard*: a vehicle that is loaded with a container travels from the rail to the yard area. The method that has been used to calculate the cycle time is first to obtain the distance between both areas and then to calculate the cycle time for each type of vehicle using their speed. The entire intermodal terminal has been divided in three parts, which are called platforms a, b and c. At the same time, each of these platforms is composed of three areas: rail, yard and connection area. It is assumed that there is not exchange of containers between the three platforms. Moreover, there are three possibilities of working in rail area. It means that it is possible to handle a train with one, two or three rail cranes working at the same time. Therefore, it is important to separate the study in these three possibilities. In order to calculate the mean value and the standard deviation, it is assigned an importance factor, which is expressed in percentage, in each platform and depends on the number of rail cranes used. These percentages are shown in Table 8-7.

Table 8-7: Importance of each Platform in Case of Using One, Two or Three Rail Cranes

PERCENTAGES	one rail crane	two rail cranes	three rail cranes
a	15%	25%	33%
b	75%	55%	34%
c	10%	20%	33%

3. *Unload vehicle*: a container is unloaded from a vehicle by yard crane. It means that the vehicle has to wait to be unloaded while the spreader of yard crane is descending. Therefore, one constant lifting time of yard crane is considered in the case that vehicle is unloaded with one container of 40’ or 20’. In the other case, when the vehicle is unloaded with one container of 40’ or two of 20’, cycle time of yard crane is also considered. These values are shown in Table 8-8, 8-9, 8-10 and 8-11.

4. *Travel from the yard to the rail area*: vehicle travels with no container from the yard to the rail area. The distance travelled by vehicles is the same as the travel from rail area to yard.

Table 8-8: Cycle Time of Truck Loaded with One Container of 40’ or 20’

	One rail crane		Two rail cranes		Three rail cranes	
Operation	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)
1. Load vehicle from train	8,910	0,000	8,910	0,000	8,910	0,000
2. Travel from rail to yard	44,809	18,592	45,215	18,123	45,381	17,641
3. Unload vehicle	10,723	0,000	10,723	0,000	10,723	0,000
4. Travel from yard to rail	44,809	18,592	45,215	18,123	45,381	17,641
TOTAL	109,252	37,184	110,063	36,245	110,395	35,281

Table 8-9: Cycle Time of AGV Loaded with One Container of 40’ or 20’

	One rail crane		Two rail cranes		Three rail cranes	
Operation	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)
1. Load vehicle from train	8,910	0,000	8,910	0,000	8,910	0,000
2. Travel from rail to yard	62,235	25,822	62,799	25,170	63,029	24,501
3. Unload vehicle	10,723	0,000	10,723	0,000	10,723	0,000
4. Travel from yard to rail	62,235	25,822	62,799	25,170	63,029	24,501
TOTAL	144,103	51,645	145,231	50,340	145,691	49,002

Table 8-10: Cycle Time of Truck Loaded with One Container of 40’ or Two of 20’

	One rail crane		Two rail cranes		Three rail cranes	
Operation	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)
1. Load vehicle from train	34,833	5,471	34,833	5,471	34,833	5,471
2. Travel from rail to yard	44,809	18,592	45,215	18,123	45,381	17,641
3. Unload vehicle	65,086	25,716	65,086	25,716	65,086	25,716
4. Travel from yard to rail	44,809	18,592	45,215	18,123	45,381	17,641
TOTAL	189,538	68,371	190,350	67,432	190,681	66,468

Table 8-11: Cycle Time of AGV Loaded with One Container of 40’ or Two of 20’

	One rail crane		Two rail cranes		Three rail cranes	
Operation	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)
1. Load vehicle from train	34,833	5,471	34,833	5,471	34,833	5,471
2. Travel from rail to yard	62,235	25,822	62,799	25,170	63,029	24,501
3. Unload vehicle	65,086	25,716	65,086	25,716	65,086	25,716
4. Travel from yard to rail	62,235	25,822	62,799	25,170	63,029	24,501
TOTAL	224,389	82,832	225,517	81,527	225,977	80,189

8.2.4. Shuttle Carrier

In order to obtain the cycle time, the followed actions are considered:

1. *Load vehicle*: in this case, rail crane picks up a container from a train and leaves it onto the ground. When a shuttle carrier is available, it picks up two containers from the ground and transports them to the yard. Therefore, the time considered to load containers on shuttle carrier is the time in which the shuttle carrier picks up two containers from the ground. There are two possibilities to calculate this time, the first one is to pick up a full container and the second is to pick up an empty container. The lifting time in case of full container is longer. A probability of 80% to pick up a full container is considered. The results are shown in Table 8-12.

2. *Travel from the rail area to the yard*: shuttle carrier travels with the containers from the rail area to the yard. The method that has been used to calculate the cycle time is

the similar to the case of vehicles with cassette. But now, the speed of shuttle carrier is 8,3m/s. Mean value and standard deviation for one, two and three rail cranes are shown in Table 8-12.

3. *Unload vehicle*: in this case, shuttle carrier unloads the containers leaving them onto the ground. Then, when yard crane is available it picks up the containers from the ground and leaves them into the suitable positions in the yard. Therefore, the time considered to unload the containers from shuttle carrier is the time in which shuttle carrier leaves them onto the ground. The time to unload a shuttle carrier is the same as loading it. So, the results are shown in Table 8-12.

4. *Travel from the yard to the rail area*: shuttle carrier travels with no container from the yard to the rail area. The distance travelled by shuttle carrier is the same as in the travel from the rail area to the yard. Table 8-12 shows the values of shuttle carrier travel times for each situation.

Table 8-12: Values of Shuttle Carrier Cycle Time

	One rail crane		Two rail cranes		Three rail cranes	
Operation	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)
1. Load vehicle from train	26,400	0,000	26,400	0,000	26,400	0,000
2. Travel from rail to yard	44,809	18,592	45,215	18,123	45,381	17,641
3. Unload vehicle	26,400	0,000	26,400	0,000	26,400	0,000
4. Travel from yard to rail	44,809	18,592	45,215	18,123	45,381	17,641
TOTAL	142,418	37,184	143,230	36,245	143,561	35,281

8.2.5. Vehicles with Cassette (Truck and AGV)

In this case cycle time for truck and AGV are different from the cases of vehicles without cassette. Travel time is the same but now the vehicle does not have to wait to be loaded by rail crane and to be unloaded by yard crane. Otherwise, after travelling, the vehicle has to connect and lift the cassette loaded with containers in the rail area in order to transport them to the yard. Then when it arrives to the transfer point in the yard area it descends and disconnects the cassette to reengage a new empty cassette and takes it back to the rail area. Another thing to take into account is the assumption of considering the same number of cassettes for each vehicle.

Table 8-13: Values of Truck Cycle Time when it Works with Cassette

Truck cycle time	one rail crane	two rail cranes	three rail cranes
Mean value (s)	177,618	178,430	178,761
Standard deviation (s)	37,184	36,245	35,281

Table 8-14: Values of AGV Cycle Time when it Works with Cassette

AGV cycle time	one rail crane	two rail cranes	three rail cranes
Mean value (s)	212,470	213,597	214,057
Standard deviation (s)	51,645	50,340	49,002

The actions considered for each cassette are as follow.

1. *Load cassette:* a cassette that has been placed onto the ground is loaded by rail crane. Two possibilities have been considered. The first one is to load the cassette with one container of 40’ or 20’. In this case the necessary time is the constant lifting time of rail crane to descend a container onto the cassette. The second one is to load the cassette with two containers of 40’ or four of 20’. In case of two containers of 40’, the cycle time of rail crane is added to the necessary time. In case of four containers of 20’, the necessary time is double time than in case of two containers of 40’. Finally, total time is calculated with the suitable percentages according to the number of containers of each type.

2. *Travel from the rail area to the yard*: travel time for a cassette is the same as for the vehicle to which is connected. Additionally, the necessary time to connect or disconnect the cassette from the vehicle is considered as well as the time to lift and descend the cassette.

3. *Unload cassette*: a cassette that has been placed onto ground is unloaded by yard crane. Two possibilities have been considered. The first one is to unload the cassette with one container of 40’ or 20’. In this case the necessary time is the constant lifting time of yard crane for lifting a container. The second one is to unload the cassette with two containers of 40’ or four of 20’. In case of two containers of 40’, the cycle time of yard crane is added to the necessary time. In case of four containers of 20’, the necessary time is double time than in case of two containers of 40’. Finally, total time is calculated with the suitable percentages according to the number of containers of each type.

4. *Travel from the yard to the rail area*: travel time for a cassette is the same as for a vehicle to which is connected. Additionally, the necessary time to connect or disconnect the cassette from the vehicle is considered as well as the time to lift and descend the cassette.

The results about cycle times in each case are shown in next tables.

Table 8-15: Cycle Times of Cassette when it Works with a Truck Loading One Container of 40' or of 20'

	One rail crane		Two rail cranes		Three rail cranes	
Operation	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)
1. Load cassette from train	8,910	0,000	8,910	0,000	8,910	0,000
2. Travel from rail to yard	88,809	18,592	89,215	18,123	89,381	17,641
3. Unload cassette	10,723	0,000	10,723	0,000	10,723	0,000
4. Travel from yard to rail	88,809	18,592	89,215	18,123	89,381	17,641
TOTAL	197,252	37,184	198,063	36,245	198,395	35,281

Table 8-16: Cycle Times of Cassette when it Works with an AGV Loading One Container of 40' or of 20'

	One rail crane		Two rail cranes		Three rail cranes	
Operation	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)
1. Load cassette from train	8,910	0,000	8,910	0,000	8,910	0,000
2. Travel from rail to yard	106,235	25,822	106,799	25,170	107,029	24,501
3. Unload cassette	10,723	0,000	10,723	0,000	10,723	0,000
4. Travel from yard to rail	106,235	25,822	106,799	25,170	107,029	24,501
TOTAL	232,103	51,645	233,231	50,340	233,691	49,002

Table 8-17: Cycle Times of Cassette when it Works with a Truck Loading Two Containers of 40' or Four Containers of 20'

	One rail crane		Two rail cranes		Three rail cranes	
Operation	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)
1. Load cassette from train	92,695	17,627	92,695	17,627	92,695	17,627
2. Travel from rail to yard	88,809	18,592	89,215	18,123	89,381	17,641
3. Unload cassette	171,413	82,864	171,413	82,864	171,413	82,864
4. Travel from yard to rail	88,809	18,592	89,215	18,123	89,381	17,641
TOTAL	441,727	137,675	442,538	136,736	442,870	135,773

Table 8-18: Cycle Times of Cassette when it Works with an AGV Loading Two Containers of 40' or Four Containers of 20'

	One rail crane		Two rail cranes		Three rail cranes	
Operation	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)	Mean value (s)	Standard deviation (s)
1. Load cassette from train	92,695	17,627	92,695	17,627	92,695	17,627
2. Travel from rail to yard	106,235	25,822	106,799	25,170	107,029	24,501
3. Unload cassette	171,413	82,864	171,413	82,864	171,413	82,864
4. Travel from yard to rail	106,235	25,822	106,799	25,170	107,029	24,501
TOTAL	476,578	152,136	477,706	150,832	478,166	149,493

8.3. Experiment Description

8.3.1. Interfaces

In all cases which truck and AGV without cassette are employed, two interfaces have been studied. The first one is the "Rail interface" and the second one is the "Yard interface". In the first, the arrivals are represented by the containers that the rail crane takes from the train and the servers are represented by vehicles for each crane. In the second, the arrivals are represented by the containers that the yard crane takes from vehicles and the servers are represented by vehicles for each crane.

And in all cases of vehicles with cassette, one more interface has been studied, which is “Vehicle interface”. In these cases, regarding the “Rail interface” and “Yard interface”, the servers are represented by cassettes for each crane. In the “Vehicle interface” the arrivals are represented by trucks or AGVs and the servers are represented by cassettes for each vehicle. In addition, the same number of cassettes has been considered for each vehicle and for each crane.

In case of shuttle carrier, three interfaces have been considered as in cases of vehicles with cassettes. But now the third interface is the “Shuttle Carrier Interface” where the interaction of containers is between shuttle carrier and a virtual platform that places two containers. So this platform represents the servers in the three interfaces.

8.3.2. Queuing Theory

- *Number of servers*

In each interface the cycle time of the suitable crane has been used as an average arrival rate and the cycle time of the vehicle as average service rate. By this way, the necessary number of servers in each case has been determined from a service factor, which has been calculated according to the average arrival rate and the average service rate. This is the reason why it is only studied the suitable number of servers for each type of horizontal transport system. However, in the cases of vehicles with cassettes, more options have been studied when it has been convenient.

