ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

ENERGETISCHE VERBRAUCHANALYSE VON CONTAINERHÄFEN

ENERGY CONSUMPTION ANALYSIS OF CONTAINER PORTS

ANALISIS DEL CONSUMO ENERGÉTICO DE LOS PUERTOS CONTENEDORES

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Madrid
Mayo de 2014

PONTIFICIA UNIVERSITAS COMILLENSIS MATRITI

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RESUMEN DEL PROYECTO

Introducción

En el área del transporte de materiales, los puertos juegan un papel principal ya que entre el 80% y el 90% (en peso y volumen) de las mercancías se trasladan a través del mar con barcos especializados según la carga a transportar.

Todo tipo de sustancias se pueden transportar vía marítima, por ello hay tanto barcos como terminales especializadas para cada sustancia. Los tipos de terminales portuarias se dividen en tres grandes grupos, carga a granel seca (dry bulk), carga a granel líquida (liquid bulk) y contenedores. Cada terminal esta preparada para recibir su tipo de carga y cargar o descargar de la manera más óptima y rápida el barco.

Las terminales de carga a granel seca manejan sustancias cómo carbón, cereales o cemento entre otros, estos materiales son transportados por unos buques especializados llamados graneleros. Las terminales de carga a granel líquida trabajan principalmente con petróleo y gas natural licuado. La naturaleza de estas sustancias hacen que la seguridad sea un factor de extrema importancia en este tipo de terminales portuarias así como en los barcos que las transportan, dichos barcos son los llamados petroleros. Por último, las terminales de contenedores son las encargadas de recibir todo tipo de carga que se transporta en contenedores, ésta puede ser de todo tipo, desde televisiones hasta productos congelados. Hay distintos tipos de contenedores ya que dependiendo de la sustancia transportada se tienen necesidades distintas, por lo general suelen ser contenedores metálicos cerrados herméticamente y sin ventilación, aunque si la carga necesita estar a una temperatura concreta, existen contenedores con sistema de conservación de temperatura, ya sea de frío o calor. Los barcos encargados de llevar dichos contenedores, son los buques portacontenedores. Existen también unas terminales utilizadas para cargas especiales como coches o maquinaria pesada.

Para funcionar de la manera más óptima posible, cada terminal posee distinto equipo y maquinaria adaptada al tipo de carga que se va a manejar. La función de la terminal es cargar y/o descargar el barco de la manera más rápida posible ya que un barco que no esté navegando, está perdiendo dinero.

Además, las terminales también tienen la capacidad de almacenar durante un periodo de tiempo la carga recibida.

Este proyecto se ha centrado en el estudio de las terminales de contenedores.

Objetivos

El principal objetivo de este proyecto es el de analizar el consumo energético en las terminales de contenedores. Haciendo diferencia entre la distinta maquinaria que puede ser utilizada así como las diferentes combinaciones de esta maquinaria usadas para hacer funcionar el puerto correctamente, ya que como se verá a continuación, no existe una combinación de maquinaria óptima, si no que cada puerto utiliza unos u otros aparatos según sus características.

Metodología

Para llevar a cabo dicho objetivo, primero se ha analizado la estructura de una terminal de contenedores con el propósito de conocer todas las actividades que se llevan a cabo para cargar y descargar un barco, almacenar los contenedores o cargar los contenedores en camiones o trenes para su posterior transporte por tierra.

Una vez conocido el funcionamiento de dichas terminales, se ha hecho un estudio de la energía consumida por los barcos en todas sus operaciones dentro de los límites del puerto, así como la consumida por las grúas y máquinas más comúnmente utilizadas. Para estudiar todos los aspectos del puerto y hacer un análisis más profundo, también ha sido considerada la energía consumida por la parte administrativa de la terminal, como los gastos derivados de los edificios o la iluminación del puerto.

Tras el análisis individual cada aspecto del puerto: barcos, maquinaria y administración, se ha procedido a hacer un estudio del consumo producido por diferentes sistemas de funcionamiento que pueden ser utilizados para el correcto funcionamiento de estas terminales portuarias. Los sistemas de funcionamiento utilizados, son las posibles combinaciones de maquinaria usadas en las terminales de contenedores, sin embargo, el cálculo individual permite hacer distintas combinaciones y adaptarlas a situaciones reales ya que los sistemas de funcionamiento estudiados no dejan de ser de carácter teórico.

Finalmente, para validar los resultados obtenidos, se ha hecho una comparación de éstos con la energía consumida por la maquinaria en el puerto de Hamburgo.

También se ha hecho un cálculo de las emisiones de CO_2 derivadas de la energía consumida, así como del diesel consumido por los barcos y las distintas máquinas que funcionan con este combustible.

Resultados

Tras analizar la estructura de las terminales de contenedores, se observó que estas terminales tienen tres zonas diferenciadas: la unión entre mar y tierra, zona de almacenamiento de contenedores y la zona de carga de los contenedores para su transporte por tierra y donde se encuentran los edificios, parkings, etc. En cada zona se llevan a cabo distintas operaciones con diferentes máquinas y grúas.

La típica operación de este tipo de terminales consiste en:

1. Descargar el barco.
2. Transporte horizontal de los contenedores hasta la zona de almacenamiento.
3. Almacenamiento de los contenedores.
4. Transporte horizontal de los contenedores hasta la zona de carga para su transporte terrestre en camiones o trenes.
5. Carga de los contenedores en camiones o trenes.

Esta operación funciona en los dos sentido. Para cada función son utilizadas distintas máquinas, en este proyecto se han estudiado y calculado el consumo de la maquinaria más utilizada.

- Carga/descarga del barco
    - Grúa STS (Ship-to-Shore)
- Transporte horizontal
    - Straddle Carrier
    - Tractor con remolque
    - Reach Stacker
    - Shuttle Carrier
    - AGV (Vehículos de guiado automático)
- Almacenamiento
    - Straddle Carrier
    - Grúa RTG (Rubber Tyred Gantry Crane)
    - Grúa RMG (Rail Mounted Gantry Crane)

- Carga/descarga en vehículos para transporte terrestre (camones, trenes)
  - Straddle Carrier
  - Grúa RTG
  - Grúa RMG
  - Reach Stacker

Tras analizar cada grúa y vehículos individualmente, se han estudiado distintos posibles sistemas de funcionamiento. Como ya se ha mencionado, no existe un sistema óptimo de funcionamiento, si no que éstos dependen de las características y posibilidades de los distintos puertos. Los sistemas estudiados han sido:

- Sistema Straddle Carrier
  - 4 – 5 SC por cada Grúa STS
- Grúa RTG + Tractor con remolque
  - 2 – 3 Grúas RTGs por cada Grúa STS
  - 4 – 5 Tractores por cada Grúa STS
- Grúa RMG + Tractor con remolque
  - 2 Grúas RMGs por cada Grúa STS
  - 4 – 5 Tractores por cada Grúa STS
- Grúa RMG + Shuttle Carrier
  - 2 Grúas RMGs por cada Grúa STS
  - 2 – 3 Shuttle Carriers por cada Grúa STS
- Grúa RMG + AGV (Vehículo de guiado automático)
  - 2 Grúas RMGs por cada Grúa STS
  - 5 – 6 AGVs por cada Grúa STS
- Reach Stacker + Tractor con remolque
  - 3 – 4 Reach Stacker por cada Grúa STS
  - 4 – 5 Tractores por cada grúa STS

Cada sistema operativo tiene distintas características con sus ventajas y desventajas, aunque todos hacen que una terminal de contenedores funcione correctamente.

Para validar los resultados obtenidos de la maquinaria, se han comparado con la energía consumida por el puerto de Hamburgo, utilizando los mismos aparatos.

En cuanto al consumo energético de los barcos en el puerto se han tenido que hacer algunas suposiciones, ya que ni todos los barcos ni los puertos son iguales. Una vez dentro del puerto, el barco tiene dos etapas de operación distintas:

- Maniobra: El barco entra en los límites del puerto y se prepara para atracar.
- Barco atracado: El barco ya está atracado. Esta etapa se divide en dos partes.
    - Carga/Descarga
    - Hotteling: El barco está atracado sin sufrir ninguna operación de carga o descarga.

En este proyecto se ha asumido que el barco para un total de 24 horas en el puerto divididas en 2 horas de maniobra de entrada, 20 horas de atraque y 2 horas de maniobra de salida.

Para finalizar el estudio, se ha investigado el consumo energético realizado por la parte administrativa del puerto. Este consumo se ha obtenido a partir de los consumos realizados por algunos de los puertos más importantes del mundo: Singapur, Hamburgo, Hong Kong y Rotterdam.

Conclusiones

En este proyecto se ha estudiado el funcionamiento estándar de las terminales de contenedores y se ha desarrollado una herramienta que permite hacer un cálculo aproximado de la energía consumida por estas terminales dependiendo de la maquinaria utilizada.

También, se ha podido observar que la tendencia en estos puertos es la de disminuir el consumo energético así como las emisiones de CO_2 gracias al avance de las tecnologías, vehículos híbridos, mayor eficiencia o el uso de combustibles alternativos. Además, estos puertos van adquiriendo un mayor grado de automatización a medida que se desarrolla más este concepto, y poco a poco, los AGVs (Vehículos de guiado automático) van adquiriendo más importancia y cada vez son más utilizados.

ABSTRACT

Introduction

In the world of goods transportation harbors play a central role as 80% to 90% (in volume and weight) of the world's goods are transported via shipping with specialized vessels depending on the transported material.

All kind of products can be transported by sea, and it is for this reason there are specialized boats as well as port terminals for each substance. There are three main types of terminals, liquid bulk, dry bulk and container terminals. Each of the terminals is prepared to receive their kind of material and load/unload the vessel in the most efficient and fastest way.

Dry Bulk terminals work with substances like coal, minerals, cement and grain. Vessels called bulkers transport these materials. For the loading and unloading ship loaders are used. The Liquid Bulk Terminals treat dangerous goods like liquefied natural gas (LNG), petroleum, gasoline or chemicals. The nature of these substances makes security an extremely important factor on this type of terminals. The vessels used to transport the liquid bulk are tankers. Finally, the container terminals receive all the materials that come in containers, those can be of all kind, from TVs to refrigerated food. There are different kinds of containers depending on the transported goods. There are also special terminals used for particular loads like cars or heavy machinery.

To work in the most efficient way, each terminal is equipped with the proper machinery adapted to the load that is going to be managed. The objective of a port terminal is to load/unload the vessel as fast as possible, since while the boat is not sailing it is losing money.

Also, the terminals have the capacity to store for a period of time the received material.

This project is focused on the container terminals.

Targets

The main objective of this project is to analyze the energy consumption in the container terminals. Making difference between the different machinery that can be used, as well as the different combinations of this machinery utilized to make the terminal work. As it will be forward explained, there is no perfect machinery combination, each harbor uses one or another depending on its characteristics.

Methodology

To carry out the mentioned targets, first it has been analyzed the standard structure of a container terminal in order to know all the processes that take place in the terminal to load/unload the vessel, store the containers, or load/unload the containers from the earth transport, trucks and trains.

Once the operation of these terminals was known, it has been analyzed the vessels energy consumption in all its operations inside the port boundaries, as well as the consumed energy of the most commonly used cranes and machinery. To study all the aspects of the ports and do a deeper analysis, it has also been considered the energy consumed by the administration of the port, like buildings, lighting and heating.

After the individual study of each aspect of the terminal: vessels, machinery and administration, it has been researched the consumption performed different operation systems used to make this kind of terminals work. The operations systems used are the possible combinations of machinery used in the container terminals, however, the individual calculations allows different combinations that can be adapted to real situations, since the studied operation systems are theoretical.

Finally, to validate the obtained results, they have been compared with the energy consumption made by the machinery in Hamburg Port.

It has also been calculated the CO_2 emissions related to this energy consumption, as well as the diesel consumption done by the vessels and the machinery that uses this fuel.

Results

After analyzing the structure of the container terminals, it was observed that these terminals have three different operational areas: junction between sea and land, container yard, where the containers are stored and the land operations area, office buildings, parking, etc. In each zone the proper equipment and cranes carry out different operations.

The standard operations of these terminals consists on:

1. Unload the vessel.
2. Horizontal transport of the containers to the container yard.
3. Storage of the container.
4. Horizontal transport of the containers to the land operations area to be loaded in trucks or trains for its inland transport.

5. Load of the containers into trucks or trains.

This operation works in both senses. For each activity, different machines are used. In this project it has been studied and calculated the most commonly used.

- Load/Unload the vessel
  - STS crane (Ship-to-Shore)
- Horizontal transport
  - Straddle Carrier
  - Trailer Truck
  - Reach Stacker
  - Shuttle Carrier
  - AGV (Automated Guided Vehicle)
- Container storage
  - Straddle Carrier
  - RTG crane (Rubber Tyred Gantry)
  - RMG crane (Rail Mounted Gantry)
- Loading/Unloading in inland transport means (trucks or trains)
  - Straddle Carrier
  - RTG crane
  - RMG crane
  - Reach Stacker

After an individual analysis of each crane and vehicle, it has been researched different operation systems. As it has been already mentioned, there isn't a perfect operation system; they depend on the characteristics and possibilities of the port. The studied systems have been:

- Pure Straddle Carrier
  - 4 – 5 SC per STS
- RTG + Trailer truck
  - 2 – 3 RTGs per STS
  - 4 – 5 Trailer trucks per STS
- RMG + Trailer truck
  - 2 RMGs per STS
  - 4 – 5 Trailer trucks per STS
- RMG + Shuttle Carrier
  - 2 RMGs per STS
  - 2 – 3 Shuttle Carrier per STS

- RMG + AGV
    - 2 RMGs per STS
    - 5 – 6 AGVs per STS
- Reach Stacker + Trailer truck
    - 3 – 4 RS per STS
    - 4 – 5 Trailer trucks per STS

Each operation system has different characteristics with its advantages and disadvantages, but they all make the terminal work.

To validate the obtained results, thy have been compared with the energy consumed by the Hamburg Port, using the same machinery.

Regarding the energy consumed by the vessels, some assumptions had to be made, since each boat and port is different. Once in the port boundaries, the boat has two different operating stages:

- Maneuver Stage: the ship has entered the port bounds and is getting ready to dock
- Berth Stage: the ship is already in the berth. At this stage there are two different parts.
    - Loading/Unloading
    - Hotteling: the ship is in the berth without any loading operation.

In this project it has been assumed that the vessel spends 24 hours in the port, divided in: 2 hours of maneuver (to enter the port), 20 hours at the berth (loading/unloading) and 2 hours of manoeuver (to exit the port).

To finish the study, it has been researched the energy consumption performed by the ports administration. This consumption has been obtained from the consumption done by some of the most important ports in the world, such as Singapore, Hamburg, Hong Kong and Rotterdam.

Conclusions

In this project it was been studied the standard operation of the container terminals and it has been developed a tool with which it can be done an estimate calculation of the consumed energy of these terminals depending on the used machinery.

Also, it has been observed that the tendency of these ports is to reduce the energy consumption and the CO_2 emissions. This can be achieved with developments like different advances in each process, hybrid vehicles, higher efficiency and use of alternative fuels. Also these ports tend to have a higher automation degree and the AGVs are getting more relevance and importance as they are being developed.

Master's Thesis

Energetische Verbrauchsanalyse von Containerhäfen

Energy consumption analysis of container ports

written by

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Abstract

In this project the main energy consuming processes that take place in a container terminal, when transporting a container from the vessel to the inland transport means or to the storage area (and vice versa) have been examined. In order to do this, analysis was undertaken of the most important energy consumers in a container terminal, such as the vessel consumption (from the moment it is inside the port boundaries until the departure), the cargo handling equipment consumption and the electricity consumption related to the usage of buildings and lighting. After analysing and calculating each individual consumption, the total energy consumption of different operation systems was evaluated. The operation systems, which were examined, are the most commonly used in standard container terminals but due to the individual energy consumption calculations, it is also possible to make different combinations and to obtain the energy consumption from other operation systems. The results obtained from the constructed model of a container terminal were validated by comparison with the actual energy consumption of a real port, namely the Hamburger Hafen and Logistik AG (HHLA). To complete the project, diesel consumption and CO_2 emissions were also determined.

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Aufgabenstellung

Masterarbeit

von

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Thema:

Energetische Verbrauchsanalyse von Containerhäfen

Energy consumption analysis of container ports

Ausgangslage:

Häfen spielen eine zentrale Rolle im Gütertransport. In Deutschland wurde 2010 ein Seegüterumschlag von 276 Millionen Tonnen erreicht. Auch die Binnenschifffahrt trug mit 230 Millionen Tonnen zum Gesamtgüteraufkommen bei. Während Seehäfen für den Außenhandel eine große Bedeutung haben, stellen Binnenhäfen wichtige Transportverbindungen im Inland und zum benachbarten Ausland dar. Somit bilden Häfen oft den Kern von großen Umschlags und Handelszentren.

Zielsetzung:

Im Rahmen dieser Arbeit soll der Energieverbrauch von Häfen untersucht werden. Der Schwerpunkt liegt dabei auf dem Aufstellen von typischen Energiebilanzen.

In einem ersten Schritt soll eine Unterscheidung unterschiedlicher Hafentypen durchgeführt und deren typische Struktur analysiert werden, so dass der Energieverbrauch bestimmten Strukturen und Prozessen zugeordnet werden kann. Für die einzelnen Teilverbraucher sind typische Energieverbräuche zu recherchieren und in Tageslastgängen und Energiebilanzen zu visualisieren. Neben dem Strombedarf soll dabei auch Wärmebedarf/Kältebedarf und Treibstoffbedarf ausgewiesen werden.

Darauf aufbauend sollen Gesamtbilanzen für typische Hafenanlagen aufgestellt werden. Neben der Zusammensetzung der benötigten Endenergie ist auch eine primärenergetische Untersuchung durchzuführen.

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Ausgabedatum: 17.06.2013

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Prof. Dr.-Ing. Ulrich Wagner

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Terms and abbreviations

AGV: Automated guided vehicle
RoRo: Roll on; Roll off
RMG: Rail mounted gantry
RS: Reach Stacker
RTG: Rubber tyre gantry
SC: Straddle Carrier
ShC: Shuttle Carrier
STS: Ship to shore
TEU: Twenty-foot equivalent unit
TTU: Tractor Trailer Unit

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Total diesel [l] = $\frac{Used\ power\ [kW]\ x\ time\ [h]\ x\ specific\ consumption\ [\frac{g}{kWh}]}{Diesel\ density\ [\frac{g}{l}]}$ [Eq.1]

Energy [MWh] = Total diesel [l] x 0,84$\frac{Kg\ diesel}{l}$ x 42,7 $\frac{MJ}{Kg\ diesel}$ x 0,0027 $\frac{MWh}{MJ}$ x η [Eq.2]

CO_2 emissions [kg] = Total diesel [l] x 2,65 $\frac{kg\ CO_2}{l\ diesel}$ [Eq.3]

Total Energy [MWh] = 7,2 x 10^6 [container] x 0,0032 [$\frac{MWh}{container}$] [Eq.4]

CO_2 Emissions [kg] = Energy [MWh] x CO_2 emission factor [$\frac{kg\ CO_2}{MWh}$]. [Eq.5]

Annual Diesel Consumption [l] = Diesel Consumption [$\frac{l}{h}$] x operation time [h]. [Eq.6]

Average Power [kW] = $\frac{Energy\ [kWh]}{operation\ time\ [h]}$. [Eq.7]

1. Introduction

1.1 General view

In the world of goods transportation harbours play a central role as 80% to 90% (in volume and weight) of the world's goods are transported via shipping.

All kind of products can be transported by sea and it is for this reason there are various types of port terminals, each one prepared to handle different types of cargo. To carry out a successful transport there are many different processes implemented, most of which take place on the port terminal. The main types of port terminals are: dry bulk, liquid bulk, container and multi-purpose terminal.

The dry bulk terminals are used to transport and/or store unpacked solid goods, such as minerals, cement, coal and grain. Furthermore specialized equipment such as ship loaders are used in these terminals. The liquid bulk is not dissimilar to the dry bulk, with the only significant difference being that the goods are liquid in their case. The main transported liquid materials are: liquefied natural gas (LNG), petroleum, gasoline or chemicals. The transportation of these liquefied goods is made possible by use of the marine loading arms equipment. The marine loading arms are hoses with the specialized purpose of handling these liquid materials**.** Due to the volatile nature of the liquid bulk goods, one of the most important issues is terminal security in the port. The multi purpose terminals are mainly utilised to transport all the goods that are not suitable for the other terminals like machinery or RoRo (wheeled vehicles). In some circumstances, the multi-purpose terminals can also be used to substitute the other terminals, normally they can also operate as container terminals to load or unload a container ship. The container terminal must be clarified further to conclude this explanation about port terminals.

1.2 Container Terminals

The primary focus of this project is the container terminals; therefore a deeper explanation than that given of the other terminals must be provided.

The container terminals are used to load or unload a container ship, to store the containers or to directly distribute them from the ship by inland transport (trains and trucks). To fulfil their role as a container, these terminals have different operational areas, where specific processes are implemented. These processes are carried out by specialized equipment such as cranes or cargo handling machinery. The combination of different equipment in order to carry out the different processes and allow the container terminal to be fully functional is called the layout of the port. There are many possibilities of combinations, but as yet to be explained; only some of the layouts are the most used ones and there are certain combinations that are not recommended. There is not an ideal operation system, since the operation of a container terminal is dependant on several factors. As to be demonstrated shortly, different cargo handling equipment can do the same work. Different layouts will be used depending on the characteristics and requirements of the container terminal itself. All terminal activities are coordinated by the port administration, which controls everything from the vessel traffic to the lighting of the port.

2. Container Terminals [1, 2]

2.1 Container Terminal areas

As explained in the introduction, the container terminals have different areas where all the activities are undertaken and different equipment is used.

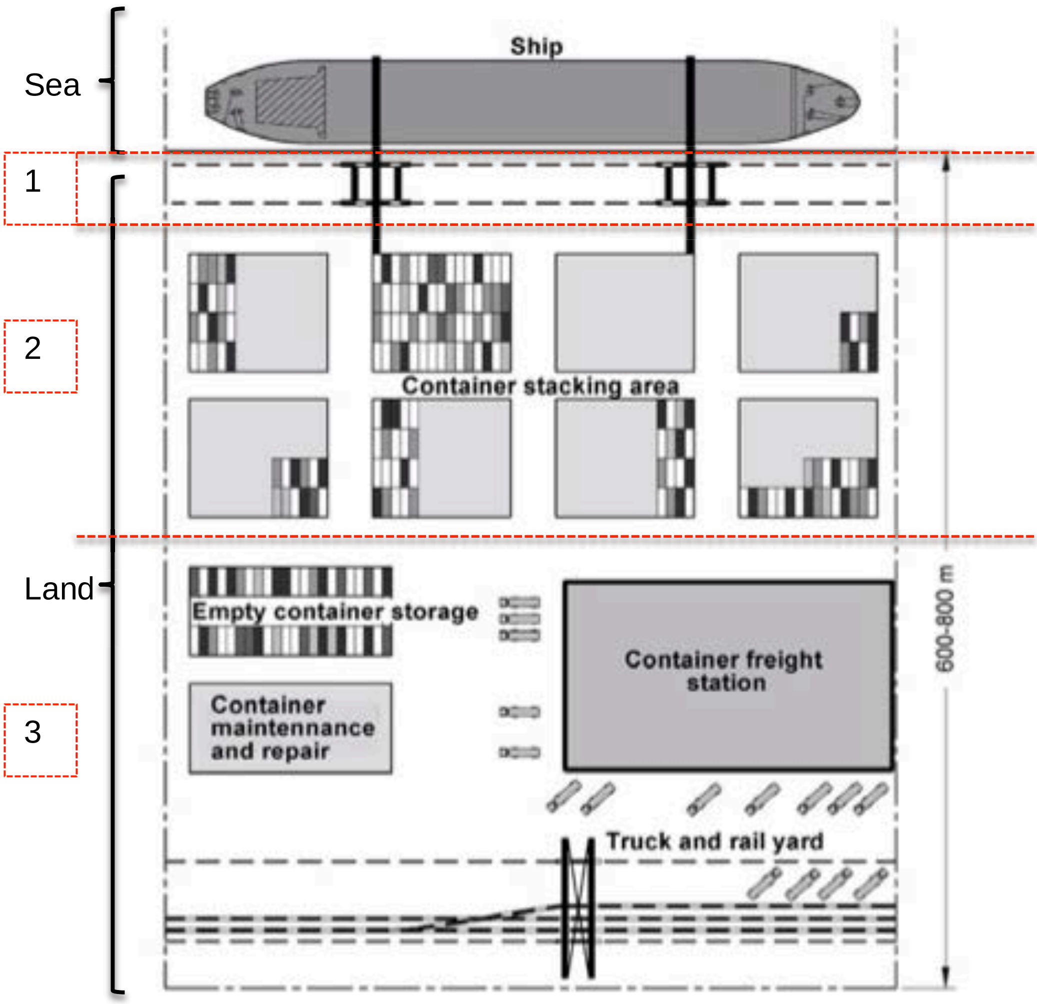

Fig. 2.1: Container Terminal general layout

In the illustration above the standard layout of a container terminal can be appreciated.

There are three operational areas [1, 2]:

- 1. Area between the quay and the stacking zone.
- 2. Container yard, where the containers are stored.
- 3. Land operations area, office buildings, parking, empty container storage, etc.

In these three operational areas different machinery is utilised. The most frequently used machinery has been studied and analysed in this project. The same tools can be used for different purposes.

2.2 Operation

In the operation of a container terminal different cranes and vehicles are involved. First, the vessel arrives at the port and after manoeuvring it is docked. During the berth time, the cranes on the 1st operational area unload the containers from the vessel. Once the containers are unloaded, they are moved to the 2nd operational area by horizontal transport equipment. In the stacking area the containers are stored by specialized cargo handling equipment. From the stacking area, the container can be transported and loaded in an inland transport mean, such as a truck or train, enabling it to reach their final destination. Each of the above mentioned activities are carried out by different cargo handling equipment.

- At the vessel (1st operational area)
    - STS Crane
- Container horizontal transport (transport between operational areas)
    - Straddle Carrier
    - TTU
    - Reach Stacker
    - Shuttle Carrier
    - AGV
- Container stacking (2nd operational area)
    - Straddle Carrier
    - RTG Crane
    - RMG Crane
    - Reach Stacker
- Truck and train loading/unloading (3rd operational area)
    - Straddle Carrier
    - RMG Crane
    - RTG Crane
    - Reach Stacker

There is not an ideal container terminal layout as all the equipment above can be combined and used in different ways, depending on the size and requirements of the container terminal.

In the first area (at the quay side), the most commonly used equipment in medium and big terminals is the STS crane. For the container's horizontal transport, all the equipment has a similar service but some of them can also be used as container stacking equipment. For the stacking zone (2nd area), there are different possibilities that can be used, depending on the machinery in use. The containers can be stored in two different ways: block stacking or linear stacking. In block stacking, the yard gantry cranes such as RMG or RTG are the used but in the linear stacking the containers are stored by Straddle Carrier or Reach Stacker. The main difference between both systems is that in the block stacking there is no space between the containers and in the linear there is space available. Also, each machine has a different stacking capacity. The land operations area is where hinterland operations are carried out, where trucks or trains are loaded or discharged. If the most used hinterland transport is the truck, the 3rd area can be integrated in the stacking area, Should the train be the primary means of transportation, both zones are separated in order to prevent rail crossing.

2.3 Operation systems

The combination between the mentioned equipment is called the operation system. Only the most commonly used combinations of working systems have been analysed for this project, due to the large variety and vast array of possible combinations.

- Pure Straddle Carrier System
- RMG + AGV
- RTG + TTU
- RMG + TTU
- RMG + Shuttle Carrier
- Reach Stacker + TTU

Each operation system has different characteristics including energy consumption as well as differing requirements. In each operation area, different processes are performed, and to move a container from one area to another, cargo handling equipment for horizontal transport is required.

There are different factors that can determine which operation system should be used:

- Number of handled containers
- Available area
- Type of hinterland transport used

Among these factors, other considerations related to the type of equipment that has to be used, like the expected size of the vessel, the aimed container throughput and the costs, should all be taken into account.

3. Energy consumption

To study the energy consumption from a container terminal, it must first be understood how does it work and which processes are involved to make the terminal work. Once this has been done, the energy consumption from each process can be analysed. Having done this research, it was possible to combine each process to make different working operating systems and study the consumption of each such system. For the individual energy consumption, the processes implemented in the land part (the three main operational areas) as well as the energy consumption in the sea part, meaning the vessel energy consumption in the port, have all been taken into consideration.

3.1 Vessel [3]

For the calculations of the vessel energy consumption to be made, several considerations were involved, such as the vessel engines power or the time that it operates in the harbour bounds. These assumptions were made according to different investigations that had been carried out. What activities are done by the vessel and how this functions, were also considered. There are two main energy consuming equipment, the main engine and the auxiliary engine.

The main engine can be categorized according to different criteria. Using the rpm criteria, it can be slow, semi-fast or fast engine, and using the propulsion criteria; there is diesel propulsion, diesel-electric propulsion or turbine propulsion.

Table 3.1: Vessel engine clasification with the rpm criteria

	RPM
Slow	80 - 300
Semi-fast	300 - 1.000
Fast	1.000

Slow Engines have lower fuel consumption and are stronger, what means that they have cheaper maintenance and fewer breakdowns, which involve also fewer stops for the vessel due to reparations; this implies lower money losses, since the vessel makes profit only when traveling. That’s why this kind of engine is used for big oil tankers, dry bulk or container vessel. The main inconvenience of these engines is their much heavier weight compared to a semi-fast engine of the same installed power

For smaller vessels like Ferry or RoRo, semi-fast engines are used due to the better manoeuvrability and lower emissions.

The other energy consuming engine is the auxiliary engine. Normally these engines are semi-fast engines connected to an electric generator. This generated electricity is used for the electric equipment of the ship and the services needed by the crew.

This project has only focused on slow diesel engines because, as it has been cleared, these are the ones used on big container ships. Different values for the main and auxiliary engine power, according to the world vessel fleet in 2002, have been used.

Table 3.2: 2002 world vessel fleet average values

	Main Engine	Auxiliary Engine
Container Ship	30.885	5.746

All powers are in kW

In the port, the ship has two different operating stages:

- Manoeuvre Stage: the ship has entered the port bounds and is getting ready to dock.
- Berth Stage: the ship is already in the berth. At this stage there are two different parts.
  - Loading/Unloading: the ship is being loaded or unloaded.
  - Hotteling: the ship is in the berth without any loading operation.

The loading/unloading stage consumes more electricity than the Hotteling stage. In each stage, the energy consumption from both engines is different, for example in the berth stage, as it can be anticipated; the main engine is not used at all. The following table shows the used power percentage in each stage and by each engine, being M.E. the main engine and A.E. the auxiliary engine.