The theoretical number of vehicles (n) in each interface is calculated with next formula where λ is the average arrival rate and μ is the average service rate [23].

$$n = \frac{\lambda}{\mu}$$

The real number of vehicles (s) is an enter value, which is the maximum of theoretical number of vehicles of all interfaces. And the utilization rate is calculated with next formula [23].

$$u = \frac{\lambda}{\mu \cdot s}$$

For instance, in the case of truck and one rail crane when trucks are loaded with only one container of 20 or 40’, Table 8-19 shows the way of determining the number of trucks, in both “Rail interface” and “Yard interface”.

Table 8-19: Values of Number of Trucks Using One Rail Crane and Utilization Rate in each Interface

	Theoretical number of trucks	Necessary number of trucks	Real number of trucks	Utilisation rate
Rail interface	1,896	2	2	0,948
Yard interface	0,904	1	2	0,452

And in the case of AGVs with cassettes and one rail crane when cassettes are loaded with two containers of 40’ or four containers of 20’, Table 8-20 shows the way of determining the necessary number of cassettes for each rail crane.

Table 8-20: Values of Number of Cassettes using AGVs and One Rail Crane and Utilization Rate in each Interface

	Theoretical number of cassettes	Necessary number of cassettes	Real number of cassettes	Utilization rate
Rail interface	8,273	9	9	0,919
Yard interface	3,945	4	9	0,438
AGV interface	2,243	3 cassettes for each AGV	3	0,748

- *Method to obtain waiting times*

In each interface three possibilities as arrival and service times have been considered:

M/M/s: arrival times according to Poisson laws, exponential service time and s servers.
D/M/s: constant arrival times, exponential service time and s servers.
M/D/s: arrival times according to Poisson laws, constant service time and s servers.

The formulas used in order to calculate the necessary parameters for the first case of M/M/s are presented as follow [23].

Where: λ is the average arrival rate in the system.
μ is the average service rate for each server.
s is the number of servers.

L is the average number of units in the system.

$$L = L_q + \frac{\lambda}{\mu}$$

L_q is the average number of units in the queuing line.

$$L_q = \frac{\left(\frac{\lambda}{\mu}\right)^s \cdot \lambda \cdot \mu}{(s-1)! \cdot (s \cdot \mu - \lambda)^2} \cdot P_0$$

P_0 is the probability that there is no unit is in the system.

$$P_0 = \frac{1}{\sum_{n=0}^{s-1} \frac{\left(\frac{\lambda}{\mu}\right)^n}{n!} + \frac{\left(\frac{\lambda}{\mu}\right)^s}{s!} \cdot \left(\frac{s \cdot \mu}{s \cdot \mu - \lambda}\right)}$$

W_q is the average time that a unit spends in the system.

$$W_q = \frac{L_q}{\lambda}$$

In the second case of D/M/s, the graph shown in Figure 8-1 has been used in order to obtain the average number of units in the system *"L"* with the value of utilisation rate *"u"* and the number of server *"s"*.

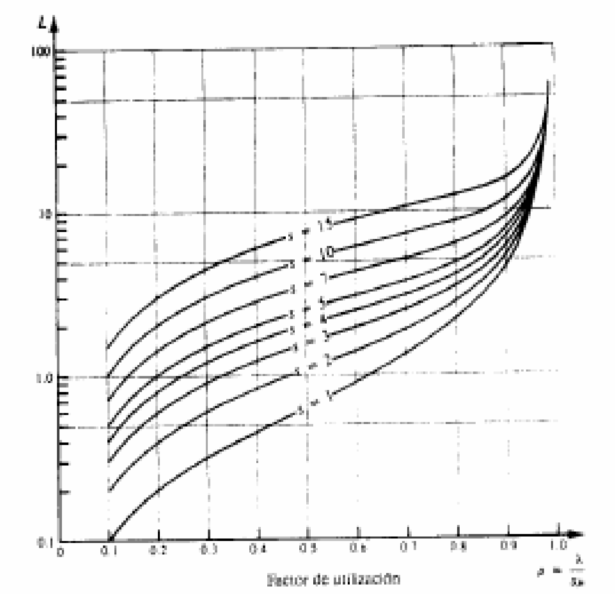

Figure 8-1: Graph for D/M/s
Source: Amaia Lusa, ETSEIB, UPC.

With the value of *"L"* to calculate the value of *"L_q"* and *"W_q"* is possible with next formulas [23].

$$L_q = L - \frac{\lambda}{\mu} \qquad\qquad W_q = \frac{L_q}{\lambda}$$

And in the third case of M/D/s, the graph shown in Figure 8-2 has been used in order to calculate the value of *L*.

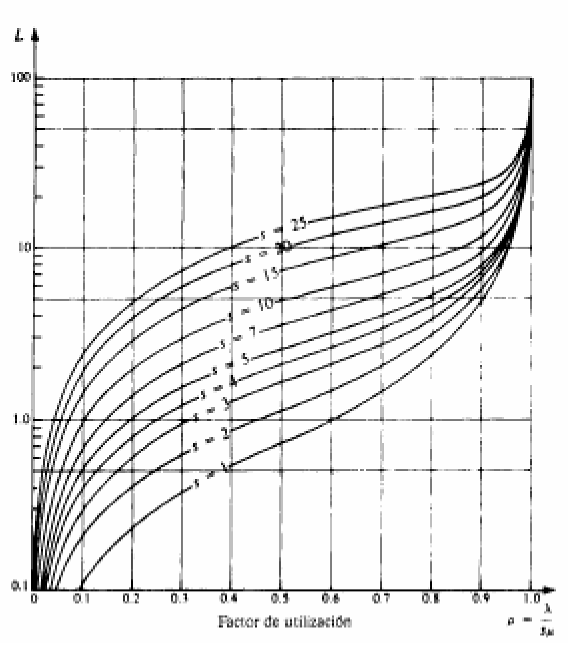

Figure 8-2: Graph for M/D/s
Source: Amaia Lusa, ETSEIB, UPC.

The formulas that have been used to obtain values of the average number of units in the queuing line *"L_q"* and the average time that a unit spends in the system *"W_q"* are the same as in the case D/M/s.

8.3.3. Method to Obtain the Results

With waiting times that have been obtained in each of these three cases explained above and for each interface, the waiting time of arrivals, which are represented by cranes or vehicles depending on the interface analyzed, is calculated. Then, waiting times of servers, which are vehicles, cassettes or a virtual platform depending on the case, are calculated with statistical theories.

With all of these values, the productivities of cranes, vehicles and cassettes have been obtained for each system and in each scenario. After this, the minimum productivity has been chosen between all the equipment used in each situation. Then, the cargo handling time for a train in order to be unloaded and loaded has been calculated. The rail cranes load a train without using vehicles because previously the containers have been placed onto the ground and yard crane and vehicles prepare cargo without using rail cranes. Therefore, loading the train and preparation of cargo are done simultaneously. This is the reason why the required time for loading and unloading a train has been calculated with the necessary time to unload the train and the maximum value between the time to load the train and the time to prepare the cargo. Finally, the spare time indicates if the system works properly or there is a delay related to the threshold time for each train[2].

For instance, the method to obtain the cargo handling time for a train in the third scenario is shown in the case of using two trucks with four cassettes each. In this case

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[2] It is calculated in chapter 8.

two rail cranes are necessary to work properly. First of all, Table 8-21 shows the productivities.

Table 8-21: Productivities Using Two Trucks with Four Cassettes each in the Third Scenario

Productivity RC (mov/h)	Productivity YC (mov/h)	Productivity truck (mov/h)	Productivity cassette (mov/h)
23,769	29,699	19,883	1,782

Second, in this case the productivities are compared between two rail cranes (2·23,769 = 47,538), one yard crane (29,669), four trucks (4·19,883 = 79,532) and sixteen cassettes (16·1,782 = 28,507). The results indicate that cassettes have the minimum productivity.

Third, the time to unload a train is calculated by the minimum productivity and the number of travels according to the number of containers that have to be unloaded from the train and the number of containers that each transport system can transfer at the same time.

Fourth, the time to load a train is determined by the rail crane cycle time, the number of containers that have to be loaded on the train and the necessary number of rail cranes in the third scenario.

Fifth, the time to prepare cargo is calculated by the cassette cycle time, the number of travels and the total number of cassettes.

With the values explained above, the cargo handling time for each train is obtained, which in this case includes the time to unload a train and the time to load a train since it is the maximum between time to load and to prepare cargo. All these results are shown in Table 8-22.

Table 8-22: Operational Times Using Two Trucks with Four Cassettes each in the Third Scenario

Min Productivity (mov/h)	28,507
Time to unload train (h)	0,526
Time to load train (h)	0,348
Time to prepare cargo (h)	0,326
Cargo handling time for a train (h)	0,874

Finally, the spare time is the difference between threshold time and real cargo handling time for a train, which is expressed in percentage related to the threshold value. Therefore, in this example the spare time is 34,416%.

Table 8-23: Spare Time Using Two Trucks with Four Cassettes each in the Third Scenario

Threshold time (h)	1,333
Spare time	34,416%

As we can see, in the third scenario with two rail cranes the system that uses two trucks with four cassettes each one works properly.

8.4. Performance Criteria

With the obtained results, it is possible to choose the best option for each scenario using performance criteria in order to evaluate and compare the analyzed horizontal transport systems. The performance criteria that have been used in this research are:

1. Waiting times for each system that are expressed in percentage of total service time, which considers active time and waiting time: it means the time that each system has to wait to be served for the others systems. In this study we compare waiting times of rail crane, yard crane, vehicle and cassette for each scenario and for the five analyzed transport systems.

2. Productivity that is expressed in movements/hour: it is the inverse of required time to complete an operation. It means that it is the inverse of the service time for each system that refers to rail crane, yard crane, vehicle or cassette.

3. Cargo handling time for each train that is expressed in hours: it is the time that includes preparation of cargo on the ground, unloading and loading a train. But rail cranes load a train without using vehicles because the containers have been placed onto the ground previously and yard crane and vehicles prepare cargo without using rail cranes. Therefore, it has been considered that loading and preparation of cargo are done simultaneously. This is the reason why the cargo handling time for a train has been calculated with the necessary time to unload the train and the maximum value between time to load and time to prepare cargo.

4. Cost: it means the variable cost expressed in €/box and the investment expressed in euros, which includes the investment in rail cranes and in the transport system for each scenario.

9. ANALYSIS OF RESULTS

9.1. Comparative Analysis of each Type of Studied Transport System

The next tables show the best option for each scenario, the cargo handling time for a train for each of these, the percentage of spare time and the equipment with the minimum productivity.

9.1.1. Truck

Two possibilities have been studied in the case of truck as a mode of transport.

- The first one is to load trucks with only one container both of 40’ and 20’. Two trucks are necessary in this case.

- The second one is to load trucks with one container of 40’ or two of 20’. Four trucks are necessary in this case.

We can see in Table 9-1 that the best possibility is the second despite using more trucks. Moreover, in the possibility of loading only one container in the second scenario with only two trucks a second rail crane is needed to handle containers and in the third scenario there is an important delay of 31,230% using three rail cranes. We will consider only the second possibility using four trucks in the comparison of the different types of transport in section 9.2.

In the first scenario, which has the lowest demand, the best option is to use only one rail crane. The cargo handling time for each train is 1,894 hours. So, the spare time for each train is 68,426%. And finally, comparing the productivities in the system, which means productivity of four trucks, productivity of a rail crane and productivity of yard crane, trucks have the lowest productivity. So, trucks limit the capacity of terminal in this case because they move fewer containers per hour than rail crane and yard crane. Despite this, more trucks are not necessary because waiting time of truck increases and the system that limits the capacity is the truck, as well.

In the second scenario, which has a medium level of demand, the best option is to use one rail crane. Therefore, the cargo handling time for each train is the same as in the first scenario, which is 1,894 hours, but the spare time for each train is 13,171%. Comparing productivities, trucks limit the capacity because they have the lowest productivity.

In the third scenario, which has the highest demand, the best option is to use three rail cranes. The cargo handling time for each train is 1,239hours and the spare time for each train is 7,081%. And finally, the yard crane is the equipment that limits t he capacity.