Table 3.3: Engines usage in the port

Manoeuvre		Berth	
M.E.	A.E.	M.E	A.E.
15%	50%	0%	40%

Both engines have different specific consumption, in the manoeuvre stage it is estimated a specific consumption from the main engine of 211 $\frac{g}{kWh}$ and the auxiliary engine has an estimated specific consumption of 208 $\frac{g}{kWh}$ in both stages.

Once the required power for each situation is known, only the required time for the manoeuvre and berth stages need to be determined. To simplify calculations, a manoeuvre stage of 2 hours and a berth stage of 20 hours have been assumed, which means that each vessel has a cycle of 24 hours in the port (2+20+2).

To make a study of the CO_2 vessel emissions it has considered the emission factor of 2,6 $\frac{kg\ CO_2}{l\ diesel}$ [4].

Having gathered all this information it is now possible to make an analysis of the ship energy consumption and CO_2 emissions at each stage. In order to do a more accurate analysis, a 7% of additional consumption is added to the total consumption. This added 7% is the estimated consumption of the auxiliary ships and tugboats that help the container vessel in the manoeuvre stage.

To do a validation of the energy consumption, the calculations are made in two different ways:

- Energy = Power x Time
- Energy = Diesel consumption x Diesel Density x Diesel calorific power x Engine performance.

Being the needed factors:

- Diesel density = 0,84 $\frac{kg}{l}$ [5]
- Diesel calorific power = 42,7 $\frac{MJ}{kg}$ [5]
- Engine performance (η) = 0,4 [6]
- 1 MJ = 0,00027 MWh.

$$\text{Total diesel [l]} = \frac{Used\ power\ [kW]\ x\ time\ [h]\ x\ specific\ consumption\ [\frac{g}{kWh}]}{Diesel\ density\ [\frac{g}{l}]} \qquad \text{[Eq.1]}$$

$$\text{Energy [MWh]} = \text{Total diesel [l] x } 0{,}84\frac{Kg\ diesel}{l}\ \text{x}\ 42{,}7\ \frac{MJ}{Kg\ diesel}\ \text{x}\ 0{,}0027\ \frac{MWh}{MJ}\ \text{x}\ \eta \qquad \text{[Eq.2]}$$

$$CO_2 \text{ emissions [kg]} = \text{Total diesel [l] x } 2{,}65\ \frac{kg\ CO_2}{l\ diesel} \qquad \text{[Eq.3]}$$

Table 3.4: Vessel energy consumption and CO_2 emissions

		Energy I [MWh]	Diesel Consumption [l]	Energy II [MWh]	CO_2 Emissions [t]
Maneuver (2+2 h)	M.E	18,53	4654,81	18,03	12,34
	A.E	11,49	2845,64	11,02	7,54
Berth (20 h)	A.E	45,97	11382,55	44,09	30,16
Total (day)		75,99	18883,00	73,15	50,04
Total (year)		27736,72	6892295,43	26698,99	18264,58
Total (extra consumption)		29678,29	7374756,11	28567,92	20911,12

An engine performance of 40% has been taken since as it has been explained, these engines have a higher performance than a normal diesel engine that has 30% to 35% approximately, and as it can be seen, the assumption is not very far from reality since both results are similar.

It can be appreciated that both calculated energies are very similar. In order to give an idea of what 18.883 litres of diesel represent, this can be compared to 1.000 cars driving 200 km, this is not that much if considering that in the biggest container vessel can fit up to 18.000 TEU, has a length of 400 metres, like putting 100 cars in a row and weights 165.000 tons, which is like the weight of 150.000 cars, and is as tall as a 19 storey building.

Fig. 3.1: Container ship

In the picture above each container represents a TEU, a unit used to describe a standard size container that measures 20 foot long (6,1 m). It is the most commonly used unit to indicate the capacity of a vessel or a port.

As it will be explained further on in the project, the ship's energy consumption and CO_2 emissions represent the main part of the total consumptions and emissions from a port, even though it is not a really a part of the harbour energy consumption, the vessel as well as the auxiliary boats and the tugboats consumption were taken into account in order to do a deeper study from all the energy that is consumed in the port bounds, also its sea part.

3.2 Inland

In the following chapter it is going to be explained the used equipment in the three operational areas. The explanation is going to detail how does these equipment work, their mission in the container terminal and their energy consumption and CO_2 emissions.

3.2.1 Ship-to-Shore Gantry Crane

The Ship to Shore gantry cranes are the connexion between sea and land, they work on the 1st operational area.

Fig. 3.2: Ship-to-Shore gantry crane

The mission of these cranes is to load or discharge the vessel. This type of cranes are the most commonly used because they allow a faster container throughput, that means that the vessel is less time at the port which is very important because as it has been said, the vessel makes profit only while shipping. The STS makes possible to lower the quay time because it can load and unload a ship at the same time, it takes a container when moving from the vessel to the land and loads a container when it moves on the other direction, from land to vessel.

The STS gantry crane operates with electric energy; it has rails that allow the STS movement along the vessel and a trolley that moves perpendicular to the ship. These movements make possible to move all through the vessel and take different containers. The spreader is the device in the trolley that holds up the container. The crane can unload the container either on the floor or on top of horizontal transport equipment, depending on which machinery is used.

This type of cranes can take approximately 30 to 35 containers per hour, they work more or less 5000 hours per year [7], this is an average of two 8 hours shift, 16 hours, 6 days per week.

Since it was difficult to find any independent data to calculate the energy consumption of an STS gantry crane, the study is based on the STS energy consumption published results from the HHLA, Hamburger Hafen und Logistik

AG, sustainability report from 2012 based on the emissions from HHLA three container terminals, CTA, Container Terminal Altenwerder, CTB, Container Terminal Burchardkai and CTT, Container Terminal Tollerort. In this sustainability report they say that 11% of the total 112 thousand CO_2 emitted tonnes, are emissions from container and rail gantry cranes, this means that between these two types of cranes the emitted, in 2012, 12,32 thousand tonnes of CO_2. To make possible the energy calculations of the STS in the HHLA container terminals it had to be known the used equipment in these terminals as well as the CO_2 emission factor in Germany per generated kWh of electricity [8, 9].

Table 3.5: HHLA container handling equipment

	CTA	CTB	CTT
STS	**15**	**25**	**12**
SC		120	59
AGV	86		
RMG	4	5	3

According to the IEA Statistics 2012 edition, the CO_2 emissions per kWh electricity generation in Germany were 461 $\frac{CO_2 gr}{kWh}$ [10].

This means that the 12,32 thousand tonnes of emitted CO_2 are done by 52 STS and 12 RMG. In this work it is assumed that 85% of the emissions correspond to the STS gantry cranes, since they work more annual hours and there is a higher number of them, 80% of the electric cranes in HHLA are STS (52) and the other 20% are RMG (13), this means:

Table 3.6: HHLA STS energy consumption and CO_2 emissions I

HHLA			
CO_2 Emissions (STS&RMG) [t]	CO_2 Emissions STS [t]	Energy per STS [MWh]	CO_2 Emissions per STS [t]
12.320	10.472	436,85	201,38

To make a validation of the assumption, the energy consumption was also calculated with another way. Taking that the average energy consumption in STS gantry cranes is 3,2 kWh per container [11] and knowing that in 2012 the container throughput in HHLA was 7 mill. container [12]. The following calculations were done:

$$\text{Total Energy [MWh]} = 7 \text{ x } 10^6 \text{ [container] x } 0{,}0032 \left[\frac{MWh}{container}\right] \quad \text{[Eq.4]}$$

$$CO_2 \text{ Emissions [kg]} = \text{Energy [MWh] x } CO_2 \text{ emission factor } \left[\frac{kg\ CO_2}{MWh}\right] \quad \text{[Eq.5]}$$

Table 3.7: HHLA STS energy consumption and CO_2 emissions II

HHLA TEU [mill]	HHLA STS	Energy [MWh]	Energy per STS [MWh]	CO_2 Emissions [t]
7	52	22400	430,8	198,6

Comparing both tables it is seen that the assumption of 85% from the emitted CO_2 came from STS gantry cranes has shown similar results as the calculations done with the value of 3,2 kWh per container.

Seeing the results from the vessel and the STS gantry crane energy consumption it is clearly observed that the consumption from the vessel is much higher than the STS, this tendency will be also maintained with the other cranes and terminal vehicles. The vessel consumes much more energy than the cargo handling equipment, which the energy consumption is very similar with one another.

3.2.2 Straddle Carrier

The Straddle Carrier is a machine that can be used both as horizontal transport as well as stacking equipment. That means that it can be used as union between areas or in the 2nd operational area.

Fig. 3.3: Straddle Carrier

The objective of the SC is to take the unloaded container by the STS from the ground, transport it to the stacking area and once there the SC can either stack the container or discharge it so a bigger crane stores it. One of the advantages of this machinery is that it can take the container from the floor and it doesn't have to be loaded, this allows the STS crane to have a higher productivity since it doesn't have to wait for the horizontal transport mean to be ready.

The SC works with a diesel engine that makes possible the operation, the diesel engine is connected to an electric or hydraulic system that is used to lift the container, the spreader holds the container and then, thanks to this system it can be lifted and transported. The height of the SC allows maximal container storage of 4 containers high. The driver cabin is in the upper part of the SC making it possible to control the movement and the surroundings.

In this study it has been assumed that a Straddle Carrier works more or less 5500 hours each year, which is almost 18 hours a day, 6 days each week.

To do a research of this equipment it has been studied the main manufacturers of SC focusing on Kalmar Industries, Noell and Liebherr, there was found which was the installed power of a regular SC. Most of them work with a Diesel engine connected to a generator, that is why the project is focused on this type of SC [13, 14, 15].

Table 3.8: SC manufacturer models

Model	Diesel Engine [kW]
Noell NSC E	354
Noell NSC H	354
Noell NSC T	290
Kalmar CSC	270
Liebherr SC 340S	350
Liebherr SC 440S	350

In order to achieve deeper calculations, the used engine in these SCs was investigated. A commonly used engine in the SC is the Volvo Penta TWD 1240 VE [14], analysing it was determined [16]:

Table 3.9: SC engine specifications and diesel consumption (Volvo Penta TWD1240VE)

Volvo Penta TWD1240VE			
Power [kW]	Specific Consumption [g/kWh]	Diesel Cosumption [l/h]	Diesel Consumption [l/year]
310	230	84,88	466845,24

The power and the specific consumption was obtained from the engine technical description and the calculation of the diesel consumption has been done in a similar way as it was with the vessel calculations, with the diesel density, diesel calorific power and taking an engine performance of 0,3325 [Eq.1]. This performance was assumed because it is the result of multiplying the performance of the diesel engine which typical value is 35% [17] and the electric generator that has a normal value of 95% [18].

Having these numbers, the annual energy consumption from the engine working at its full power was calculated. The calculations were done in a similar way as they were with the vessel with the vessel [Eq.2], obtaining:

Table 3.10: SC engine energy consumption at 100% power (Volvo Penta TWD1240VE)

Engine Energy [MWh/year]
1503,26

The SC doesn't operate at its installed power, since it doesn't have a continuous operation; they have many waiting hours, accelerations and decelerations being empty or with full load, but to do an average consumption, it can be said that a SC works at about 20% of the power. Knowing this fact and with deeper studies, this project has been done assuming a diesel consumption of $22\frac{l}{h}$ which is a very plausible value [19]. Taking this number, the following results were determined:

Table 3.11: SC energy consumption and CO_2 emissions calculated from model

Diesel Consumption [l/h]	Diesel Consumption [l/year]	Energy [MWh/year]	Average Power [kW]	CO_2 Emissions [t]
22	121000	389,63	70,84	320,65

$$\text{Annual Diesel Consumption [l]} = \text{Diesel Consumption } [\frac{l}{h}] \text{ x operation time [h]} \quad \text{[Eq.6]}$$

$$\text{Average Power [kW]} = \frac{Energy\ [kWh]}{operation\ time\ [h]}. \quad \text{[Eq.7]}$$

The annual energy consumption was obtained from the litres of diesel needed, with the calorific power, diesel density and the performance [Eq.2].

Comparing both tables, it can be seen that the SC operates at 22'8% of it's installed power which is, as it has been explained before, a very reasonable operating number.

These calculations give an approximate energy consumption of a SC, but they are based on different factors and they can change in each port since they can have different operation, standby and waiting hours and handled containers per hour.

To make a validation of this consumption, the obtained results have been compared with the consumption of the SC in HHLA where they operate in CTB and CTT container terminals.

Table 3.12: HHLA container handling equipment

	CTA	CTB	CTT
STS	15	25	12
SC		**120**	**59**
AGV	86		
RMG	4	5	3

In the HHLA sustainability report from 2012, they say that the SC in the terminals made 52% of the emissions and knowing that they emitted 112 thousand CO_2 tonnes [8], this means that 58,24 thousands tonnes of CO_2 were emitted by 179 SC. Knowing this the energy and diesel consumption were calculated [Eq.2] [Eq.3] [Eq.6] [Eq.7].

Table 3.13: HHLA SC energy consumption and CO_2 emissions

HHLA				
Diesel Consumption [l/h]	Diesel Consumption [l/year]	Energy [MWh/year]	Average Power [kW]	CO_2 Emissions per SC [t]
22,32	122778,54	392,35	71,34	325,36

Watching these results it is noticed that taking an average consumption of $22\frac{l}{h}$ is not very far from the reality in a port like HHLA, that's why the research has been done with such value.

If the consumption and emissions from a SC with the ones from a vessel are compared, it is seen how the tendency continues and the vessel values are much higher than the Straddle Carriers.

3.2.3 Automated Guided Vehicles

The AGV is a container handling equipment used for the horizontal transport of a container between the different operation areas within the container terminal.

Fig. 3.4: Automated Guided Vehicle

The main characteristic of this type of vehicles is that they work without driver, this means that there is no personal needed and therefore less money is used for that purpose, on the other side, the STS has to unload the container on top of the AGV since it doesn't have a system to lift the container, this process lowers the productivity of the STS gantry crane because it has to wait for the AGV to be placed. The AGV is not a very used horizontal transport method because it is relatively new, however the AGV are implemented in the CTA container terminal from HHLA and as it was said before they have in operation 86 AGV [9].

The AGV, like the SC, works with a diesel engine connected to an electric generator, but unlike the SC it cannot lift a container or store it.

To study the consumption of the AGV, similar assumptions as with the SC were made; they work an average of 5.500 hours per year.

Looking at different AGV manufacturers it was found out [20]:

Table 3.14: AGV manufacturer model

Model	Diesel Engine [kW]
Hyundai	294

As it can be appreciated, the installed power is similar as the Straddle Carriers. As it has been done with the SC, the AGV most commonly used engine was also analysed. The used engine in the AGV is similar as the SCs but with less power; Volvo Penta TWD 1420 VE [20].

Table 3.15: AGV engine specifications and diesel consumption (Volvo Penta TWD1240VE)

Volvo Penta TWD1240VE			
Power [kW]	Specific Consumption [g/kWh]	Diesel Consumption [l/h]	Diesel Consumption [l/year]
294	230	80,50	442750,00

These results were obtained doing the same calculations as with the SC and taking also an engine-generator performance of 33,25% (30% from the diesel engine and 95% from the electric generator) [Eq.1].

With these values and doing the same calculations [Eq.2], an annual energy consumption from the engine was determined:

Table 3.16: AGV engine energy consumption at 100% power (Volvo Penta TWD1240VE)

Engine Energy [MWh/year]
1425,68

Like the SC, the AGV doesn't operate at its full installed power, it does at about 20%, that is why, in this project has been assumed a diesel consumption of $16\frac{l}{h}$, it is a little lower compared with the consumption of the SC, since the AGV has lower installed power and it is only used for horizontal transport, it doesn't lift the container. Then it was calculated [Eq.2] [Eq.3] [Eq.6] [Eq.7]:

Table 3.17: AGV energy consumption and CO_2 emissions calculated from model

Diesel Consumption [l/h]	Diesel Consumption [l/year]	Energy [MWh/year]	Average Power [kW]	CO_2 Emissions [tons]
16	88000	283,36	51,52	233,22

If the tables are compared, it is appreciated that the AGV operates at 17,5% of its installed power, it is a lower than the SC operation, but still a realistic value for the energy and diesel consumption.

Just like the SC, these results are dependant on different factors and they can vary from one port to another, but the showed results are based on a standard use and even though they can vary, there shouldn't be a big difference between the ports.

Again, to make a validation of the calculated energy consumption, it has been compared with the AGV consumption in HHLA.

Table 3.18: HHLA container handling equipment

	CTA	CTB	CTT
STS	15	25	12
SC		120	59
AGV	**86**		
RMG	4	5	3

According to the 2012 sustainability report the AGV emissions were 18% of the total, this represents 20,16 thousand CO_2 emitted tones [8]. These emissions were carried out by the 86 AGV operating in the CTA container terminal. With this data, the calculations were done [Eq.2] [Eq.3] [Eq.6] [Eq.7] obtaining the following results:

Table 3.19: HHLA AGV energy consumption and CO_2 emissions

HHLA				
Diesel Consumption [l/h]	Diesel Consumption [l/year]	Energy [MWh/year]	Average Power [kW]	CO_2 Emissions per AGV [t]
16,1	88459,85	284,85	71,34	234,82

The obtained results in real operation are very similar as the ones made with the assumptions, the assumed value of 16 $\frac{l}{h}$ of diesel consumption is almost the same as the one calculated on HHLA, proving it is a realistic energy consumption for an AGV.

While doing this research, other models of AGV with much lower consumption due to their hybrid working system were also found. For example Gottwald is an AGV manufacturer that has hybrid AGV that consumes 8 $\frac{l}{h}$ [21], this represent half of the used consumption in this project, however this work is done using the value of 16 $\frac{l}{h}$ because it is the consumption of the HHLA AGVs and it was possible to compare the calculated and the HHLA AGVs consumption.

3.2.4 Tractor Trailer Unit

This type of vehicle is used, like the AGV, only for the horizontal transport of the containers in the terminal.

Fig. 3.5: Tractor Trailer Unit

The operation of this vehicle is very similar to the AGV with the difference that the TTU has a driver. Like in the AGV, the container has to be unloaded on top of the trailer because it doesn't have an own system to lift the container. This method of horizontal transport is more used than the AGV, mostly because it is not as new; this means that a TTU operation, performance, use, etc. is better known than the AGV values. A TTU has similar appearance than a normal truck but with a smaller cabin for the driver, as it can be appreciated in the picture.

The TTU operation is also similar to a normal truck, as they also work with a diesel engine, but with lower energy consumption, as it will be explained.

Taking also an annual usage of 5.500 hours. In order to do a deeper study different models of TTUs by various manufacturers have been researched [20, 22].

Table 3.20: TTU manufacturer models

Model	Diesel Engine [kW]
Kalmar TRX 182	179
Kalmar/Sisu	174
MOLCY NV	174

The power is lower than the SC or AGVs, knowing this; it had also been found two commonly used engines in these vehicles, Volvo Penta TAD 720 VE and Mercedes Benz OM 906 AC. These engines are similar to the others only smaller and with lower power. With this, the obtained results were [Eq.1] [23, 24].

Table 3.21: TTU engine specifications and diesel consumption I (Volvo Penta TAD720VE)

Volvo Penta TAD720VE			
Power [kW]	Specific Consumption [g/kWh]	Diesel Cosumption [l/h]	Diesel Consumption [l/year]
174	230	47,64	262035,71

Table 3.22: TTU engine specifications and diesel consumption II (Mercedes-Benz OM906AC)

Mercedes-Benz OM906AC			
Power [kW]	Specific Consumption [g/kWh]	Diesel Cosumption [l/h]	Diesel Consumption [l/year]
170	210	42,5	233750

Calculating the energy consumption from both engines the same way I did with the other machinery [Eq.2]:

Table 3.23: TTU engines energy consumption at 100% power (Volvo Penta TAD720VE; Mercedes-Benz OM906AC)

Volvo Energy [MWh/year]	Mercedes Energy [MWh/year]
843,77	752,69

Just like the other cargo handling equipment, the TTU doesn't operate a its full power. Mr Ricardo de Prado from the APM container terminal in Algeciras, Spain, contributed to this project giving the information that the TTUs in APM terminal Algeciras, consume 6,95 $\frac{l}{h}$ [7]. With this value and doing the same calculations it was determined [Eq.2] [Eq.3] [Eq.6] [Eq.7]:

Table 3.24: TTU energy consumption and CO_2 emissions calculated from model

Diesel Consumption [l/h]	Diesel Consumption [l/year]	Energy [MWh/year]	Average Power [kW]	CO_2 Emissions [t]
6,95	31970	102,94	18,72	84,72

It is clearly noticed that the consumption from a TTU is much lower than the others. Also, it can be seen that the TTU operates at around 11% of its installed power. This value is lower than the other equipment but on the same range, this is because the TTUs are only used from horizontal transport (the AGV had also a lower value) and if compared to the AGV it is also lower because the installed power of the TTU and the diesel consumption of these vehicles is less than the ones on the AGV.

In the conversations with Mr de Prado, he also informed that the future TTUs in Algeciras will consume only 5,5 $\frac{l}{h}$ which is 1,5 litres less and it will be traduced in a big amount of savings.

3.2.5 Shuttle Carrier

The Shuttle Carrier is a cargo handling equipment with the same function as the AGV and TTU, the container horizontal transport in the terminal.

Fig. 3.6: Shuttle Carrier

The ShC is a mixture between the Straddle Carrier and the cargo handling equipment used for horizontal transport like TTU or AGV. Like the last two, the ShC works only for horizontal transport between operation areas but with the important difference that the ShC has the possibility to lift the container, like the SC, that means that the STS has a higher productivity since it doesn't have to wait for the vehicle to unload the container on top of it. The ShC has a similar appearance as the SC but with the difference that the SC is taller, that's why the Straddle Carrier can store the container and the Shuttle Carrier can't.

The operation of the ShC is very alike to the SC; it has a diesel engine and either an hydraulic or electric system that allows the vehicle to lift the containers with a spreader.

For the Shuttle Carrier, the same assumption of the annual working hours was made. Like with the other machinery, it has been assumed an amount of 5.500 hours of work each year.

Doing the research on Shuttle Carrier manufacturers, Kalmar Industries has been deeply looked since it's the main ShC manufacturer and useful models for the project were found [25]:

Table 3.25: ShC manufacturer models

Model	Diesel Engine [kW]
Kalmar SCH 240	272
Kalmar SCH 250	294

Once the typical power values for a standard ShC were obtained, it has been investigated and calculated the typical values of a normally used engine for this kind of vehicle, Scania DI 13 074A [25] [Eq.1]:

Table 3.26: ShC engine specifications and diesel consumption (Scania DI13074A)

Scania DI13 074A			
Power [kW]	Specific Consumption [g/kWh]	Diesel Consumption [l/h]	Diesel Consumption [l/year]
294	195	68,25	375375

With these values, the annual energy consumption was determined [Eq.2]:

Table 3.27: ShC engine energy consumption at 100% power (Scania DI13074A)

Engine Energy [MWh/year]
1028,73

Just like the other equipment, the ShC doesn't operate at its full power. Since it wasn't possible to find information from a real port in order to compare results as it has been done with the other equipment, an estimate consumption has been done based on the consumption of a SC but adapted to the ShC characteristics, so it has been assumed a diesel consumption of 15 $\frac{l}{h}$. With this estimation and doing the same calculations [Eq.2] [Eq.3] [Eq.6] [Eq.7]:

Table 3.28: ShC energy consumption and CO_2 emissions calculated from model

Diesel Consumption [l/h]	Diesel Consumption [l/year]	Energy [MWh/year]	Average Power [kW]	CO_2 Emissions [t]
15	82500	265,65	48,30	218,63

With the obtained numbers, it is appreciated that the ShC operates at about 17% of the total power, this is a similar value as the SC but a little lower since the ShC has lower installed power and even though it has to lift containers, it doesn't have to lift them as high as the SC because the ShC doesn't store the containers. That's why it is reasonable to think that 15 $\frac{l}{h}$ is a possible energy consumption for a Shuttle Carrier.

Unfortunately no data from real ports could be found in order to compare and validate the obtained results

3.2.6 Reach Stacker

Reach Stackers are cargo handling equipment used for the horizontal transport in the container terminal and the container storage.

Fig. 3.7: Reach Stacker

As it has already been said, the RS has the same function as the SC, transport and storage, however there are differences between these two tractors being the main ones the storage capacity and the required number of each one for the successful performance of a container terminal.

Like the SC, the RS was a diesel engine and a hydraulic system used to pick the containers. Once the container is picked, it is moved to the 2nd operational area where it is stored or left so other cranes can store it.

At first, the assumption of 5.500 annual working hours was done, but then, speaking to Mr de Prado he informed that a standard RS has an annual use of about 4.500 hours [7]; this means it works almost 14 hours 30 min. each day, 6 days per week.

To search for valid information, the same processes as with the other equipment were done and it has been searched data given by the RS manufacturers [20, 26].

Table 3.29: RS manufacturer models

Model	Diesel Engine [kW]
Kalmar DRF	246
Kalmar DRFII	280
SMV 4545 TBX5	280

Once the average power was known, the most commonly used engines were looked for and their characteristics analysed. Two different engines that are both normally used, Volvo Penta TWD 1240 VE and Scania DC13 047A have been studied. Both of the engines have an installed power similar to the models studied above [16, 27] [Eq.1]:

Table 3.30: RS engine specifications and diesel consumption I (Volvo Penta TWD1240VE)

Volvo Penta TWD1240VE			
Power [kW]	Specific Consumption [g/kWh]	Diesel Cosumption [l/h]	Diesel Consumption [l/year]
240	205	58,57	263571,43

Table 3.31: RS engine specifications and diesel consumption II (Scania DI13074A)

Scania DC13 074A			
Power [kW]	Specific Consumption [g/kWh]	Diesel Cosumption [l/h]	Diesel Consumption [l/year]
294	195	68,25	307125

It can be appreciated that both engines have a similar consumption. Calculating the energy consumption from both engines [Eq.2]:

Table 3.32: RS engines energy consumption at 100% power (Volvo Penta TWD1240VE; Scania DC13074A)

Volvo Energy [MWh/year]	Scania Energy [MWh/year]
848,71	988,96

The Scania engine has higher consumption due to the higher installed power.

In order to do a real research, since the RS don't operate at full power, the consumption from the RS in APM container terminals in Algeciras, Spain, was obtained. According to Mr de Prado, in this terminal, the average diesel consumption of the RS is 17,5 $\frac{l}{h}$ [7]. Having this number, the following was calculated [Eq.2] [Eq.3] [Eq.6] [Eq.7]:

Table 3.33: RS energy consumption and CO_2 emissions calculated from model

Diesel Consumption [l/h]	Diesel Consumption [l/year]	Energy [MWh/year]	Average Power [kW]	CO_2 Emissions [t]
17,5	78750	253,58	56,35	208,69

Comparing these numbers, it can be said that the RS use about 19% of its power (depending with which engine is compared), this value is very similar to the 22,8% of the SC which was something expected since both have similar functions in the container terminal.

As it will be explained, the RS and the SC have lower stacking capacity, compared with the stacking cranes (RMG and RTG), despite their lower capacity, they are also used equipment in smaller container terminals or terminals with a big stacking area where there is no space problems. Even though the RS and the SC can store the containers, they can be combined with bigger stacking cranes, depending on the requirements or the needs of the container terminals, they can also be combined with pure horizontal transport systems, in which case they would be used for the container storage.

The already explained processes are the most commonly used vehicles in a container terminal, each one with its own function (horizontal transport or container storage). In the coming part it is going to be explained the cranes used in the storage yard for the container piling, RMG and RTG cranes.

3.2.7 Rubber Tyre Gantry Crane

These cranes are located in the 2nd operational area and are used for the container storage.

Fig. 3.8: Rubber Tyre Gantry Crane

The RTG pick the transported containers and store them as it can be seen on the picture. These cranes have a diesel engine connected to an electric generator that supplies the needed power for a successful operation. The RTG have the special characteristic (like its name says) that they have wheels, this means that they can be moved and can work in different parts of the container terminal. As it can be also appreciated in the figure 3.8, the stacking capacity of this crane is much bigger than the storage capacity of the already mentioned Straddle Carrier and Reach Stacker. Being the storage capacity the stacked containers per area unit, in this project it will be used hectare as area unit. This higher stacking capacity is the fact why the RTGs (and RMGs) are the cranes used in bigger container terminal like HHLA or Jurong Port in Singapore.

These cranes have different movements and different powers are required for each one: idle, trolley with/without load, gantry with/without load. Apart from these energy consuming movements, a RTG also consumes energy in the engine used to move the crane in the storage yard, and in auxiliary systems such as lighting or the on-board computer among others. In this project it has been considered that the crane doesn't move in the yard and the auxiliary power demand is taken into account at the idle stage of the working cycle.

According to the RTG Load Factor Study made by the Port of Long Beach and The Port of Los Angeles [28], usual values for these movements are:

Table 3.34: RTG motion study

RTG Motion	Time [s]	Duty Cycle[%]	Power Required [kW]	Total Power [kW]
Hoist	118	49,2	100 to 350 + Idle	113 to 363
Trolley	42	17,5	15 + Idle	28
Gantry	20	8,3	45 + Idle	58
Idle	60	25,0	13	13
Total	240	100,0		212 to 462

In this study, they also run test on an operating RTG obtaining the following:

Table 3.35: RTG power test

Test	Power [kW]
Idle	7,36
Gantry	38,84
Trolley without load	16,57
Trolley with load	18,15
Lift without load	60,06
Lift with load	118,58
Total/Cycle (240s)	98,98

The power needed per cycle was calculated with the power of each activity and its duty cycle [%]. With these results it was possible to calculate energy consumption. The required energy per cycle was determined from the obtained power and the time per cycle, which is 240 seconds, with that value it has been calculated the annual energy assuming that the RTG operates 2.500 hours per year. With these values, and doing the same calculations as the ones already done, it was worked out the diesel consumption as well as the CO_2 emissions. To do these calculations it was also assumed an engine performance of 33,25% (30% from the diesel engine and 95% from the electric generator) [Eq.2] [Eq.3].