Table 9-1: Values for Best Options of Trucks

Type of vehicle	Number of vehicles for each RC	First scenario			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
Truck	2 (loading always 1container)	1 RC	3,108	48,200%	Trucks
	4 (loading sometimes more than 1container)	1 RC	1,894	68,426%	Trucks
Type of vehicle	**Number of vehicles for each RC**	**Second scenario**			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
Truck	2 (loading always 1container)	2 RC	1,851	15,181%	YC
	4 (loading sometimes more than 1container)	1 RC	1,894	13,171%	Trucks
Type of vehicle	**Number of vehicles for each RC**	**Third scenario**			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
Truck	2 (loading always 1container)	3 RC	1,750	-31,230%	YC
	4 (loading sometimes more than 1container)	3 RC	1,239	7,081%	YC

9.1.2. Automated Guided Vehicle (AGV)

In the case of AGV, two possibilities have been studied as well.

- The first one is to use three AGVs loaded with one container both of 40’ and 20’.
- The second one is to use four AGVs loaded with one container of 40’ or two of 20’.

According to values of total time for a train showed in Table 9-2, the best possibility is the second one for the same reasons as explained above. Therefore, for the comparative analysis in section 9.2, only the second possibility with four AGVs has been considered.

The best option in the first scenario is to use one rail crane. The cargo handling time for a train is 2,350 hours and the spare time is 60,827%. Furthermore, comparing productivities of the equipments, AGVs have the lowest productivity.

The best option in the second scenario is to use two rail cranes. The cargo handling time for a train is 1,358 hours and the spare time is 37,738%. In this case, yard crane is the equipment with lower productivity.

The best option in the third scenario is now three rail cranes. In this case, the cargo handling time for a train is 1,242 hours with a spare time of 6,825%. And finally, the equipment that moves fewer containers per hour is also yard crane.

Table 9-2: Values for Best Options of AGVs

Type of vehicle	Number of vehicles for each RC	First scenario			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
AGV	3 (loading always 1container)	1 RC	2,448	59,196%	AGVs
	4 (loading sometimes more than 1container)	1 RC	2,350	60,827%	AGVs
Type of vehicle	Number of vehicles for each RC	Second scenario			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
AGV	3 (loading always 1container)	2 RC	1,854	15,025%	YC
	4 (loading sometimes more than 1container)	2 RC	1,358	37,738%	YC
Type of vehicle	Number of vehicles for each RC	Third scenario			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
AGV	3 (loading always 1container)	3 RC	1,740	-30,495%	YC
	4 (loading sometimes more than 1container)	3 RC	1,242	6,825%	YC

9.1.3. Shuttle Carrier

Shuttle carrier only has one way of handling containers. It is to pick up two containers and transfer them. So, only this possibility has been studied. Of this mode, two shuttle carriers are needed to handle all cargo.

One rail crane is necessary in the first scenario. The cargo handling time for a train with two shuttle carriers is 1,627 hours and therefore, the spare time is 72,883% for each train. The yard crane is the equipment that limits the capacity of the intermodal terminal instead of vehicles as in the other modes of transport using only one rail crane.

In the second scenario, one rail crane is necessary. So, the cargo handling time for a train is the same as in the first scenario but now the spare time is 25,429%. And the yard crane limits the capacity as well.

In the third scenario two rail cranes are necessary. The cargo handling time for each train is 1,184hours and the spare time is 11,187%. The lowest productivity is also related to the yard crane.

Table 9-3: Values for Best Options of Shuttle Carrier

Type of vehicle	Number of vehicles for each RC	First scenario			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
Shuttle carrier	2	1 RC	1,627	72,883%	YC
Type of vehicle	Number of vehicles for each RC	Second scenario			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
Shuttle carrier	2	1 RC	1,627	25,429%	YC
Type of vehicle	Number of vehicles for each RC	Third scenario			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
Shuttle carrier	2	2 RC	1,184	11,187%	YC

9.1.4. Truck with Cassette

In this case, each truck uses the same number of cassettes. It has been studied two possibilities.

- The first one is to load the cassette with only one container of 40’ or 20’. According to the utilization rate, at least two trucks with two cassettes each one are necessary.

- The second one is to load the cassette with two containers of 40’, one upon the other, or with four containers of 20’. In this case, two trucks with four cassettes in each one are necessary.

However, more cases have been studied in order to know the effect when more trucks or cassettes are added. So, in the first possibility of loading, two options have been studied: two trucks with two cassettes for each one and two trucks with three cassettes for each one (four and six cassettes in total respectively). And in the second possibility of loading, three options have been studied: two trucks with four each one (eight cassettes in total), two trucks with five cassettes each one (ten cassettes in total) and three trucks with three cassettes each one (nine cassettes in total). Moreover in the second possibility, despite decreasing the cargo handling time for a train when one more truck is added, it is not useful because there is too much spare time for each train and this option is more expensive.

In the first scenario, the best option is to use one rail crane in all cases explained above. As it is shown in Table 9-4, regarding cargo handling time for a train in the possibility of loading always only one container, it is not necessary to add a third cassette due to the fact that total time increases, so the spare time decreases from 44,434% to 39,557%. However, in the possibility of loading more than one container, when a cassette is added the cargo handling time for each train decreases from 1,924 hours to 1,677 hours . On the contrary, if a truck is added but each truck has only three cassettes, the cargo handling time for a train decreases in more proportion than before from 1,924 hours to 1,382 hours. Still, according to productivities cassettes move fewer containers than trucks, yard crane and rail crane.

In the second scenario, two rail cranes are necessary in case of loading one container and in case of loading more than one container only one rail crane is needed. In both case of loading only one container the cargo handling time and the spare time are the same, so it is not necessary a third cassette either. And in case of loading more than one container, the cargo handling times for a train are the same as in the first scenario but the spare times decreases a lot compared to the first scenario. Furthermore, comparing productivities, yard crane has the lowest productivity in case of loading one container and the cassettes have the lowest productivity in case of loading more than one container.

In the third scenario, in the case of loading one container three rail cranes are necessary while in the case of loading more than one container only two rail cranes are necessary. Apart from that, as it is explained in the other scenarios the option of adding a third cassette for each truck in case of loading only one container is not useful. Furthermore, the delay is not solved. In case of loading more than one container the cargo handling time for a train is 0,987 hours with two trucks and four cassettes for each one. If a cassette is added for each truck or a truck is added but with one cassette less than before the cargo handling time for a train in both cases decreases a little. Finally, yard crane is the equipment that limits the capacity of the intermodal terminal except in case of two trucks with four containers each one, where eight cassettes have the lowest productivity.

In all scenarios, comparing total times between the possibility of loading one container and the possibility of loading more than one container, the first one is worse than the second one because it always requires more time for a train. In addition, in the second and third scenario the first possibility needs one more rail crane. Therefore, in analysis with graphs of different systems in section 9.2, we will consider only the second possibility.

Table 9-4: Values for Best Options of Truck with Cassette

Type of vehicle	Number of vehicles for each RC	First scenario			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
Truck + cassette	2 truck + 4 cassettes (loading always 1container)	1 RC	3,334	44,434%	Cassettes
	2 truck + 6 cassettes (loading always 1container)	1 RC	3,627	39,557%	Cassettes
	2 truck + 8 cassettes (loading more than 1container)	1 RC	1,924	67,925%	Cassettes
	2 truck + 10 cassettes (loading more than 1container)	1 RC	1,677	72,056%	Cassettes
	3 truck + 9 cassettes (loading more than 1container)	1 RC	1,382	76,968%	Cassettes
Type of vehicle	Number of vehicles for each RC	Second scenario			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
Truck + cassette	2 truck + 4 cassettes (loading always 1container)	2 RC	2,059	5,638%	YC
	2 truck + 6 cassettes (loading always 1container)	2 RC	2,058	5,671%	YC
	2 truck + 8 cassettes (loading more than 1container)	1 RC	1,924	11,795%	Cassettes
	2 truck + 10 cassettes (loading more than 1container)	1 RC	1,677	23,155%	Cassettes
	3 truck + 9 cassettes (loading more than 1container)	1 RC	1,382	36,663%	Cassettes
Type of vehicle	Number of vehicles for each RC	Third scenario			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
Truck + cassette	2 truck + 4 cassettes (loading always 1container)	3 RC	1,860	-39,499%	YC
	2 truck + 6 cassettes (loading always 1container)	3 RC	1,859	-39,448%	YC
	2 truck + 8 cassettes (loading more than 1container)	2 RC	0,987	25,963%	Cassettes
	2 truck + 10 cassettes (loading more than 1container)	2 RC	0,964	27,673%	YC
	3 truck + 9 cassettes (loading more than 1container)	2 RC	0,852	36,137%	YC

9.1.5. AGV with Cassette

As in case of trucks, each AGV uses the same number of cassettes. The same two possibilities of loading have been studied. According to utilization rate, at least two AGVs with three cassettes each one are necessary to use in the first possibility of loading and two AGVs with five cassettes each one in the second possibility. However, it has been also studied other cases in order to know which is the effect when more AGVs or cassettes are added. So, in the first possibility of loading one container of 20’ or 40’, two options have been studied: two AGVs with three cassettes for each one and three AGVs with three cassettes each one (six and nine cassettes in total respectively). And in the second possibility of loading more than one container, three options have been studied: two AGVs with five cassettes each one (ten cassettes in total), three AGVs with three cassettes each one (nine cassettes in total) and three AGVs with four cassettes each one (twelve cassettes in total). Moreover, in the second possibility, despite decreasing the cargo handling time for a train when a fourth truck is added, it is not useful because there is too much spare time for each train and this option is more expensive.

In the first scenario, one rail crane is necessary. As we can see in Table 9-5, comparing both options of loading only one container, the first one requires a little more time for a train than second but one more truck is not necessary due to the fact that the first option has enough spare time. And comparing options of loading more than one container, according to cargo handling time for a train, the best options seems to be in first place, three AGVs with four cassettes each one (1,405 hours), in second place three AGVs with three cassettes each one (1,452 hours) and in third place two AGVs with five cassettes each one (1,452 hours). However, these times resemble each other, so a cost analysis is necessary in order to choose the best option. In all of these cases cassettes are the equipments with the lowest productivity.

In the second scenario, two rail cranes are necessary to use in case of loading one container and one rail crane in case of loading more than one container. In case of loading one container it is necessary 2,164 hours for a train with two AGVs and three cassettes each one but with a spare time of 0,798% related to threshold time for a train in the second scenario that is 2,182 hours. If an AGV is added this time decreases a little. In case of loading more than one container the cargo handling time is the same as in the first scenario but the spare times decrease. Finally, in case of loading one container yard crane limits the capacity while in case of loading more than one container cassettes limits the capacity of the system.

In the third scenario, although three rail cranes are needed for possibility of loading one container and two rail cranes in the possibility of loading more than one container, yard crane has the lowest productivity in all of them. In case of loading one container, the cargo handling time for a train is 1,930 hours and it decreases with one more truck. But in both cases there is a large delay because the threshold time for each train in the third scenario is 1,333 hours. So, the option of adding other AGV does not solve the delay problem. In case of loading more than one container, with two AGVs and five cassettes each one the cargo handling time for a train is 1 hour. However, if a cassette is added for each AGV or an AGV is added with one less cassette for an AGV, the necessary time is in both cases 0,85 hours. Therefore, the choice depends on the cost due to the fact that all these times are quite similar.

In all scenarios, comparing cargo handling times between the two possibilities of loading, the first is worse than the second because it always requires more time for a train and sometimes it leads to a delay in the schedule. Furthermore, in the second and the third scenario the first possibility needs one more rail crane. Therefore, in the analysis with graphs of different systems in section 9.2 we will consider only the second possibility.

Table 9-5: Values for Best Options of AGV with Cassette

Type of vehicle	Number of vehicles for each RC	First scenario			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
AGV + cassette	2 AGV + 6 cassettes (loading always 1container)	1 RC	3,908	34,863%	Cassettes
	3 AGV + 6 cassettes (loading always 1container)	1 RC	3,021	49,645%	Cassettes
	2 AGV + 10 cassettes (loading more than 1container)	1 RC	1,807	39,882%	Cassettes
	3 AGV + 9 cassettes (loading more than 1container)	1 RC	1,452	75,801%	Cassettes
	3 AGV + 12 cassettes (loading more than 1container)	1 RC	1,405	76,590%	Cassettes
Type of vehicle	Number of vehicles for each RC	Second scenario			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
AGV + cassette	2 AGV + 6 cassettes (loading always 1container)	2 RC	2,164	0,798%	YC
	3 AGV + 6 cassettes (loading always 1container)	2 RC	1,930	11,562%	YC
	2 AGV + 10 cassettes (loading more than 1container)	1 RC	1,807	17,176%	Cassettes
	3 AGV + 9 cassettes (loading more than 1container)	1 RC	1,452	33,454%	Cassettes
	3 AGV + 12 cassettes (loading more than 1container)	1 RC	1,405	35,623%	Cassettes
Type of vehicle	Number of vehicles for each RC	Third scenario			
		Best option	Cargo handling time for a train (h)	Spare time	Min productivity
AGV + cassette	2 AGV + 6 cassettes (loading always 1container)	3 RC	1,930	-44,785%	YC
	3 AGV + 6 cassettes (loading always 1container)	3 RC	1,774	-33,020%	YC
	2 AGV + 10 cassettes (loading more than 1container)	2 RC	1,001	24,923%	YC
	3 AGV + 9 cassettes (loading more than 1container)	2 RC	0,852	36,130%	YC
	3 AGV + 12 cassettes (loading more than 1container)	2 RC	0,851	36,144%	YC

9.2. Comparative Analysis of the Studied Types of Transport Systems

In this part, a comparative analysis of transport systems is presented in three different scenarios, using the performance criteria explained at part 8.4. of this report.