Table 3.36: RTG calculated energy consumption and CO_2 emissions

E/Cycle [kWh]	E [kWh] (1h)	E/year[MWh] (2500h)	Diesel Consumption [l/year]	CO_2 Emissions [t]
6,60	98,98	247,47	76849,75	203,65

In order to validate these calculations, the calculated results were compared with the showed results in the Carbon Footprint Report 2011 from the Jurong Port in Singapore [29]. In this report they stated that the CO_2 emitted by the RTGs were 6.788 tonnes, at that point the port owned 34 RTGs. Knowing this and taking also a factor of 2,65 kg of emitted CO_2 per litre of diesel, the following was obtained [Eq.2] [Eq.3]:

Table 3.37: RTG energy consumption and CO_2 emissions from Jurong Port, Singapore

JURONG PORT SINGAPORE				
RTG	CO_2 Emissions [t]	CO_2 Emissions per RTG [t]	Diesel Consumption [l]	Energy [MWh]
34	6822	200,65	75715,87	243,81

As it can be appreciated in both tables, the consumed energy as well as the CO_2 emissions are very similar numbers, so it can be said that the assumptions made to obtain these results are not very far from reality. All the calculations are approximate numbers, since each RTG can work in different ways or different hours however, these numbers can be considered as an average consumption and emissions from a standard RTG and can give an accurate idea of which is the consumption range of this kind of cranes.

3.2.8 Rail Mounted Gantry Crane

The RMG is the other type of crane used for the storage of the containers in the stacking yard.

Fig. 3.9: Rail Mounted Gantry Crane

Like the RTG, the RMG crane picks the transported containers and stores them in the yard. The RMGs are fully electrified cranes and as its name says, they move along rails, this can be appreciated in the picture above; these two are the main differences with the RTG cranes. The fact that they move in these rails doesn't make possible for this type of cranes to work in different parts of the terminal, however this is not usually needed. These cranes are also normally used to load and/or unload containers from trains.

In the same way as the RTG crane, the RMG has a much bigger stacking capacity than the SC and RS. They also have similar operation, with similar movements and duty cycle of each movement.

To make an analysis of these cranes, it has been studied the installed power for each movement of the RMGs in the Duisburg port, Germany and it was obtained [30]:

Table 3.38: RMG installed power in Duisburg Port, Germany

	DIT	RRT	Duss PKV
Main Hoist [kW]	2x120	1x180	2x200
Gantry Drive [kW]	26x24	26x13	24x18
Trolley Drive [kW]	4x22	4x16	4x26
Slewing [kW]	2x7	1x7	2x7

Being:

- DIT: Duisburg Intermodal Terminal.
- RRT: Rhein Ruhr Terminal Duisburg.

Having these values and knowing the duty cycle of each movement (as said, the duty cycle is similar to the RTG), the total installed power and energy consumption for a full power work of each terminal was calculated.

Table 3.39: RMG energy study from DIT terminal, Duisburg Port, Germany

		DIT		
	Time[s]	E/Cycle (180s) [kWh]	E (1h) [kWh]	E/year [MWh]
Main Hoist	118	7,87	157,33	865,33
Gantry Drive	20	3,47	69,33	381,33
Trolley Drive	42	1,03	20,53	112,93
Total	180	12,36	247,20	1359,60

Table 3.40: RMG energy study from RRT terminal, Duisburg Port, Germany

		RRT		
	Time[s]	E/Cycle (180s) [kWh]	E (1h) [kWh]	E/year [MWh]
Main Hoist	118	5,90	118,00	649,00
Gantry Drive	20	1,88	37,56	206,56
Trolley Drive	42	0,75	14,93	82,13
Total	180	8,52	170,49	937,69

Table 3.41: RMG energy study from Duss PKV terminal, Duisburg Port, Germany

		Duss PKV		
	Time[s]	E/Cycle (180s) [kWh]	E (1h) [kWh]	E/year [MWh]
Main Hoist	118	13,11	262,22	1442,22
Gantry Drive	20	2,40	48,00	264,00
Trolley Drive	42	1,21	24,27	133,47
Total	180	16,72	334,49	1839,69

Taking an average consumption of the RMGs in Duisburg port, it was obtained 1378 MWh per RMG working at full power. Since they don't work at full power but at about 20% of the installed power, it is fair to say that an average energy consumption and CO_2 emissions for a RMG can be [Eq.5, using Germany CO_2 emission factor]:

Table 3.42: RMG calculated energy consumption and CO_2 emissions

Energy Consumption [MWh]	CO_2 Emissions [t]
275	126,75

In order to prove these assumptions, the calculated results were compared with the RMG energy consumption in HHLA.

Table 3.43: HHLA cargo handling equipment

	CTA	CTB	CTT
STS	15	25	12
SC		120	59
AGV	86		
RMG	**4**	**5**	**3**

As it has been explained in the STS part, HHLA emitted 112 thousand CO_2 tonnes of which 11% were made by the STS and RMG in the port [8]; this means that 12.320 CO_2 tonnes were emitted by this equipment. Since it was already assumed that 85% of these emissions were made by the STS, the other 15% are made by the 13 RMGs that operate in the container terminals, this makes [Eq.5]:

Table 3.44: HHLA RMG energy consumption and CO_2 emissions

HHLA			
CO_2 Emissions (STS&RMG) [t]	CO_2 Emissions RMG [t]	Energy per RMG [MWh]	CO_2 Emissions per RMG [t]
12.320	1.848	308,36	142,15

It can be appreciated how these values are on the same range that the ones calculated from the data of Duisburg port. However, comparing both results, they are not as similar as the comparison made with other equipment, this difference between the calculated energy from Duisburg port and the calculated from HHLA, may be due to the assumptions made in both ports and also because an average value of the energy consumption was taken. It can also be because it wasn't taken into account the auxiliary energy consumption since it wasn't possible to find any useful data for this matter. Despite this deviation, the showed numbers give a fair approximation of the consumption and emissions made by the RMG cranes.

The described machinery in this chapter is the most commonly used container handling equipment in a container terminal, however there are less utilized equipment like forklifts, container handler or mobile gantry cranes, that hasn't been analysed in this project. All the vehicles and cranes can be combined making different layouts of the container terminal, each one with its advantages and disadvantages, however, not all of the horizontal transport equipment and the cranes should be combined.

There is one more energy consumer in a container terminal, the administration of the terminal. With administration it is implied the buildings, gates, lighting and all the necessary activities involved in order to do a successful operation in a container terminal.

3.2.9 Administration

As it has been said, the administration role is to control everything in the terminal as well as the vessel traffic in order to make everything work. To be able to coordinate all the activities in the port, inland and sea activities, there is different used equipment that consumes electric energy.

This electricity consumptions comes from different sources of the port, like:

- Lighting in the port.
- Buildings.
- Security.
- Gates, entrance to the port.
- Heating.

In this project, it has been analysed the consumed energy from the administration of 4 of the biggest ports in the world, Hamburg, Rotterdam, Hong Kong and Jurong (Singapore). To obtain the needed information, their respective sustainability report, or similar was researched. Looking at these reports it has been gathered the following information:

Hamburg (HHLA) [8]:

According to their Sustainability Report of 2012, 11% of the 112.000 emitted CO_2 tonnes were made by lighting for buildings, open areas, etc. Knowing that 461 grams of CO_2 per generated kWh of electricity in Germany, it has been determined [Eq.5]:

Table 3.45: HHLA Authority energy consumption and CO_2 emissions

HHLA Authority	
Energy [MWh]	CO_2 Emissions [t]
26724,51	12320

It would be appropriate to mention the needed energy for reefer containers in HHLA. These containers are a special type used to transport material that has to be at a special temperature; normally they are used for food that needs to be frozen or at a specific temperature. In HHLA, the emissions of this kind of containers are 5% of the total emissions; with this value it was calculated the consumed energy [Eq.5]:

Table 3.46: HHLA Reefer container energy consumption and CO_2 emissions

	Energy [MWh]	CO_2 Emissions [t]
Reefer Container	12147,51	5600

Rotterdam [31]:

The 2012 Annual Report of the Rotterdam port, states that the Rotterdam Port Authority emitted 9,2 thousand CO_2 tonnes, they divide these emissions in 3 scopes.

- 1st Scope: Direct emissions by fuel consumption
- 2nd Scope: Electricity and heating.
- 3rd Scope: Business flights and employees transport.

With the information given on each scope, the energy derivate from each emission was calculated. In the 1st and 3rd scope, it has been assumed that these emissions were made by a diesel engine, which is why first, the total litres of diesel consumed were calculated, and from that value, the total energy consumption was obtained in the same way as it has been already done with other equipment, with the diesel density, the diesel calorific power and assuming an engine performance of 30%. The obtained results were [Eq.2] [Eq.3]:

$$\text{Diesel litres} = \frac{CO_2\ Emissions}{2{,}65\ \frac{Kg\ CO_2}{Diesel\ litre}};$$

The consumed energy in the 2nd scope was obtained directly from the CO_2 emissions. According to the IEA 2012 Statistics, the CO_2 emission factor from the generated kWh of electricity in Holland is 415 CO_2 grams per generated kWh [10], and with this factor it is easily determined the energy related to the scope 2 emissions [Eq.5].

And with these calculations the following values are worked out:

Table 3.47: Rotterdam Port Authority energy consumption and CO_2 emissions

	Energy [MWh]	CO_2 Emissions [t]
Scope 1	6689,67	6100
Scope 2	1686,75	700
Scope 3	2631,22	2400
Total	22168,67	9200

It can be appreciated that the determined energy consumption is similar to HHLA energy consumption.

Hong Kong [32]:

In the 2012 Marine Department Environmental Report of Hong Kong, they say that the energy consumption made by this department is 21723,7 MWh. To obtain the CO_2 emissions, the emission factor per kWh of generated electricity was looked in the IEA 2012 Statistics being such number 723 grams of CO_2 per generated kWh [10][Eq.5].

Table 3.48: Hong Kong Marine Department energy consumption and CO_2 emissions

MD Energy Consumption [MWh]	CO_2 Emissions [t]
21723,7	15706,2

Again, the obtained value is similar to the ones in the other 2 ports.

Jurong Port (Singapore) [29]:

To analyse the energy consumption and the emissions made by this port, the 2011 Jurong Port Footprint Report was analysed. In this report, like the Rotterdam Port, they divide the emissions in 3 scopes:

- 1st Scope: Refers to the direct green house gas (GHG) emissions occurring from sources that are owned or controlled by the port.

- 2nd Scope: Refers to the indirect GHG emissions from generating electricity by sources that are not owned by the port, but such electricity is used by the port.
- 3rd Scope: Refers to the indirect GHG emissions that are a consequence of port activities, but occur from sources not owned or controlled by the port.

In this report the CO_2 emissions from each scope are given. The IEA 2012 Statistics gives a CO_2 emission factor per generated kWh of electricity of 499 CO_2 grams each kWh [10][Eq.5].

Having this information the energy consumption was determined:

Table 3.49: Jurong Port Administration energy consumption and CO_2 emissions

Authority Energy [MWh]	Authority CO_2 Emissions [t]		
326,65	163	Building (Tenant Use)	Scope 3
144,29	72	Warehouse & Yard (Tenant Use)	Scope 3
3641,28	1817	Area Lighting	Scope 2
3260,52	1627	Warehouses	Scope 2
1144,29	571	Jurong Port Admin Building	Scope 2
721,44	360	Reefer Yard	Scope 2
424,85	212	General Cargo Office Building	Scope 2
260,52	130	West Gate	Scope 2
30,06	15	Bulk Cargo Site Office	Scope 2
9953,91	4967	Total	

It is seen that the energy consumption in each port is a similar value apart from the Jurong Port energy consumption which is approximately half of the others consumptions.

These values are from the administration of the port, and apart from HHLA that only has container terminals, the other ports have also other type of terminals. This means that the calculated energy consumption is not only referred to the container terminals, however, the container terminal part of the total consumption shouldn't vary much because all the coordination from the port is carried out in the same buildings, that is why the obtained value in HHLA doesn't differ much with the ones in Rotterdam and Hong Kong. The administration consumption as influenced as the used equipment by the size of the port or the container throughput of the terminal, it can be considered as fix consumption. In order to do calculations in this project, a value of 20.000 MWh of energy consumption and 9.220 tonnes of CO_2 emissions will be taken.

In the next chapter is going to be explained the operation, advantages, disadvantages and used equipment of different container terminal layouts that can be used taking the explained vehicles and cranes. Having calculated the energy consumption of each part of the layout, it will determined the emitted CO_2 and the total energy needed to unload the container from the vessel, transport the container to the stacking area and store it.

4. Container Terminal Operation Systems [33, 34]

As it has already been explained, the layout of the container terminal comes from the different combinations of equipment. In this project it is only analysed 6 different combinations, all of them are combinations between horizontal transport and container stacking machinery, this means that all the layouts work with a STS gantry crane in the 1st operational area, for the loading and unloading of the vessel. Once the container is unloaded from the ship, is where the influence and operation of the different layouts begin.

4.1 System 1: Pure Straddle Carrier System

In this layout the only used equipment, apart from the already mentioned STS, is the SC, they are used as horizontal transport for the container and also for their storage.

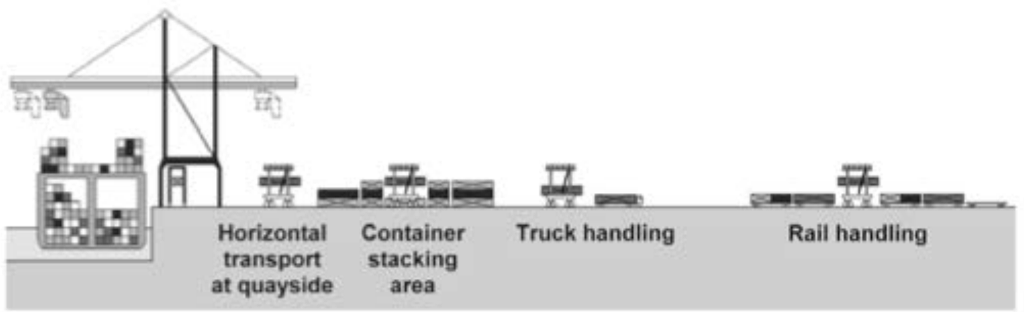

Fig. 4.1: Pure Straddle Carrier operation system

The STS gantry crane unloads the container from the vessel to the quay. There, the SC picks the container and transport it to the stacking yard. After that, it's also the SC the used machinery to stack the container. The Straddle Carrier also carries out the loading of the containers in the hinterland transport, like trucks or trains. As it is appreciated, in this layout the SCs are responsible of the container from the moment it is unloaded.

Some of the characteristics of this operation system are:

- This system is used for medium and large container terminals.
- The container can be stacked in 2-high having a storage capacity of 500 TEU per ha or in 3-high, with a capacity of 750 TEU. A maximum of 4-high can be achieved.
- It is estimated that it is needed 4-5 SC per STS gantry crane.
- The SCs is combined in some terminals with other equipment like RMGs.

Like all the different operation systems, it has its advantages and disadvantages.

Advantages:

- Only SCs are needed for the transport and stacking of the containers in the terminal.
- The containers can be unloaded in the ground by the STS, because the SCs are able to lift the container, this allows a higher operation of the STS because there is no waiting time.
- Different activities are carried out at the same time.
- The failure of a SC doesn't have a big influence in the operation performance.
- Low operation costs due to small number of vehicles.
- It is a flexible system. The SCs can be moved and used in different parts of the terminal.

Disadvantages:

- High investment costs.
- High maintenance and energy costs.
- High area requirement.
- SCs are not very useful when they have to travel long distances.

To determine the energy consumption of this system, the values that had already been calculated were taken. Several assumptions were made to model a real operation:

- 5 STS gantry cranes are used to unload a vessel.
- A STS unloads an average of 35 containers per hour
- 4 SCs per STS, having a total of 20 SCs per vessel.
- The vessel stays only 24 hours in the port, 4 as manoeuvre time and 20 in the quay.
- The vessel size is 8000 TEUs, which is a normal size for a container vessel.