9.2.1. Waiting Times

We can observe waiting times of all the equipment used within the intermodal terminal in the three studied scenarios in Figures 9-1, 9-2 and 9-3. All values for the equipment are expressed by percentages of their service times. We can see that their waiting times in the three different studied scenarios are close to each other.

The highest waiting time for each analysed system is always the waiting time of vehicles, in cases of using trucks or AGVs without cassette, or the waiting time of cassette, in cases of truck or AGV with cassette. In cases of vehicles without cassette, they have to wait to be served by both rail crane and yard crane. This waiting time is around 70% in the three scenarios. In the cases of vehicles with cassettes, vehicles do not wait to be loaded or unloaded, so their waiting times decrease. On the other hand, cassettes wait the service of cranes and the vehicles; therefore their waiting times are higher than both vehicles and cranes. In these cases, the waiting times for cassettes are between 70% and 78% in the three scenarios. Related to the case of using shuttle carriers, the highest waiting time is for the rail crane, but it is only around 15%. In this case, the cranes unload and pick up the containers directly onto or from the ground and the shuttle carriers pick up or unload the containers from or onto the ground, it means that any equipment does not wait for the service of the others, this is the reason why the waiting times in this case are low.

Regarding waiting time of rail cranes, we can see that it is quite different depending on the transport system employed. For instance, the RC waiting time with four AGVs is close to 20%. If five AGVs are used instead of four, RC waiting time would decrease so much.

We can see the evolution of rail cranes waiting times in systems using trucks with cassettes or AGVs with cassettes. For instance, in case of two trucks and eight cassettes, rail crane waiting time is close to 60%. In case of using two trucks and ten cassettes (only adding one cassette more per vehicle), rail crane waiting time decreases to 4%. In case of using three trucks and nine cassettes, which means to add one vehicle per rail crane related to the first alternative, rail crane waiting time decreases to 18%, it is lower than in the second alternative because we are using now one cassette less. The truck waiting time increases in the third alternative to 17% (in the two first alternatives are close to 0%). In the case of AGVs and cassettes, the evolution of all the equipment is the same as using trucks and cassettes because the performance of AGVs is similar to the performance of trucks.

Related to waiting time of yard crane, the graphs show that it is close to zero in all scenarios and for all different options in horizontal transport systems. It means that yard crane is always active or transferring containers in yard area and it has to wait for neither vehicles nor cassettes.

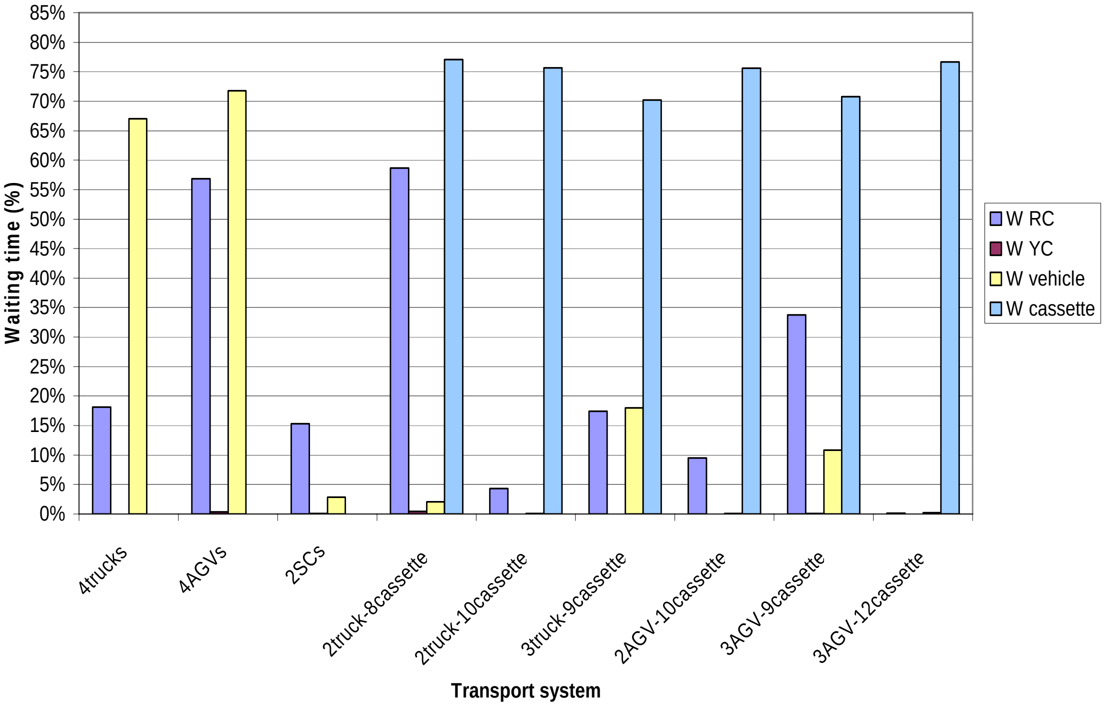

Figure 9-1: Waiting Times in the First Scenario

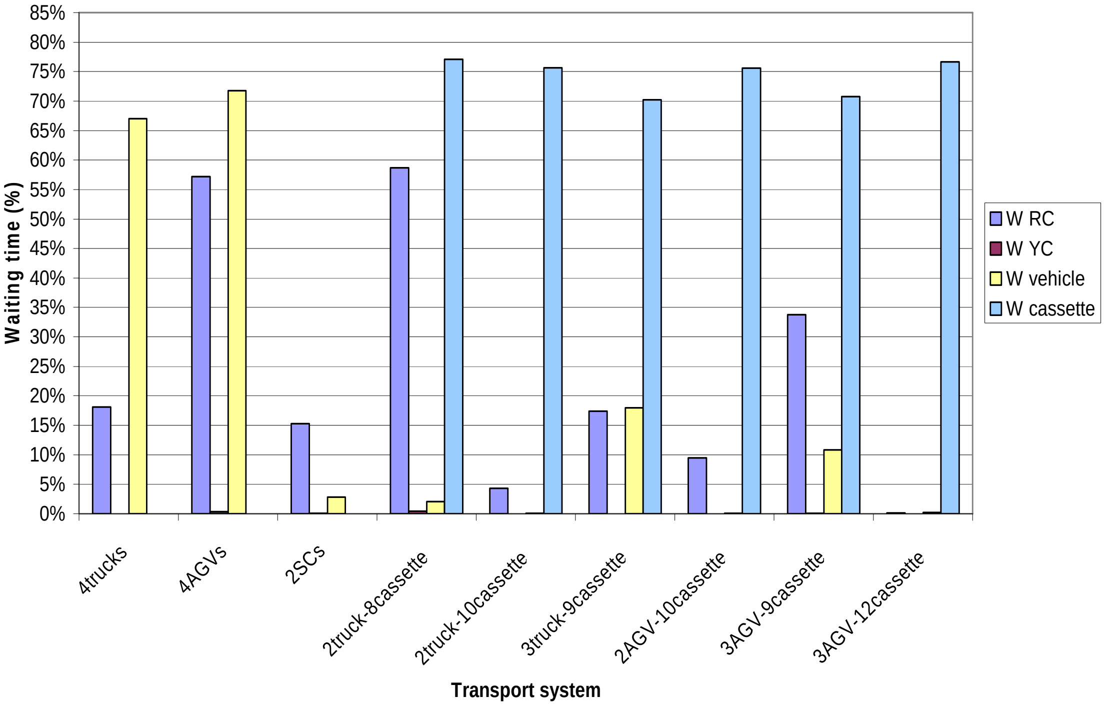

Figure 9-2: Waiting Times in the Second Scenario

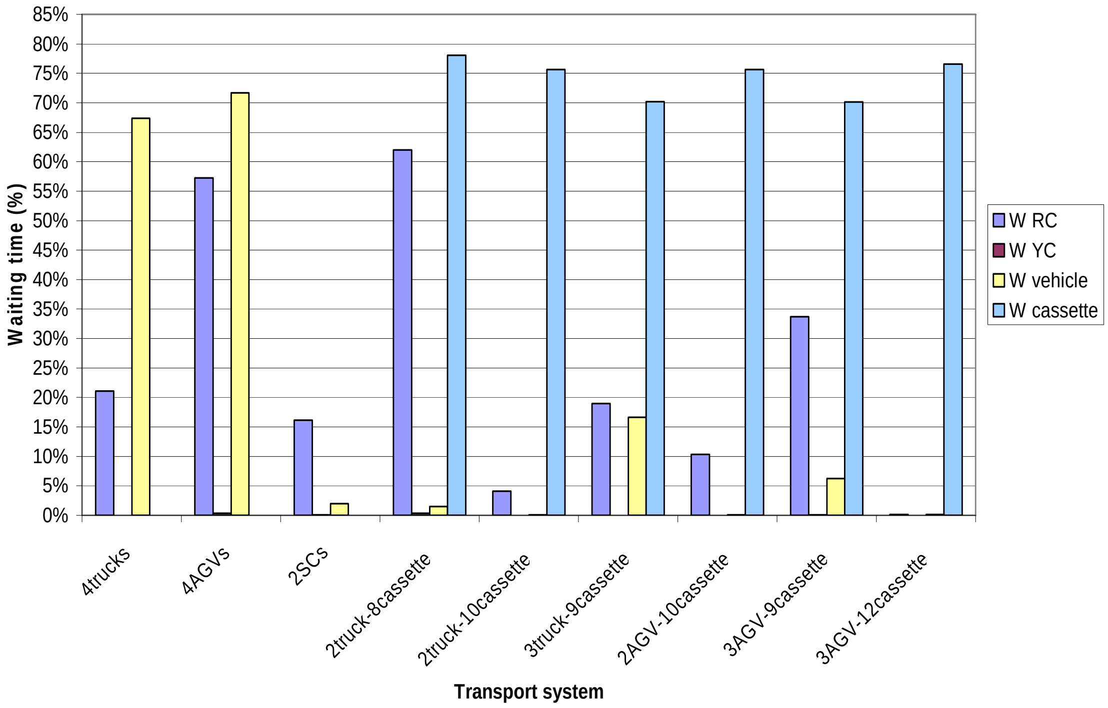

Figure 9-3: Waiting Times in the Third Scenario

9.2.2. Productivities

We can observe productivities of all the equipment used within the intermodal terminal in the three scenarios in Figures 9-4, 9-5 and 9-6. These values are expressed in movements per hour for each system; it means movements that can be done for one rail crane, one yard crane, one vehicle and one cassette. It is possible to observe that productivities for all the equipment are similar in the three scenarios.

The objective of this point is to compare the performance of each system when we use different types of horizontal transport in the intermodal terminal.

We can see that the highest productivity is for rail crane except in the case of using four AGVs or two trucks and eight cassettes. In these two cases, the highest productivity is for yard crane.

In relation to productivities for yard crane, they are near 30mov/h in all analysed modes of transport and in all studied scenarios.

In case of rail crane, these values are quite different depending on the mode of transport used. The lowest one is in the case of using two trucks and eight cassettes, which is close to 25mov/h, and the highest one is in the option of using three AGVs with twelve cassettes, which is more than 60mov/h.

It is possible to observe the evolution of rail crane productivities in options using trucks with cassettes or AGVs with cassettes. We can see that when we add cassettes to the transport system, the productivity of rail crane increases too much, it is because rail crane does not wait to serve a cassette, so the waiting time decreases.

Regarding productivities of vehicles (trucks, AGVs or shuttle carrier), we can see that is quite different depending on the mode of transport used. In the two first cases, using four trucks or four AGVs, the productivity of them is between 4,5 and 6,5mov/h. However, in the other cases, using vehicles with cassettes, vehicles productivities are between 15 and 20mov/h. This difference is because vehicles do not wait to be served by cranes so their waiting times are lower. We can observe the evolution of trucks or AGVs productivity; we can see that if more cassettes are added for each vehicle, the vehicle productivity increases because they are busier and do not wait cassettes. On the other hand, in the case of using two shuttle carriers, the productivity of this vehicle increase so much related to the others vehicles; it is close to 25mov/h.