Having done these assumptions, and since a standard STS works 16 hours per day, this means that there is a container throughput of 2800 containers per vessel, staying the vessel only one day in the port.

It has been calculated the needed energy for the unloading process of the containers in a vessel since it arrives in the port:

Table 4.1: Pure SC operation system energy consumption and CO_2 emissions

	Diesel [l/h]	Diesel [l/year]	Energy [MWh]	CO_2 Emissions [t]
Vessel	786,79	7374756,11	28567,92	19543,10
STS			440,31	202,98
5 STS			2201,54	1014,91
SC	22,00	121000,00	389,63	320,65
20 SC (4/STS)	440,00	2420000,00	7792,52	6413,00
Total	1226,79	9794756,11	38561,98	26971,01

The table above illustrates the annual energy needed to do a container throughput of 2800 containers in a vessel per day during 312 days, since the STS work only 6 days per week; this represents a container throughput of 873.600 containers per year. Since a standard container terminal doesn't work only in one vessel at a time, further on it will be studied the total energy consumption of a terminal.

In order to clarify these numbers, two graphics have been made taking into account the energy consumption from the vessel, the total consumption from the STS cranes (5) and the total consumption from the SCs (20).

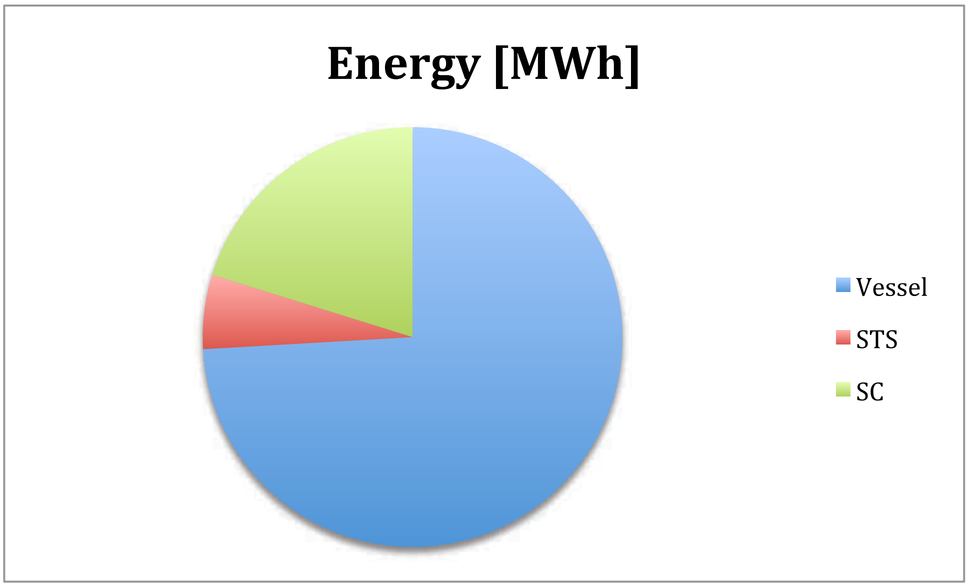

Fig. 4.1.1: Pure Straddle Carrier operation system energy consumption graphic

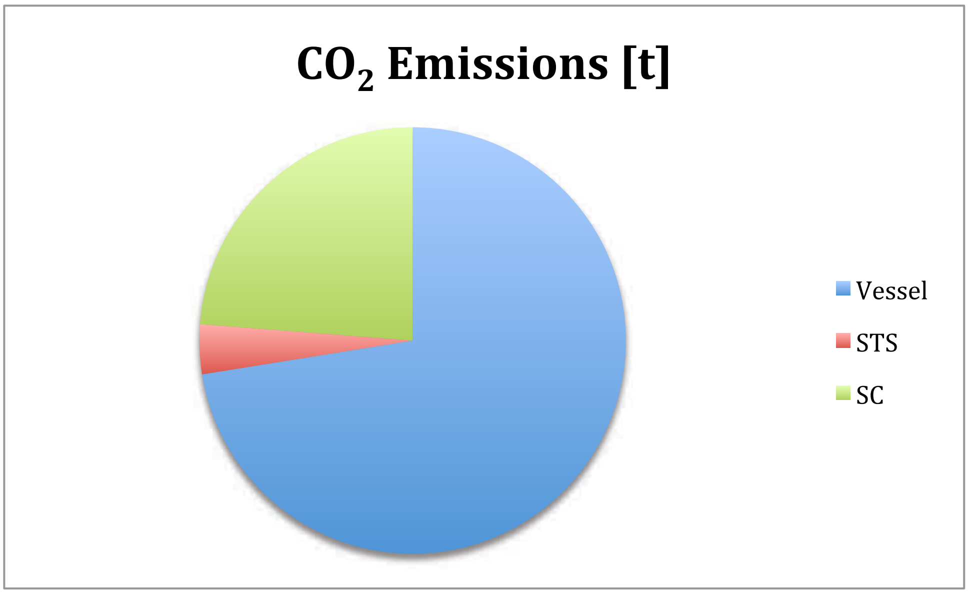

Fig. 4.1.2: Pure Straddle Carrier operation system CO_2 emissions graphic

It can be clearly appreciated how the main energy consumption and the main CO_2 emissions come from the vessel. If the ship is not taken into account, the SC consumption is much higher than the STS that is because even though they have similar consumption, there are four times more SC than STS cranes (20 SC; 5 STS). In these graphics, it is also seen how there is not the same proportion between energy consumption and CO_2 emissions wit the STS cranes and the SCs, that is because the STS are fully electrified and the SCs have diesel operation, this means that they have different CO_2 emission factor.

4.2 RMG + AGV

In this operation system, Automated Guided Vehicles and Rail Mounted Gantry Cranes are combined. The AGV are in charge of the horizontal transport of the container while the RMG must store them.

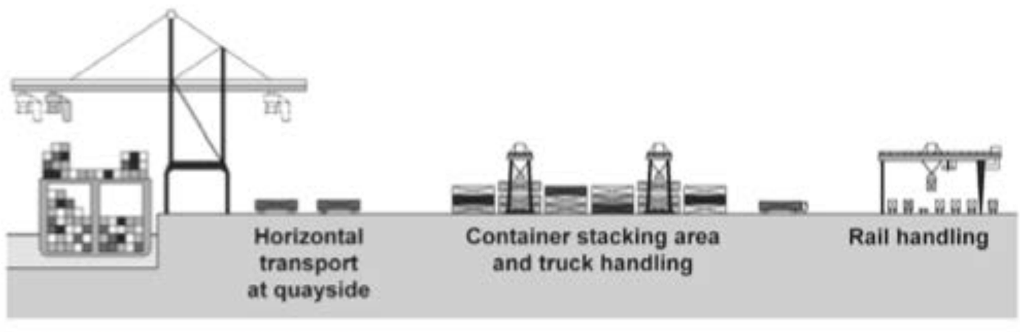

Fig. 4.2: Rail Mounted Gantry Crane + Automated Guided Vehicle operation system

The STS crane unloads the container on top of the AGV, the container is transported to the stacking area where its picked and stored by a RMG crane.

Since the AGV have no driver and are fully automated, there has to be a separation between manned and unmanned areas due to safety reasons, that is why the stacking is done by RMGs, because they can also be automated and thus unmanned.

The combination of this equipment gives the following characteristics layout:

- It is estimated that 3 – 4 AGVs are needed per STS gantry crane, but the AGVs don’t work with the same crane all the time, it depends on its position.
- Normally 2 RMGs are needed per STS crane.
- It has a storage capacity of 1000 or more [TEA/ha], this can be achieved because containers can be stored up to 5-high.

This layouts advantages and disadvantages are:

Advantages:

- Low personal costs, since it is an automated system.
- High productivity of horizontal transport. The most favourable positioned AGVs are the ones used.
- High system availability.

Disadvantages:

- Very high investment costs.
- High maintenance costs.
- High trained personal is required.
- It is a rigid system. It is very difficult to introduce changes.

Once the operation, characteristics, advantages and disadvantages of this layout have been explained, it has been built a model in order to make an analysis of the consumptions and emissions of this operation system. The model was constructed with the obtained data from the individual consumptions from the vessel, AGV and RMG, to complete the model different assumptions have been made.

- 5 STS gantry cranes are used.
- A STS gantry crane unloads 35 containers per hour
- 4 AGVs per STS crane, making a total of 20 AGVs.
- 2 RMGs per STS crane having 10 RMGs.
- The vessel stays 24 hours in the port, 20 of them are berthing time.
- The vessel has 8000 TEUs.
- The container throughput in this time is 2800 containers.

With these assumptions and the consumptions, the model was made, and it was determined the following results.

Table 4.2: RMG + AGV operation system energy consumption and CO_2 emissions

	Diesel [l/h]	Diesel [l/year]	Energy [MWh]	CO_2 Emissions [t]
Vessel	786,79	7374756,11	28567,92	19543,10
STS			440,31	202,98
5 STS			2201,54	1014,91
RMG			275,00	126,78
10 RMG (2/STS)			2750,00	1267,75
AGV	16,00	88000,00	283,36	233,20
20 AGV (4/STS)	320,00	1760000,00	5667,29	4664,00
Total	1106,79	9134756,11	36436,74	25222,01

These are the obtained results for the needed energy per year to have a container throughput of 2800 containers in one vessel per day, working 312 days each year. As it has been said, these results don't correspond to a normal container terminal, since a terminal have more than one vessel being worked on at the same time and these ones are only from one ship.

In order to compare these results, energy consumption and a CO_2 emissions graphic have been made, like with the pure SCs layout.

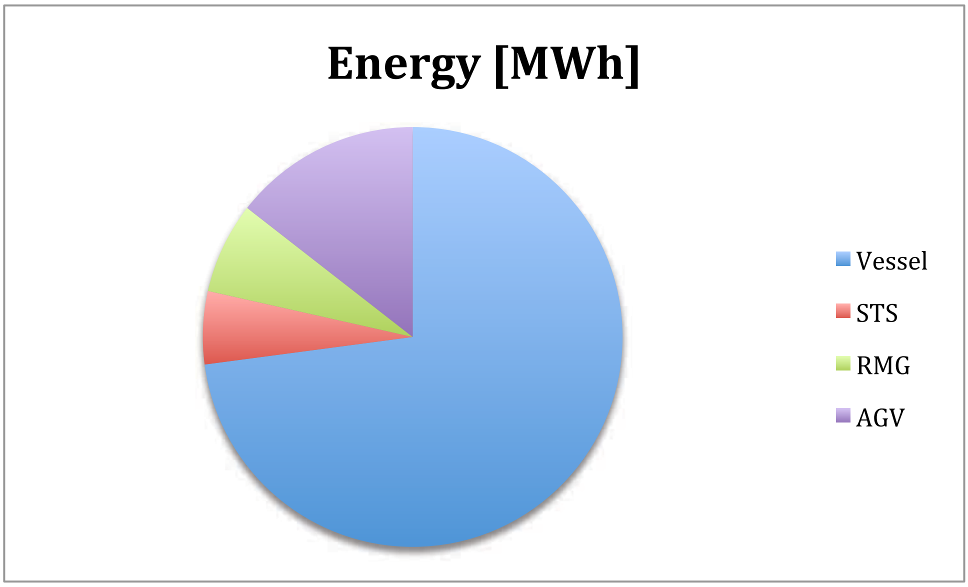

Fig. 4.2.1: Rail Mounted Gantry Crane + Automated Guided Vehicle operation system energy consumption graphic

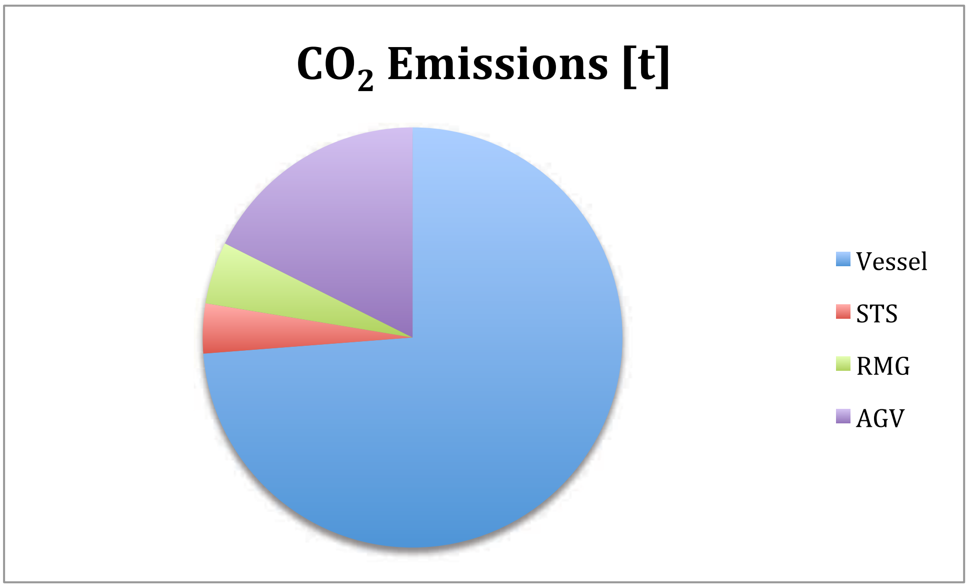

Fig. 4.2.2: Rail Mounted Gantry Crane + Automated Guided Vehicle operation system CO_2 emissions graphic

Just like in the other operation system, the vessel consumption and emissions are correspond to the main part. The equipment energy consumption in both operation systems is similar, about 25% of the total consumption; with the emission something similar happens. Without taking into account the ship consumption it can be seen how the horizontal transport (AGV) consumption and emissions are higher than the other equipment, this is because despite the AGV has lower individual consumption, there are four times more AGV than STS and twice more AGV than RMG. It can be appreciated also how the consumption and emissions doesn't have the same proportions, this is due to the different CO_2 emission factor from each operation, the vessel and AGV work with diesel engines while the STS and RMG cranes are fully electrified.

4.3 RTG + TTU

The needed equipment for this operation system is tractor trailer units (TTU) used for the horizontal transport of the containers and rubber tired gantry cranes (RTG) used in the stacking yard for the container storage.

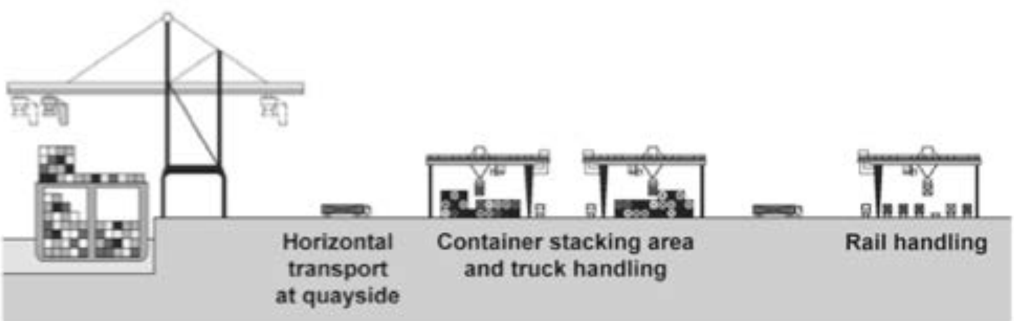

Fig. 4.3: Rubber Tyre Gantry Crane + Tractor Trailer Unit operation system

This operation system has a similar work as the RMG + AGV. The STS picks the container from the vessel and unloads it on top of the TTU, since the TTU hasn't got any lifting device to pick the container, it has to be unloaded on top of it, and then it is transported to the stacking area, where a RTG takes the container from the TTU and stores it. The main difference with the other operation system (RMG + AGV) is that the TTU, unlike the AGV, is a manned vehicle; this means that is not an automatized operation system.