Related to productivities of cassettes, they are close to each other with different options of transport. They are about 2mov/h in all options.

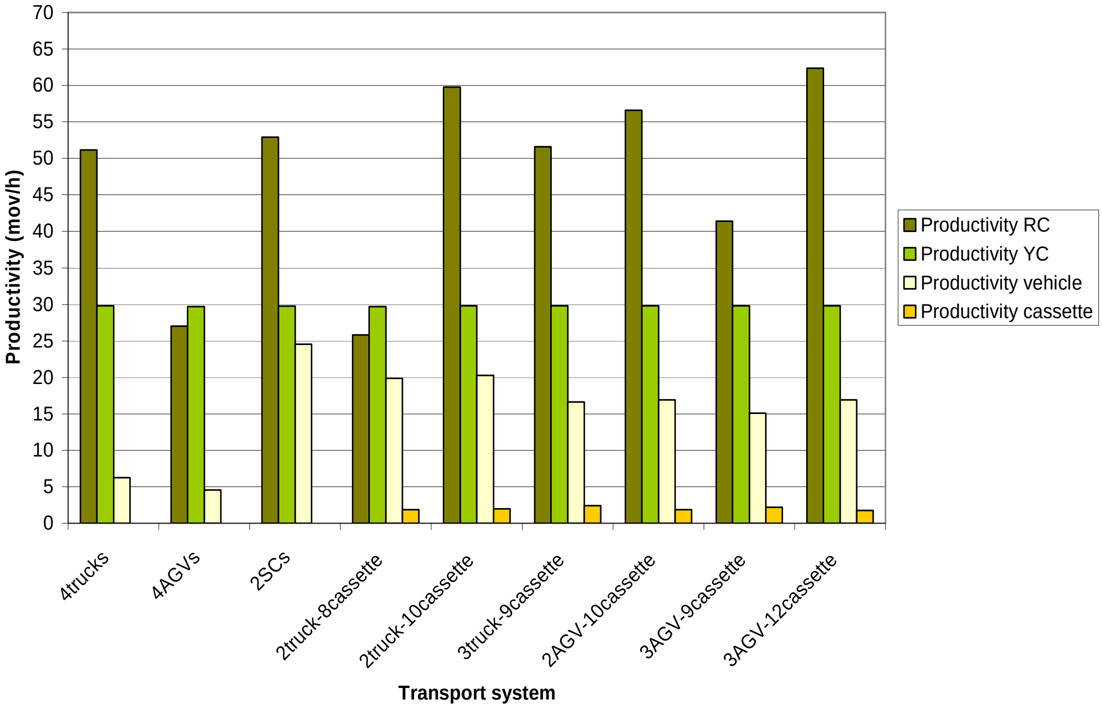

Figure 9-4: Productivities in the First Scenario

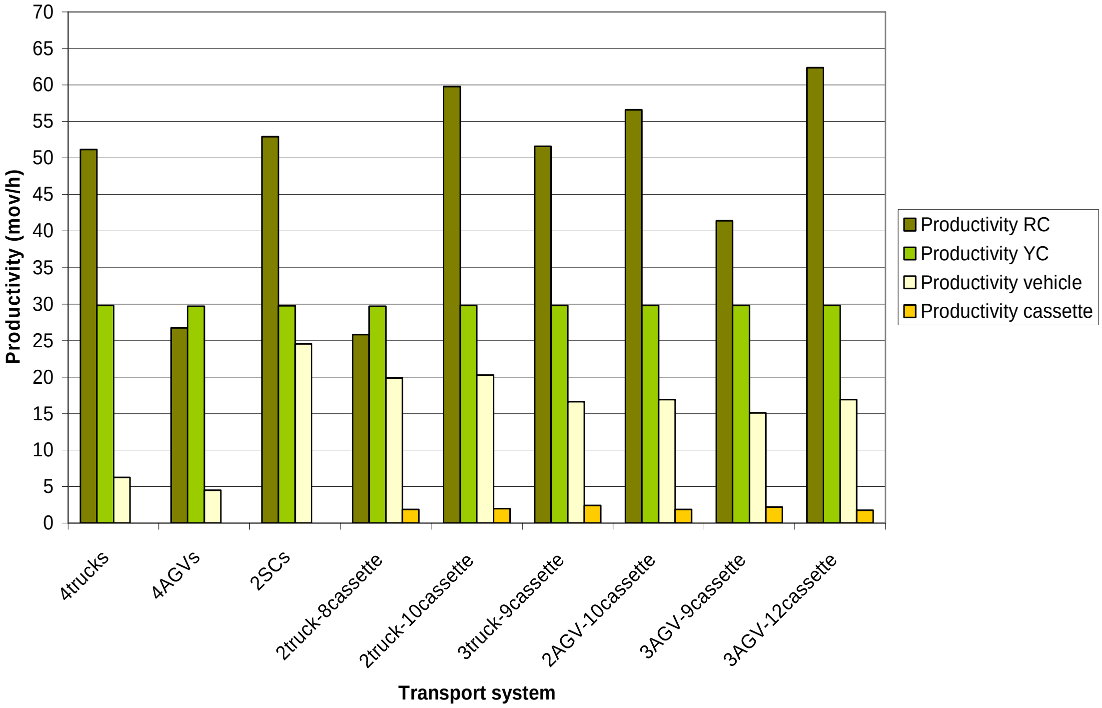

Figure 9-5: Productivities in the Second Scenario

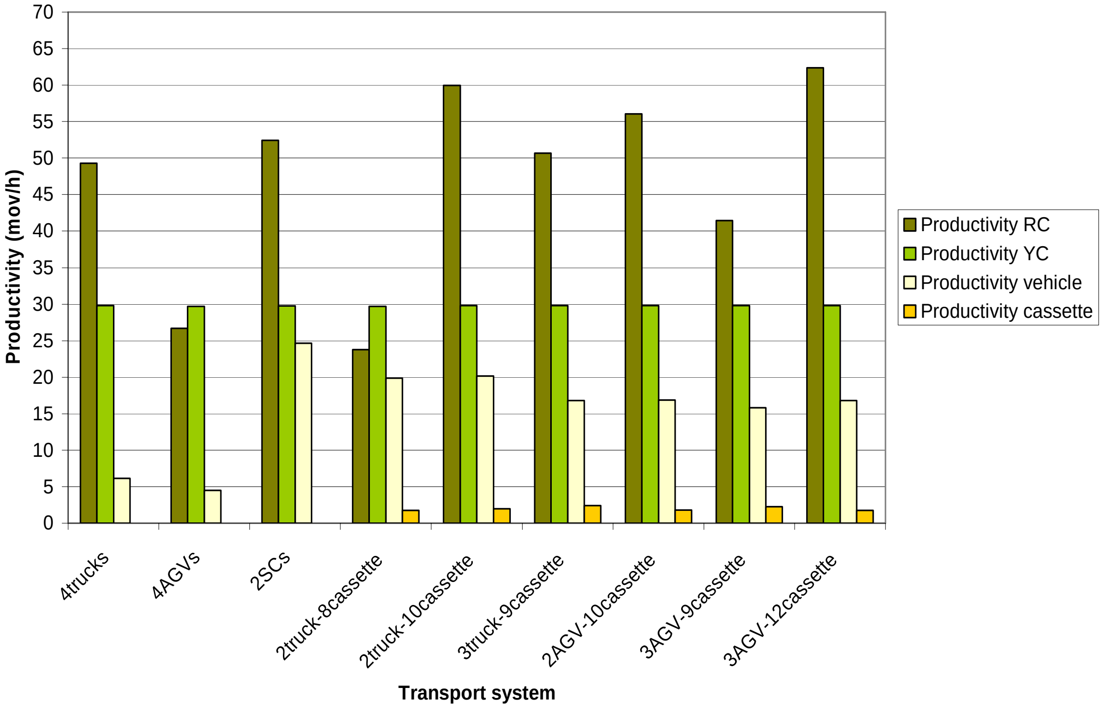

Figure 9-6: Productivities in the Third Scenario

9.2.3. Cargo Handling Time for each Train

The graphs in this section represent cargo handling time in hours for each train to prepare cargo, unload goods of train and load others goods on it. Figure 9-7 represents these values for the first scenario, Figure 9-8 for the second and Figure 9-9 for the third.

Regarding the first scenario, the best option is working with one rail crane in all modes of transport and the cargo handling time for each train has to be lower than 6 hours. It is possible to observe in Figure 9-7 that in all alternatives cargo handling time for a train is lower than the threshold value. If the criterion to choose the suitable alternative in modes of transport is the minimum cargo handling time to each train, the ranking for different options is the following:

Table 9-6: Cargo Handling Time for each Train in the First Scenario

Modes of transport	Cargo handling time for a train
3truck-9cassette	1,382
3AGV-12cassette	1,405
3AGV-9cassette	1,452
2SCs	1,627
2truck-10cassette	1,677
2AGV-10cassette	1,807
4trucks	1,894
2truck-8cassette	1,924
4AGVs	2,350

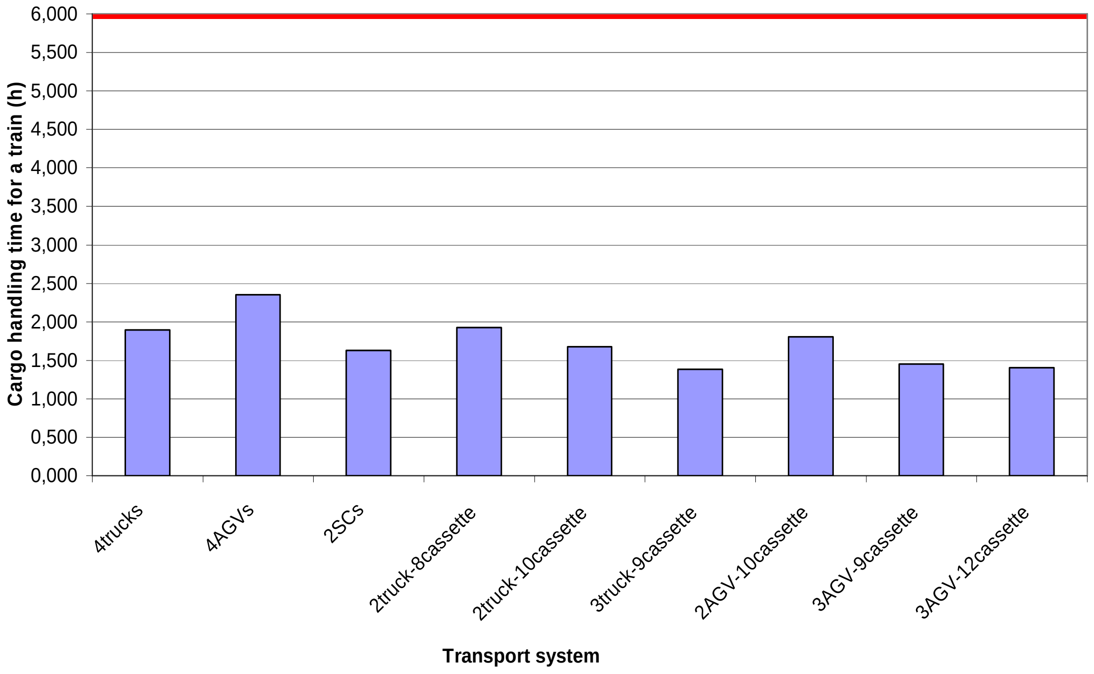

Figure 9-7: Cargo Handling Time for each Train in the First Scenario

In relation to the second scenario, the best option is to work with one rail cranes in all cases except in the case of using four AGVs. The cargo handling time for each train has to be lower than 2,182 hours. It is possible to observe in Figure 9-8 that in all alternatives cargo handling time for a train is lower than maximum time. If the criterion to choose the suitable alternative in modes of transport is the minimum cargo handling time to each train, the ranking for different options is the following:

Table 9-7: Cargo Handling Time for each Train in the Second Scenario

Modes of transport	Cargo handling time for a train
4AGVs	1,358
3truck-9cassette	1,382
3AGV-12cassette	1,405
3AGV-9cassette	1,452
2SCs	1,627
2truck-10cassette	1,677
2AGV-10cassette	1,807
4trucks	1,894
2truck-8cassette	1,924