Some of the characteristics from this layout are:

- It is an operation system used in large and very large container terminals.
- Long travelling distances are not a problem (unlike the pure SC system).
- The RTGs can be also used to load road trucks or trains.
- RTGs can be relocated. They can work in the yard or the hinterland.
- An average of 4 – 5 TTUs per STS gantry crane are needed.
- An average of 2 – 3 RMGs per STS gantry crane are needed.
- The containers can be stored up to 7-high in five rows.
- Has a very high stacking capacity, 1000 TEUs per hectare using a 4-high storage.

Another characteristic, not of the layout but of the container terminal using this layout, is that heavy concrete paving is required to support the heavy load of the RTGs, also, there has to be turning areas.

The advantages and disadvantages of this operation system have to be detailed.

Advantages:

- Small area needed thanks to the high density storage (up to 7-high).
- Flexible systems, as the RTGs can be relocated and work in different areas of the container terminal.
- Medium investment costs.

Disadvantages:

- In order no to reshuffle containers (high density storage) there has to be a very efficient administration.
- High personal costs.
- Not very productive STS crane, since they have to wait for the TTUs.
- Mixed traffic in the terminal, disturbances between TTUs.

To study this operation system it has been made a model, like with the other operation systems. This model consists of adapting each individual energy consumption to a real operation to unload a vessel. To make the model different assumptions, similar to the other layouts assumptions, were made.

- 5 STS gantry cranes are used.
- A STS gantry crane unloads 35 containers per hour
- 4 TTUs per STS crane, making a total of 20 TTUs.
- 2 RTGs per STS crane having 10 RTGs.
- The vessel stays 24 hours in the port, 20 of them are docking time.
- The vessel has 8000 TEUs.
- The container throughput in this time is 2800 containers.

Adapting the calculated consumptions to these assumptions it has been determined:

Table 4.3: RTG + TTU operation system energy consumption and CO_2 emissions

	Diesel [l/h]	Diesel [l/year]	Energy [MWh]	CO_2 Emissions [t]
Vessel	786,79	7374756,11	28567,92	19543,10
STS			440,31	202,98
5 STS			2201,54	1014,91
RTG	30,74	76849,75	247,46	203,65
10 RTG (2/STS)	61,48	768497,46	2474,60	2036,52
TTU	6,95	38225,00	102,94	101,30
20 TTU (4/STS)	139,00	764500,00	2058,90	2025,93
Total	925,79	8139256,11	32828,36	22583,94

This table shows the calculated results of the annual needed energy consumption and CO_2 emissions to have a container throughput of 2800 containers in an average sized vessel that stays 20 hours at the dock and 4 manoeuvre hours and working 312 days per year.

With this operation system has been followed the same procedure as with the already explained, so also two graphics have been made in order to clarify the results showed above.

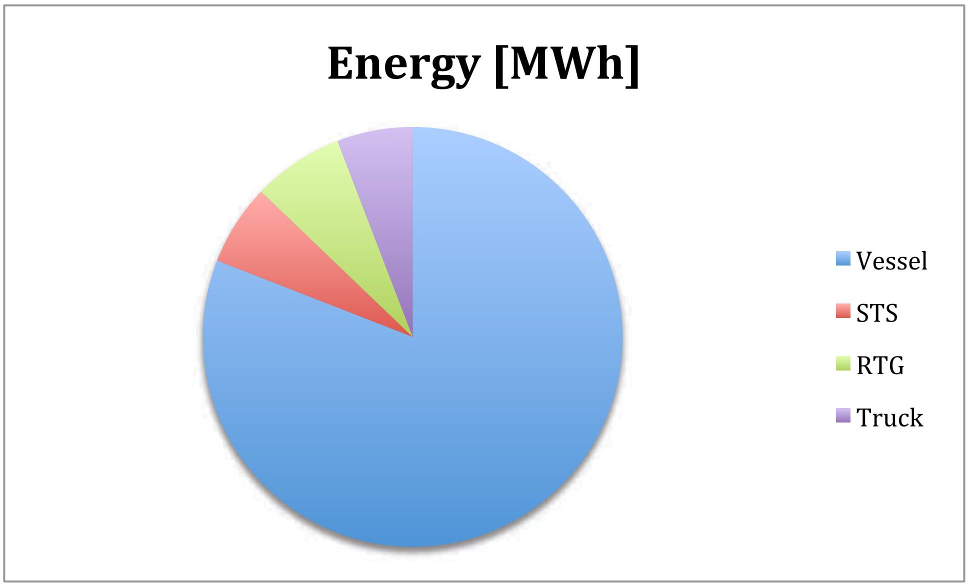

Fig. 4.3.1: Rubber Tyre Gantry Crane + Tractor Trailer Unit operation system energy consumption graphic

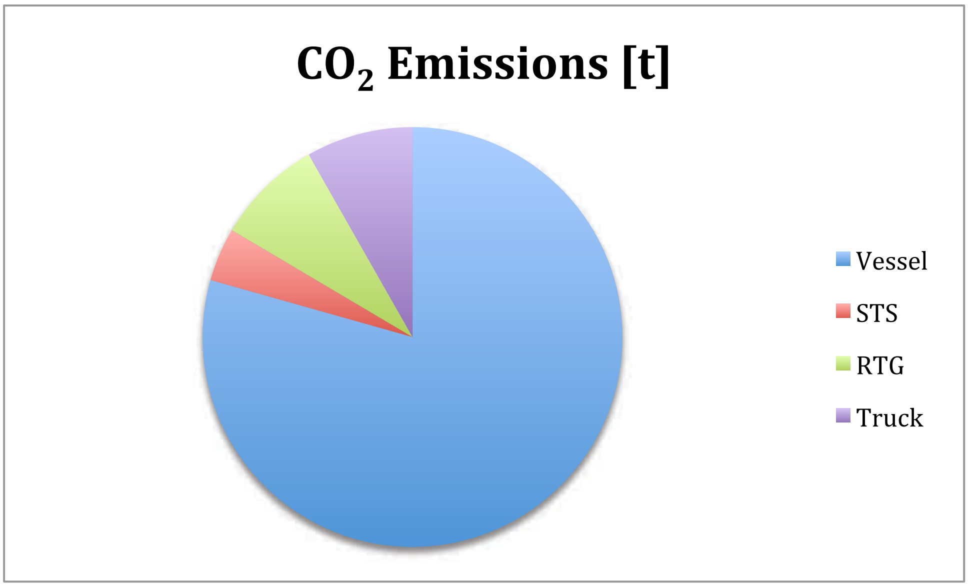

Fig. 4.3.2: Rubber Tyre Gantry Crane + Tractor Trailer Unit operation system CO_2 emissions graphic

Like in the other operation systems the vessel consumption and emissions are much higher compared to the equipment. Also, it can be appreciated that the equipment consumption is a little less than 25%, this means that the equipment energy consumption from this layout is lower than with the other operation systems, but in a similar range of values, 20% - 25% of the energy consumption and CO_2 emissions are from the cargo handling equipment. Like it happened on the other operation systems, it can be seen how the energy consumption and CO_2 emissions don't have the same proportion, this is because the different operation of each equipment, diesel operation and electric operation have different CO_2 emission factor as it has already been explained.

4.4 RMG + TTU

This operation system is similar to the last one explained but with a rail mounted gantry crane (RMG) instead of a RTG used to store the containers in the stacking yard.

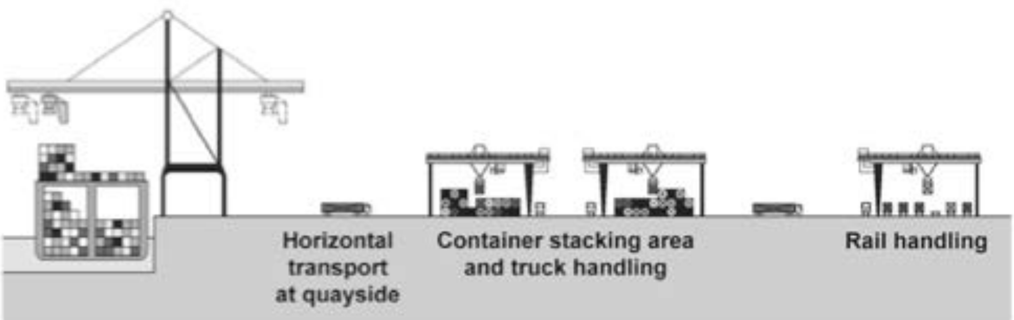

Fig. 4.4: Rail Mountad Gantry Crane + Tractor Trailer Unit operation system

This operation systems works in a similar way as the last one explained (RTG + TTU). The STS gantry crane unloads the picked container on top of the TTU. The TTU transport the container to the 2nd operation area, the stacking yard, where a RMG takes the container and stores it. The only difference on the used equipment with the last operation system is the used crane for the container storage. In this case, the cranes move along to rails instead of having wheels.

This operation system has similar characteristics as the last one explained. If both systems are compared, this layout has some advantages and disadvantages.

Advantages (compared to RTGs)

- RMGs normally have a higher stacking capacity, since they are wider. 7-high and 12 rows.
- The stacking density is higher than with RTGs. They can store more than 1000 TEUs per hectare.
- RMGs are more durable and reliable.
- The maintenance and repair costs are lower.
- Easier to be automatized than the RTGs

Disadvantages (compared to RTGs):

- Installation is more expensive because of the rails.
- If a crane fails there is a big disturbance on the terminal.
- High investment costs.
- Rigid system. It is difficult to change the layout because of the rails.

In the same way as it has been done with the other operation systems, a model has been made in order to analyse the energy consumption. The model has been made under similar assumptions as it has been made in the last layout.

- 5 STS gantry cranes are used.
- A STS gantry crane unloads 35 containers per hour
- 4 TTUs per STS crane, making a total of 20 TTUs.
- 2 RMGs per STS crane having 10 RMGs.
- The vessel stays 24 hours in the port, 20 of them are docking time.
- The vessel has 8000 TEUs.
- The container throughput in this time is 2800 containers.

With these assumptions the energy consumption and the CO_2 emissions have been determined based on the consumption and emissions from each crane and vehicle. Doing this it has been obtained:

Table 4.4: RMG + TTU operation system energy consumption and CO_2 emissions

	Diesel [l/h]	Diesel [l/year]	Energy [MWh]	CO_2 Emissions [t]
Vessel	786,79	7374756,11	28567,92	19543,10
STS			440,31	202,98
5 STS			2201,54	1014,91
RMG			275,00	126,78
10 RMG (2/STS)			2750,00	1267,75
TTU	6,95	38225,00	102,94	101,30
20 TTU (4/STS)	139,00	764500,00	2058,90	2025,93
Total	925,79	8139256,11	32828,36	22583,94

These results represent the consumption and emissions each year from working on a vessel and having a container throughput of 2800 containers per day during 312 days each year.

The following graphics that show this energy consumption and emissions help to see the proportion of this consumption and emissions of the vessel and the equipment.

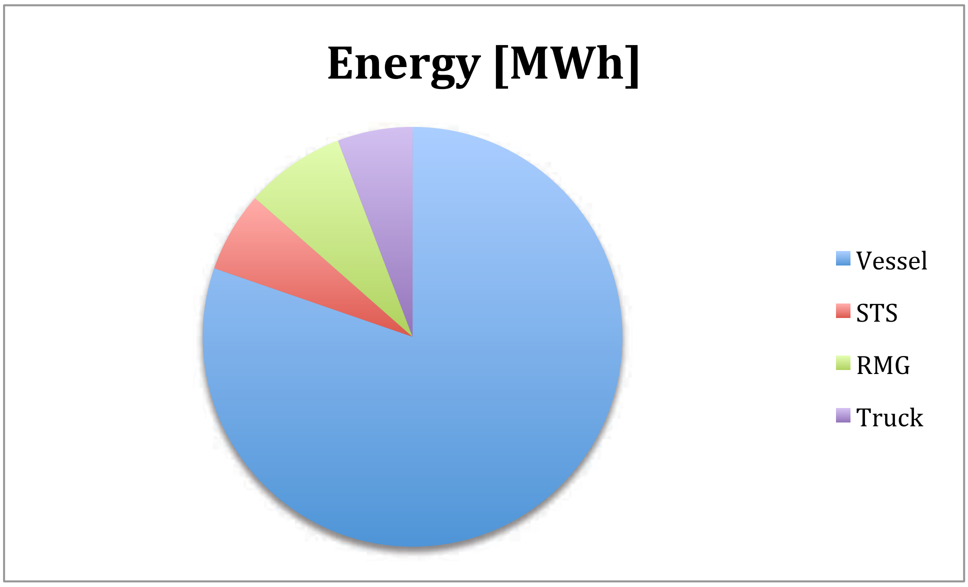

Fig. 4.4.1: Rail Mountad Gantry Crane + Tractor Trailer Unit operation system energy consumption grahic

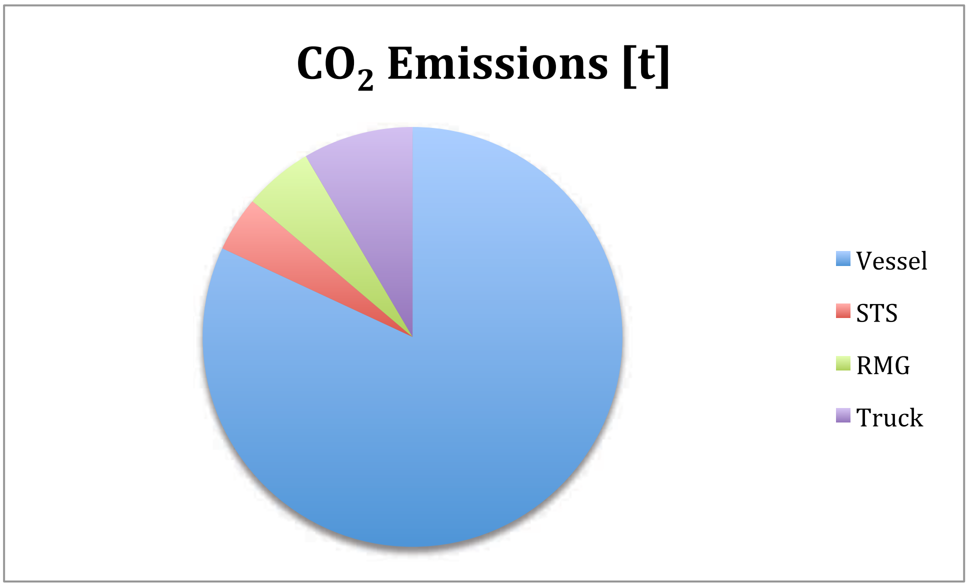

Fig. 4.4.2: Rail Mountad Gantry Crane + Tractor Trailer Unit operation system CO_2 emissions graphic

It can be seen how the energy consumption of this operation system is very similar to the one of the last operation system (RTG + TTU), this is because both the RMG and the RTG cranes have similar energy consumption. However, the emissions differ a little, the reason of this is that the RMG has a full electric operation while the RTG works with a diesel engine, and because the diesel CO_2 emission factor is higher than the electric, the RTG emissions are higher than the RMG. Apart from that, it can be seen how, again, the range of values is similar to the other layouts, the equipment consumption is between 20% and 25%.