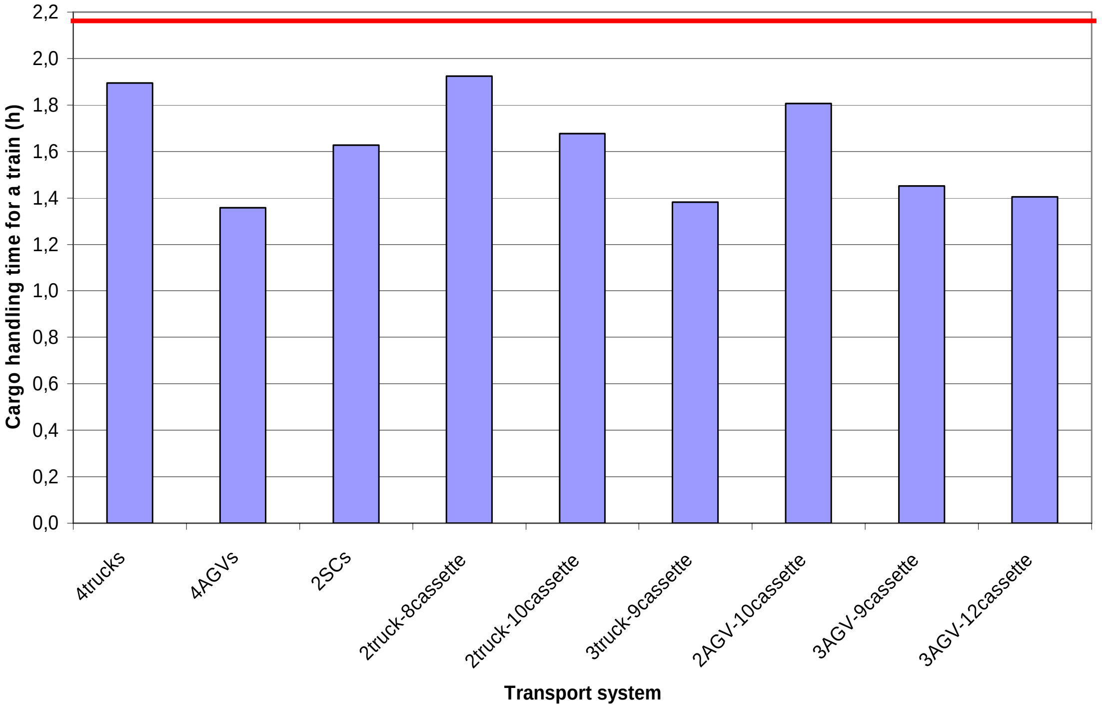

Figure 9-8: Cargo Handling Time for each Train in the Second Scenario

Related to the third scenario the best option is working with three rail cranes in case of using trucks or AGVs without cassette and two rail cranes in case of vehicles with cassettes and shuttle carrier. The cargo handling time for each train has to be lower than 1,333 and it is possible to observe in Figure 9-8 that in all alternatives cargo handling time for a train is lower than this threshold time. If the criterion to choose the suitable alternative in modes of transport is the minimum cargo handling time to each train, the ranking for different options is the following:

Table 9-8: Cargo Handling Time for each Train in the Third Scenario

Modes of transport	Cargo handling time for a train
3AGV-12cassette	0,851
3truck-9cassette	0,852
3AGV-9cassette	0,852
2truck-10cassette	0,964
2truck-8cassette	0,987
2AGV-10cassette	1,001
2SCs	1,184
4trucks	1,239
4AGVs	1,242

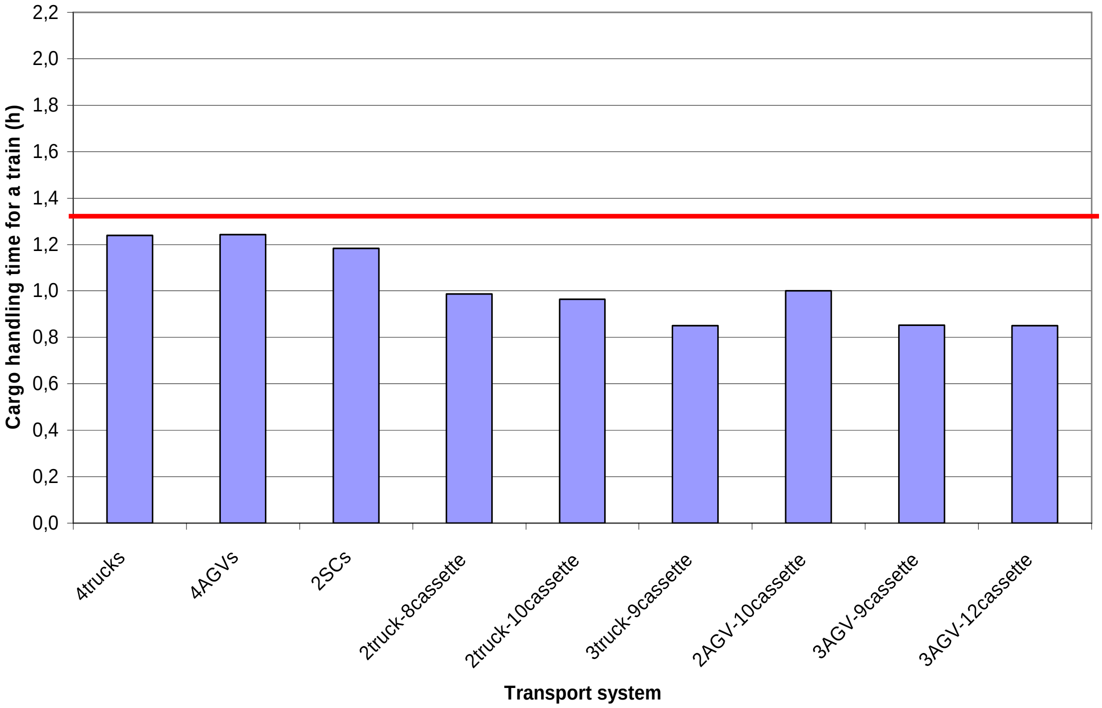

Figure 9-9: Cargo Handling Time for each Train in the Third Scenario

But maybe, it would be more interesting to consider another kind of criteria such as investment and variable cost per movement to help to choose the suitable mode of transport for each scenario. These criteria are analyzed in the next chapter.

10. COST ANALYSIS

10.1. Methodology and Assumptions

The purpose of this cost analysis is to obtain the variable cost per box and the investment for each transport system.

The variable cost includes the depreciation of the equipment, the personnel and the vehicles including the maintenance, the fuel and the interest. Regarding depreciation, ten years has been assumed for the devaluation of trucks and fifteen years for the devaluation of AGVs and shuttle carriers. The maintenance and the fuel that is consumed by vehicles in a year represent a 5% of the investment of the transport system. It is necessary to take into account a 4% of the investment of the transport system related to the interest. And finally, the personnel cost has been obtained with the assumptions explained below.

1. The company that manages the container terminal pays 70.000 € per year for each worker.

2. Each labour works 1.200 hours in a year.

3. The operational hours are the gross working hours, which are calculated with the capacity and the productivity of the system, with an additional 10%.

The investment is divided in two parts. The first one refers to the rail cranes and the second one refers to the transport system. As follow the price of the equipment is shown.

Table 10-1: Price of the equipment

	Price (€)
Rail crane	1.500.000
Truck	117.000
T-AGV	300.000
Shuttle carrier	425.000
IPSI-AGV	350.000
Cassette	8.000

As we can see in Table 10-1, a truck is the vehicle with the lowest price and shuttle carrier is the most expensive. Furthermore, the price of a cassette is cheaper compared with the vehicles. With these values, the necessary investment of each transport system and its variable cost has been calculated with one rail crane. The results are shown in Appendix 4.

In relation to the cost analysis in the different studied scenarios, the variable cost for each box is independent of the number of rail cranes that are used. However, the necessary investment for each system is different because it depends on the number of rail cranes. Therefore, when a system needs two or three rail cranes depending on the scenario, the investment is double or triple respectively than the values expressed in the Appendix 4, which are for one rail crane.

10.2. Analysis of Results

- Variable cost

According to the variable cost of each system, Figure 10-1 shows the significant difference between them.

The first systems with the lowest variable cost are AGVs both with and without cassettes. The case of using two AGVs with five cassettes each one is the best with a variable cost of 1,50 €/box.

The next systems with a low variable cost are two shuttle carriers with a variable cost of 5,97 €/box.

The third place according to the variable cost is for trucks with cassettes and the best one is the case of using two trucks with five cassettes each one. The reason is because of the operational hours. Comparing the systems that use two trucks with four or five cassettes each one, the fact of using one more cassette for each truck requires less working hours in trucks. It implies fewer personnel. And at the same time, if one more truck is used with only three cassettes for each one, the variable cost increases due to one additional worker.

And the last one is for trucks without cassettes with a variable cost of 11,25 €/box.

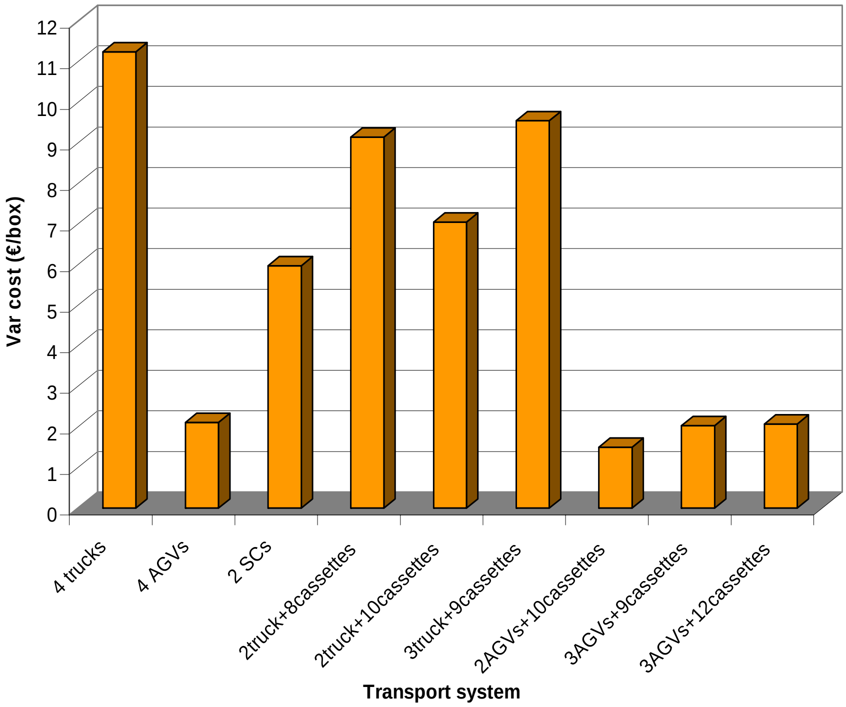

Figure 10-1: Variable Cost

- Investment

The investment in rail cranes and the investment in vehicles and cassettes have been calculated in order to compare the necessary investment for each system. The values are shown in Appendix 5 and also in figures 10-2, 10-3 and 10-4.

1. *First scenario:* The investment in rail cranes is the same for all types of transport, which refers to one rail crane and it is 1.500.000 euros. On the contrary, the investment in vehicles is different for each system. According to the Figure 10-2, trucks with or without cassette have the lowest investment between 356.500 to 526.500 euros. Then, AGVs with or without cassettes and shuttle carriers have an investment between 955.000 to 1.350.000 euros. Another factor to take into account is that trucks resemble AGVs in that if they work with cassettes the investment is smaller than if they work without cassettes. Only two or three trucks and AGVs are necessary when they work with cassettes instead of four when they work without cassette. Moreover, the investment in cassettes is smaller in proportion with the vehicles.

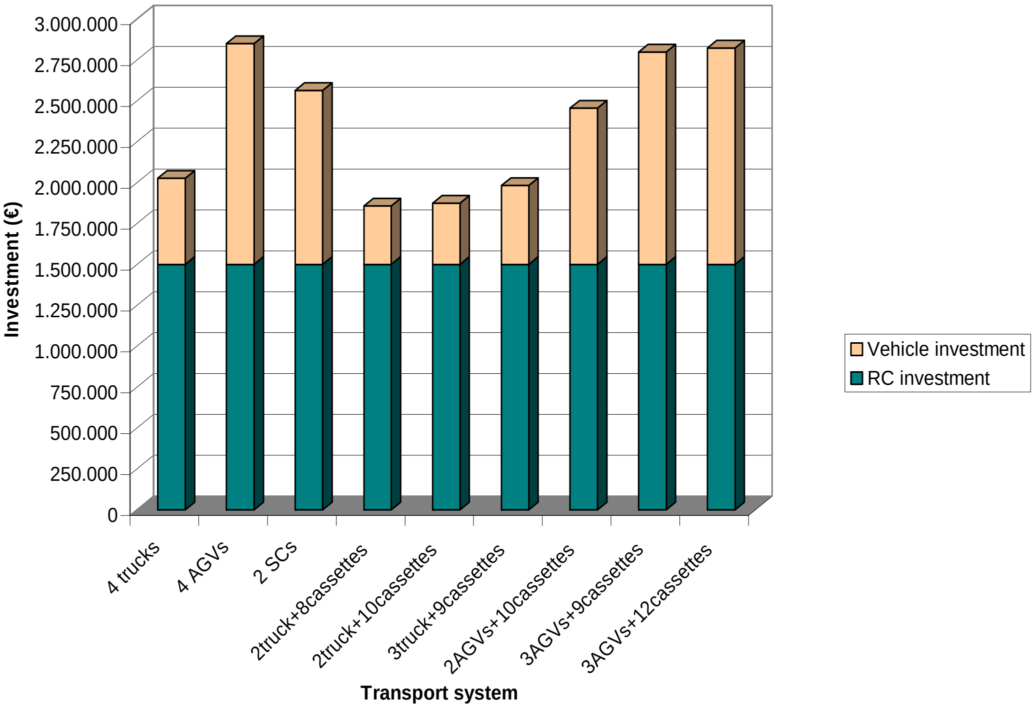

Figure 10-2: Investment in the First Scenario

2. *Second scenario:* In order to satisfy the demand of this scenario, in all cases except when four AGVs are used, the investment in rail cranes is only one. In the case of using four AGVs there is an investment of two rail cranes, so the investment in vehicles is double than in the first scenario. Therefore, according to the Figure 10-3 the systems that use trucks with cassettes have the smallest total investment because of using only one rail crane and two or three trucks instead of four without cassettes.

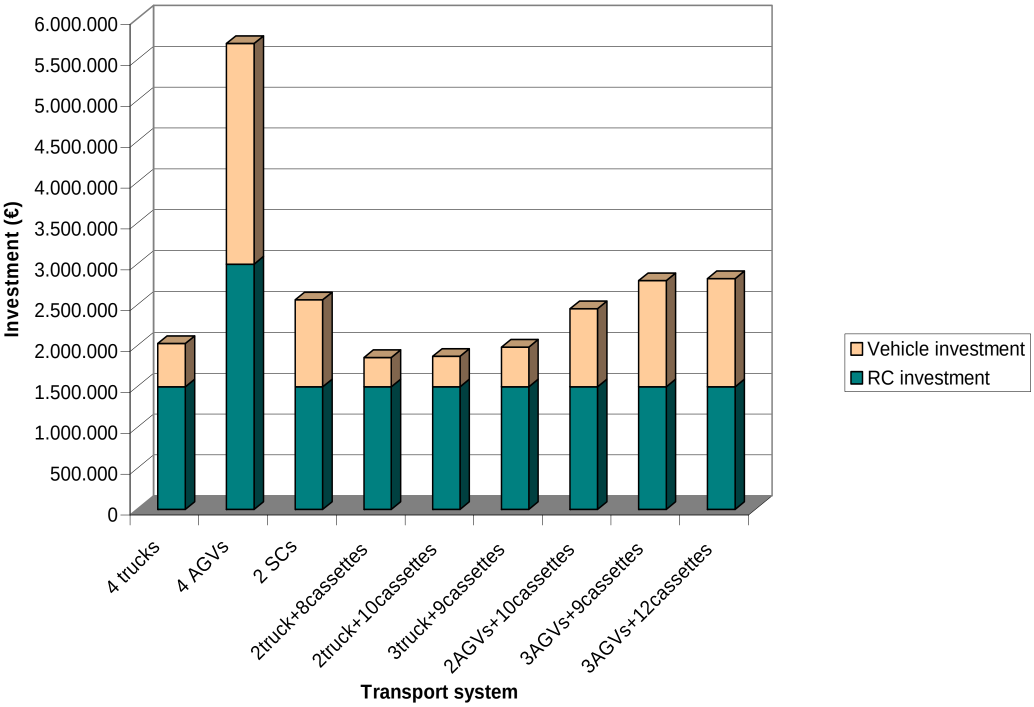

Figure 10-3: Investment in the Second Scenario

3. *Third scenario:* While the systems that work with cassettes or shuttle carrier only need a double investment in the equipment than in the first scenario, trucks and AGVs without cassettes need a triple investment because they require three rail cranes due to the demand. As it is shown in Figure 10-4, trucks working with cassettes is the mode of horizontal transport which requires the lowest total investment as well for the same reasons as in the second scenario.

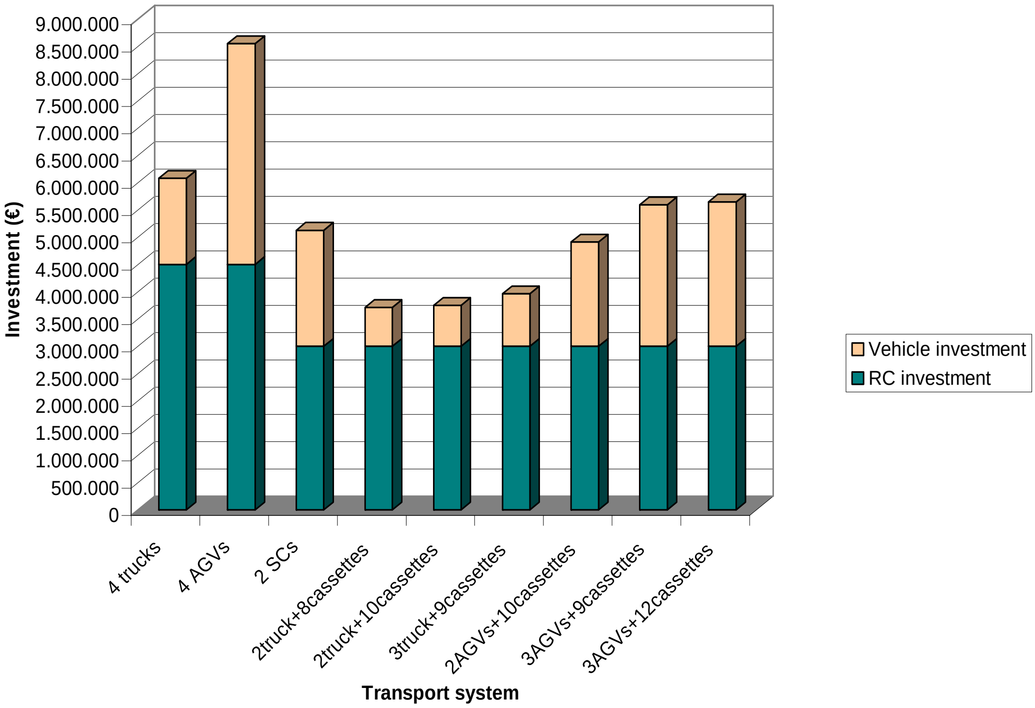

Figure 10-4: Investment in the Third Scenario

11. COMPARATIVE ANALYSIS

With our model, all the options shown in Table 11-1 are viable related to times in order to satisfy the demand because the cargo handling times for each train, which are shown in the first column, do not exceed the threshold time for a train in each. Therefore, the choice of the suitable horizontal transport system depends on the criteria of managers at the port of Barcelona. This is the reason why the cost analysis is included in this table.

Table 11-1: Comparison of the Studied Horizontal Transport Systems

	First scenario		
	Cargo handling time for a train (h)	Variable cost (€/box)	Total investment (€)
4trucks	1,894	11,25	2.026.500
4AGVs	2,350	2,12	2.850.000
2SCs	1,627	5,97	2.562.500
2truck-8cassette	1,924	9,15	1.856.500
2truck-10cassette	1,677	7,05	1.872.500
3truck-9cassette	1,382	9,56	1.981.500
2AGV-10cassette	1,807	1,50	2.455.000
3AGV-9cassette	1,452	2,03	2.797.000
3AGV-12cassette	1,405	2,07	2.821.000
	Second scenario		
	Cargo handling time for a train (h)	Variable cost (€/box)	Total investment (€)
4trucks	1,894	11,25	2.026.500
4AGVs	1,358	2,12	5.700.000
2SCs	1,627	5,97	2.562.500
2truck-8cassette	1,924	9,15	1.856.500
2truck-10cassette	1,677	7,05	1.872.500
3truck-9cassette	1,382	9,56	1.981.500
2AGV-10cassette	1,807	1,50	2.455.000
3AGV-9cassette	1,452	2,03	2.797.000
3AGV-12cassette	1,405	2,07	2.821.000
	Third scenario		
	Cargo handling time for a train (h)	Variable cost (€/box)	Total investment (€)
4trucks	1,239	11,25	6.079.500
4AGVs	1,242	2,12	8.550.000
2SCs	1,184	5,97	5.125.000
2truck-8cassette	0,987	9,15	3.713.000
2truck-10cassette	0,964	7,05	3.745.000
3truck-9cassette	0,852	9,56	3.963.000
2AGV-10cassette	1,001	1,50	4.910.000
3AGV-9cassette	0,852	2,03	5.594.000
3AGV-12cassette	0,851	2,07	5.642.000

In this chapter, we have done a comparison between the studied vehicles and between transport systems that work with or without cassettes.

11.1. Truck vs. AGV vs. Shuttle Carrier

First of all, the main advantage of truck is the price, which is the cheapest. So, the total investment of the system is the lowest compared with the other vehicles in the first and the second scenario. In the third scenario, two shuttle carriers have the lowest investment due to the fact that two rail cranes are needed to handle all the demand. However, the main disadvantage of truck is that its variable cost is the highest due to the personnel cost.

Related to AGVs, the cargo handling time for a train is longer than in case of using trucks in the first scenario because of its lower speed than trucks. But on the contrary, in the second scenario, the cargo handling time is shorter when four AGVs are used than when four trucks are used because two rail cranes are necessary to handle the demand. Finally, in the third scenario, the cargo handling time for a train is quite similar because the equipment with the minimum productivity is the yard crane instead of the vehicles as in the first scenario. In addition, the investment is higher than in trucks. The main advantage of the systems that work with AGVs is their variable cost. As we can see in Table 11-1 the variable cost for trucks is 11,25 €/box and for AGVs it is 2,12 €/box. The AGV does not require a driver. This is the reason why the variable cost is so different.

Currently, at the port of Barcelona there is an important difficulty to introduce this type of vehicles because working with AGVs leads to a reduction in the workforce and a consequent social problem.

Another disadvantage when containers are transferred from rail to yard area with AGVs is that the transport system is not flexible because any alteration in the way, which can be caused by a presence of an obstacle or another vehicle, leads to a possible delay in the schedule due to the fact that the AGV has to wait to receive new orders related to the new way.

On the contrary, shuttle carriers are often used in container terminals because their high level of flexibility. Moreover the results show that they have an intermediate level of investment and variable cost between trucks and AGVs.

11.2. Work with or without Cassette

As we can see in Tables 11-1, when either trucks or AGVs work with cassettes, the total investment is smaller than when vehicles work without cassette due to the fact that fewer vehicles are needed to do the same work and the investment in cassettes is lower than in vehicles. The variable cost of the transport systems with cassettes is lower for the same reason and in the case of using trucks, fewer personnel are necessary.

Another advantage of working with cassettes is the fact that less time for a train is required because the use of cassettes increases the productivity of vehicles considerably. It happens due to the fact that either trucks or AGVs do not wait to be served by cranes, which means they are continuously travelling, and because they transfer more than one container in each movement. These times are shown in Table 11-1.

At the same time, the cassette is used as a temporally storage stacking containers one upon the other, while they wait to be allocated in their appropriate place in the yard.

12. CONCLUSIONS AND FUTURE WORK

This research is focused on the new container terminal, which is called “Prat Pier” at the port of Barcelona that will start working during the year 2009. The analysed area is the train terminal where the containers are transferred between rail and yard area. The objective of this project is to compare the performance of different types of vehicles as horizontal transport systems in order to move containers. The transport systems analysed in this report are truck, AGV, shuttle carrier, truck with cassette and AGV with cassette.

With several interviews with a project manager of TERCAT, which is the company that is going to manage the new container terminal, we obtained the information about the possible policies for operating. By this way, we chose one of them that we considered the most appropriate. It is preparation of cargo on the ground, unloading when train arrives directly onto a vehicle and then loading cargo onto the train.

Different levels of demand were considered in order to analyse all the transport systems in different scenarios. The total demand in the container terminal is 3.000.000 TEU per year. The demand in the first scenario represents a 5% of total demand and it is related to the first years of operation, the demand of the second scenario represents a 15% and the demand of the third scenario represents a 25%, which refers to maximum stability of the container terminal that is forecasted to achieve in about fifteen or twenty years.

The main part of our study was the design of the analytical model with an Excel worksheet that let us analyse the performance in the focused area in order to compare the different types of the studied transport systems. Three possibilities were studied according to the number of rail cranes to handle the containers of each train depending on if one, two or three rail cranes were used. This model is based on the queuing theory and statistics with the calculated cycle times of all the equipments involved. The model let us determine the suitable number of vehicles and cassettes for all studied transport systems and in the different scenarios. With the cycle times and the waiting times that were obtained from the model, the productivities were calculated. Then, it was possible to determine the cargo handling for a train. With this value, the appropriate number of rail cranes was chosen in each scenario.

Finally, the cost analysis was done for the viable alternatives of transport systems, which had been selected with the cargo handling time for a train. The cost analysis is divided in two parts, the first one is related to the variable cost for each movement and the second one is the investment in the necessary equipment.

The results indicate that some horizontal transport systems are more efficient than others. This report tries to help managers to choose the best equipments depending on their criteria. It shows the viable options of horizontal transport within the container terminal with their costs and the advantages and disadvantages between truck, AGV and shuttle carrier and the option of working with or without cassette.

A possible future work will use data from this project in order to simulate the performance of the equipments that will be working in the studied area in the container terminal. The simulation will check if the results of this analytical model represent real operations in the port before the investment.

Another possibility is to use this analytical model in other ports adapting it to the characteristics of the new port and to its demand. If the demand is so high, it is possible to design another model based on the first policy of operating presented in chapter 7.3., which refers to unload and load the train simultaneously while the train is in the rail terminal.

Moreover, this analysis can be the first step to analyse the whole container train terminal, studying all the processes from the arrival of containers by ship to its departure by train or on the contrary, from the arrival by train to the departure by ship.

We have focused on the train terminal within a port, but the analytical model can be also used in any intermodal terminal.

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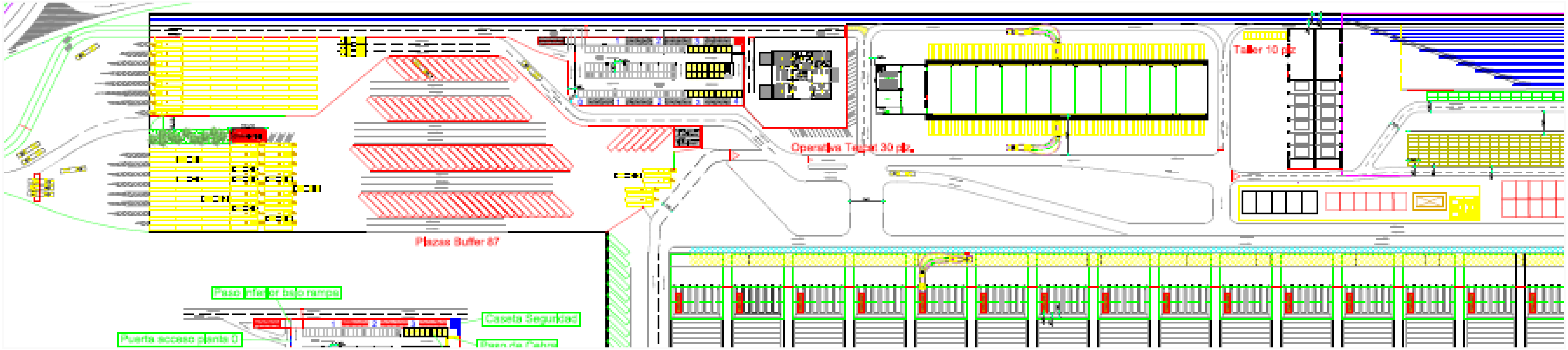
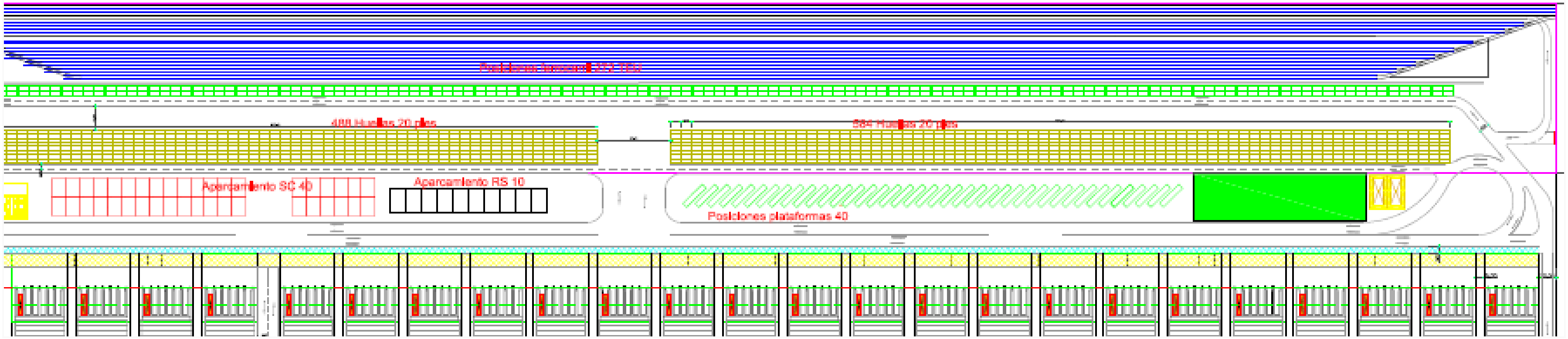
APPENDIX 1: Geographical Situation of the Port of Barcelona

APPENDIX 2: Layout of the Port of Barcelona

APPENDIX 3: Layout of the Prat Pier





APPENDIX 4: Cost Analysis

	Assumptions	unit	calculation	4 trucks	4 AGVs	2 SCs	2truck+8cassettes
	Rail crane						
A1	Production RC	box/year		100.000	100.000	100.000	100.000
A2	Gross productivity RC	box/h		25,034	18,135	29,775	14,937
A3	Gross working hours RC	h/year	A1/A2	3.995	5.514	3.358	6.695
	Vehicles						
B1	Operational vehicles per RC	num of vehicles		4	4	2	2
B2	Additional vehicles per RC	num of vehicles		0,5	0,5	0,5	0,5
B3	Total vehicles per RC	num of vehicles	B1+B2	4,5	4,5	2,5	2,5
B4	Total cassettes per RC	num of cassettes		0	0	0	8
B5	Gross working hours	h/year	A3*B1	15.978	0	6.717	13.390
B6	Vehicle investment	€/vehicle		117.000	300.000	425.000	117.000
B7	Cassette investment	€/cassette		8.000	8.000	8.000	8.000
B8	Total investment	€	B3*B6+B4*B7	526.500	1.350.000	1.062.500	356.500
B9	Depreciation	number of years		10	15	15	15
B10	Equipment variable cost	% of investment		5%	5%	5%	5%
B11	Interest	% of investment		4%	4%	4%	4%
	Manning						
C1	Operational hours per RC	h/year	B5*1,1	17.576	0	7.389	14.728
C2	Manning (1 worker = 1200 h/year)	workers	C1/1200	15	0	6	12
C3	Personnel cost	€/(worker*year)		70.000	70.000	70.000	70.000
	Vehicle cost (per RC)						
D1	Depreciation	€/year	B8/B9	52.650	90.000	70.833	23.767
D2	Variable cost vehicle	€/year	(B10+B11)*B8	47.385	121.500	95.625	32.085
D3	Variable cost personnel	€/year	C2*C3	1.025.257	0	431.007	859.160
	Total						
E1	Total variable cost	€/(year*RC)	D1+D2+D3	1.125.292	211.500	597.465	915.011
E2	Variable cost/box	€/box	E1/A1	11,25	2,12	5,97	9,15
E3	Vehicle investment	€/RC	B8	526.500	1.350.000	1.062.500	356.500

Assumptions	**unit**	**2truck+10cassettes**	**3truck+9cassettes**	**2AGVs+10cassettes**	**3AGVs+9cassettes**	**3AGVs+12cassettes**
Rail crane						
Production RC	box/year	100.000	100.000	100.000	100.000	100.000
Gross productivity RC	box/h	19,832	21,872	18,423	19,846	21,172
Gross working hours RC	h/year	5.042	4.572	5.428	5.039	4.723
Vehicles						
Operational vehicles per RC	num of vehicles	2	3	2	3	3
Additional vehicles per RC	num of vehicles	0,5	0,5	0,5	0,5	0,5
Total vehicles per RC	num of vehicles	2,5	3,5	2,5	3,5	3,5
Total cassettes per RC	num of cassettes	10	9	10	9	12
Gross working hours	h/year	10.085	13.716	0	0	0
Vehicle investment	€/vehicle	117.000	117.000	350.000	350.000	350.000
Cassette investment	€/cassette	8.000	8.000	8.000	8.000	8.000
Total investment	€	372.500	481.500	955.000	1.297.000	1.321.000
Depreciation	number of years	15	15	15	15	15
Equipment variable cost	% of investment	5%	5%	5%	5%	5%
Interest	% of investment	4%	4%	4%	4%	4%
Manning						
Operational hours per RC	h/year	11.093	15.088	0	0	0
Manning (1 worker = 1200 h/year)	workers	9	13	0	0	0
Personnel cost	€/(worker*year)	70.000	70.000	70.000	70.000	70.000
Vehicle cost (per RC)						
Depreciation	€/year	24.833	32.100	63.667	86.467	88.067
Variable cost vehicle	€/year	33.525	43.335	85.950	116.730	118.890
Variable cost personnel	€/year	647.100	880.128	0	0	0
Total						
Total variable cost	€/(year*RC)	705.459	955.563	149.617	203.197	206.957
Variable cost/box	€/box	7,05	9,56	1,50	2,03	2,07
Vehicle investment	€/RC	372.500	481.500	955.000	1.297.000	1.321.000

APPENDIX 5: Variable Cost and Investment

- Variable Cost and Investment in First Scenario

	4 trucks	4 AGVs	2 SCs	2truck + 8cassettes	2truck + 10cassettes	3truck + 9cassettes	2AGVs + 10cassettes	3AGVs + 9cassettes	3AGVs + 12cassettes
Variable cost/box	11,25	2,12	5,97	9,15	7,05	9,56	1,50	2,03	2,07

RC investment	1.500.000	1.500.000	1.500.000	1.500.000	1.500.000	1.500.000	1.500.000	1.500.000	1.500.000
Vehicle investment	526.500	1.350.000	1.062.500	356.500	372.500	481.500	955.000	1.297.000	1.321.000
Total investment	2.026.500	2.850.000	2.562.500	1.856.500	1.872.500	1.981.500	2.455.000	2.797.000	2.821.000

- Variable Cost and Investment in Second Scenario

	4 trucks	4 AGVs	2 SCs	2truck + 8cassettes	2truck + 10cassettes	3truck + 9cassettes	2AGVs + 10cassettes	3AGVs + 9cassettes	3AGVs + 12cassettes
Variable cost/box	11,25	2,12	5,97	9,15	7,05	9,56	1,50	2,03	2,07

RC investment	1.500.000	3.000.000	1.500.000	1.500.000	1.500.000	1.500.000	1.500.000	1.500.000	1.500.000
Vehicle investment	526.500	2.700.000	1.062.500	356.500	372.500	481.500	955.000	1.297.000	1.321.000
Total investment	2.026.500	5.700.000	2.562.500	1.856.500	1.872.500	1.981.500	2.455.000	2.797.000	2.821.000

- Variable Cost and Investment in Third Scenario

	4 trucks	4 AGVs	2 SCs	2truck + 8cassettes	2truck + 10cassettes	3truck + 9cassettes	2AGVs + 10cassettes	3AGVs + 9cassettes	3AGVs + 12cassettes
Variable cost/box	11,25	2,12	5,97	9,15	7,05	9,56	1,50	2,03	2,07

RC investment	4.500.000	4.500.000	3.000.000	3.000.000	3.000.000	3.000.000	3.000.000	3.000.000	3.000.000
Vehicle investment	1.579.500	4.050.000	2.125.000	713.000	745.000	963.000	1.910.000	2.594.000	2.642.000
Total investment	6.079.500	8.550.000	5.125.000	3.713.000	3.745.000	3.963.000	4.910.000	5.594.000	5.642.000