4.5 RMG + ShC

In this operation system the equipment used are shuttle carriers for the horizontal transport of the containers from the 1st to the 2nd operation area and RMG cranes for the storage of the containers in the stacking area.

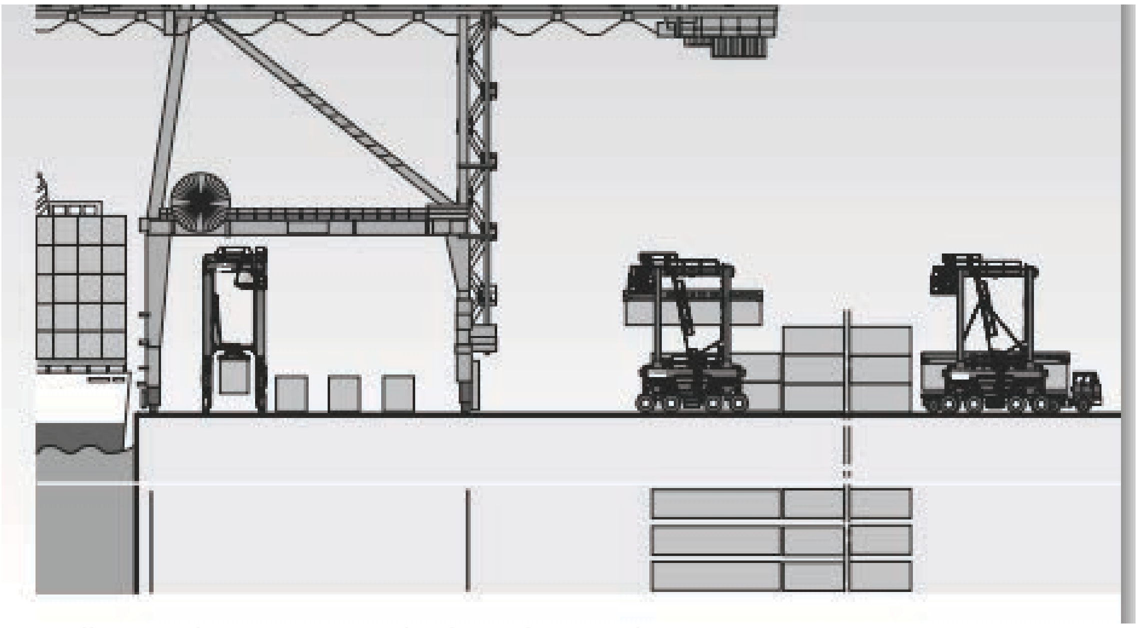

Fig. 4.5: Rail Mounted Gantry Crane + Shuttle Carrier operation system

The operation of this system is very similar to the last explained (RMG + TTU). The STS unloads the container in the floor, there, the ShC lifts it and transports the container to the stacking area where its picked by the RMG crane and stored. The main difference with the RMG + TTU operation system is that in this system, the STS unloads the container on the ground instead of unloading it on top of the TTU, this is possible because the ShC has a systems that allows to pick the container. This difference makes the STS crane more productive since they don't have to wait for the horizontal transport vehicle to be ready.

This operation system has the same characteristics as the RMG + TTU layout, but it is used in terminals with a higher efficiency in the transport between the STS cranes and the stacking area where the RMGs are. The ShC can't store the containers, but is capable of loading a road truck or a train. Also, lower number of ShC are needed if compared to the needed number of TTUs in the last operation system, for this layout it is estimated the use of 2 – 3 ShC per STS crane.

If compared to the operation system with the TTU, this layout has a few advantages.

Advantages (compared TTUs)

- Higher productivity of the STS cranes, as it has been explained.
- Lower personal costs, since lower number of vehicles is needed.
- No disturbance between the ShC.

Having explained this. The consumption and emissions are analysed making the following assumptions:

- 5 STS gantry cranes are used.
- A STS gantry crane unloads 35 containers per hour
- 3 TTUs per STS crane, making a total of 15 TTUs.
- 2 RMGs per STS crane having 10 RMGs.
- The vessel stays 24 hours in the port, 20 of them are docking time.
- The vessel has 8000 TEUs.
- The container throughput in this time is 2800 containers.

With these assumptions and the individual consumptions, the calculations are made and it was obtained:

Table 4.5: RMG + ShC operation system energy consumption and CO_2 emissions

	Diesel [l/h]	Diesel [l/year]	Energy [MWh]	CO_2 Emissions [t]
Vessel	786,79	7374756,11	28567,92	19543,10
STS			440,31	202,98
5 STS			2201,54	1014,91
RMG			275,00	126,78
10 RMG (2/STS)			2750,00	1267,75
ShC	15,00	82500,00	265,65	218,63
15 ShC (3/STS)	225,00	1237500,00	3984,81	3279,38
Total	1011,79	8612256,11	34754,27	23837,39

These are the calculated results of the consumed energy and the emitted CO_2 each year, when a container throughput of 2800 containers is achieved on one vessel in the time it is in the port, one day (20 hours of berthing time; 4 hours of manoeuvre) and working in total 312 days each year; making a container throughput of 873.600 containers per year.

Like with the other operation systems, energy consumption and CO_2 emissions graphics have been made.

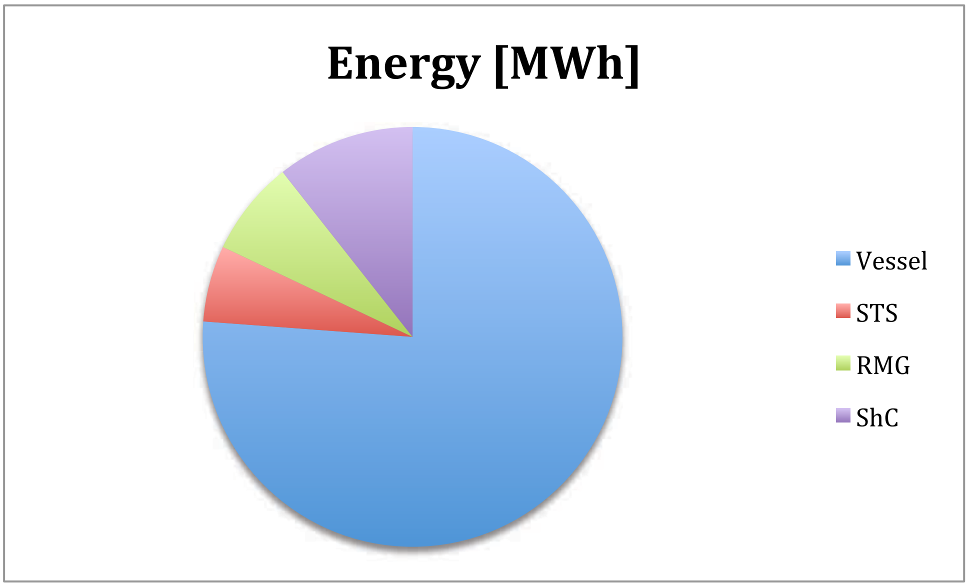

Fig. 4.5.1: Rail Mounted Gantry Crane + Shuttle Carrier operation system energy consumption graphic

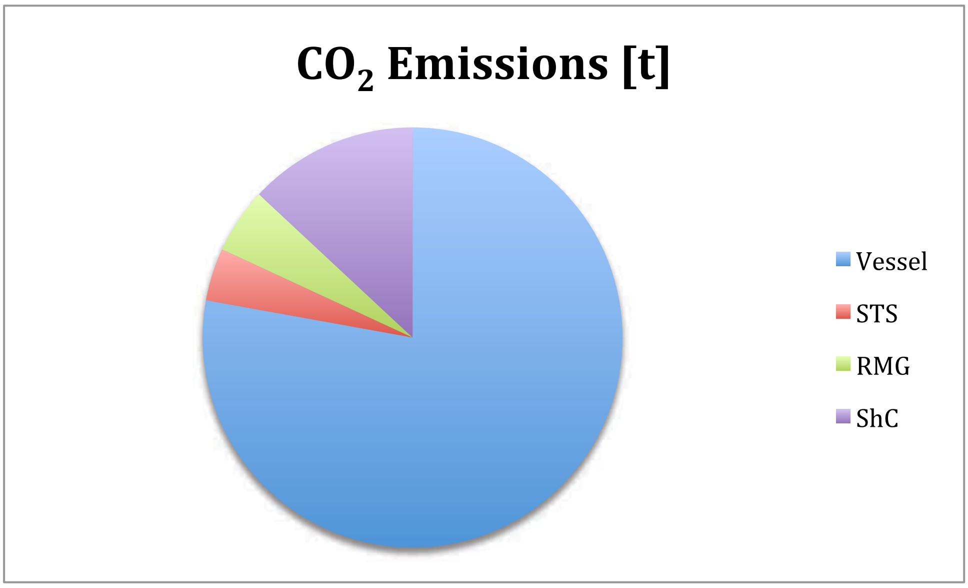

Fig. 4.5.2: Rail Mounted Gantry Crane + Shuttle Carrier operation system CO_2 emissions graphic

As it can be appreciated these graphics show similar results as with the other operation system, being the equipment consumed energy almost 25% of the total consumed energy, however, if the energy graphic is compared to the one from the last explained layout (RMG + TTU) it can be seen how despite they are less in number, the ShCs consumption is higher than the TTUs, this is due to the higher individual consumption of the ShC. If the results tables from both layouts are compared, it can be observed how the ShC energy consumption is more than double than the consumed energy from a TTU.

4.6 RS + TTU

In this layout, the tractor trailer units are used for the horizontal transport of the containers and the reach stackers is the equipment that takes care of the stacking of the containers.

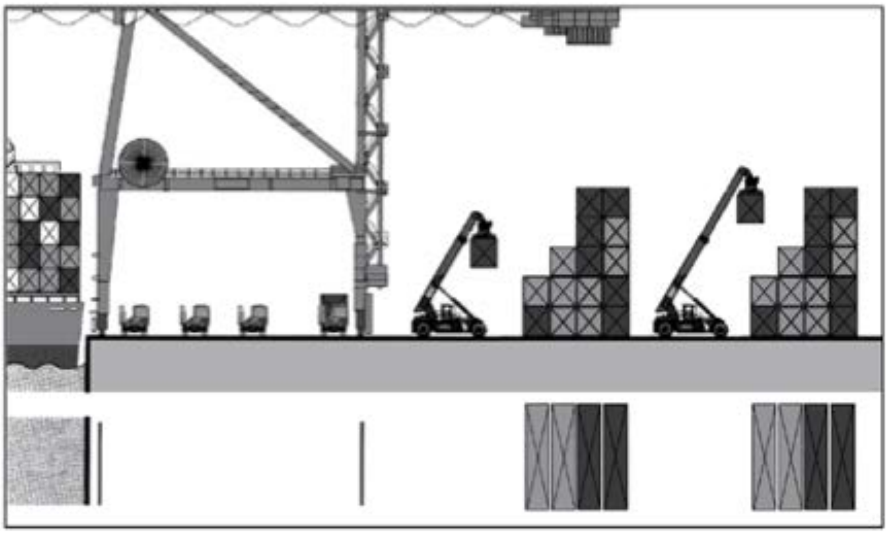

Fig. 4.6: Reach Stacker + Tractor Trailer Unit operation system

The STS crane unloads the container on top of the TTU, it transport the to the 2nd operational area, the stacking area, where the containers are picked and stored by the reach stackers.

This kind of layout has the following characteristics:

- It is a recommended layout for small or medium container terminals.
- It is an easy operation system so not highly trained personal is needed.
- RS can be also used for short distances horizontal transport.
- It is estimated that 3 – 4 RS per STS gantry crane are needed.
- An average of 4 – 5 TTU per STS gantry crane are needed.
- It has a storage capacity of 300 TEU per hectare when 3 – high storage is used and 500 TEU per hectare when 4 – high storage is used. The maximum storage capacity is 5 – high.
- RS can be easily relocated in other parts of the terminal.

With these characteristics, this layout has different advantages and disadvantages.

Advantages:

- Low investments and capital costs.
- Low operating costs.
- Low trained personal.

Disadvantages:

- High number of personal needed.
- Disturbance between TTUs while being un/loaded.
- TTUs can't lift the containers. Lower productivity of the STS gantry cranes.
- 2 handover operations are needed for the container transport between the container areas.

Having analysed the characteristics, advantages and disadvantages of this operation system, it has been then studied the energy consumption. To do this study, similar assumptions as with the other layouts have been made:

- 5 STS gantry cranes are used.
- A STS gantry crane unloads 35 containers per hour
- 4 TTUs per STS crane, making a total of 20 TTUs.
- 3 RS per STS crane having 15 RS.
- The vessel stays 24 hours in the port, 20 of them are docking time.
- The vessel has 8000 TEUs.
- The container throughput in this time is 2800 containers.

With these assumptions, the following results were obtained:

Table 4.6: RS + TTU operation system energy consumption and CO_2 emissions

	Diesel [l/h]	Diesel [l/year]	Energy [MWh]	CO_2 Emissions [t]
Vessel	786,79	7374756,11	28567,92	19543,10
STS			440,31	202,98
5 STS			2201,54	1014,91
RS	17,50	78750,00	253,58	208,69
15 RS (3/STS)	262,50	1181250,00	3803,68	3130,31
TTU	6,95	38225,00	102,94	101,30
20 TTU (4/STS)	139,00	764500,00	2058,90	2025,93
Total	925,79	8139256,11	32828,36	22583,94

These calculated results are the annual needed energy and emitted CO_2 in a container throughput of 2800 containers in one vessel the time it is in the port (24 hours) during 312 days per year.

Energy and emissions graphics have been made with these results.

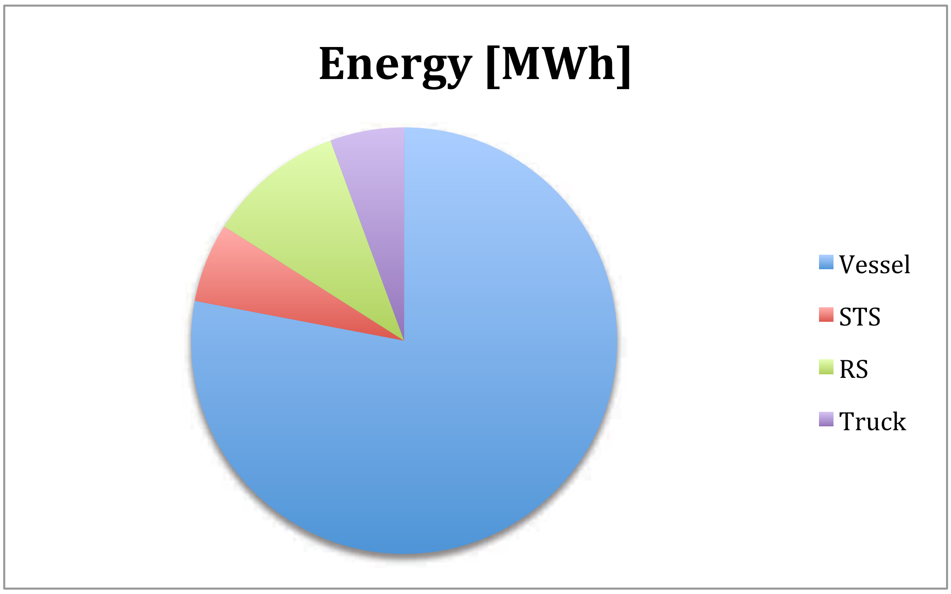

Fig. 4.6.1: Reach Stacker + Tractor Trailer Unit operation system energy consumption graphic

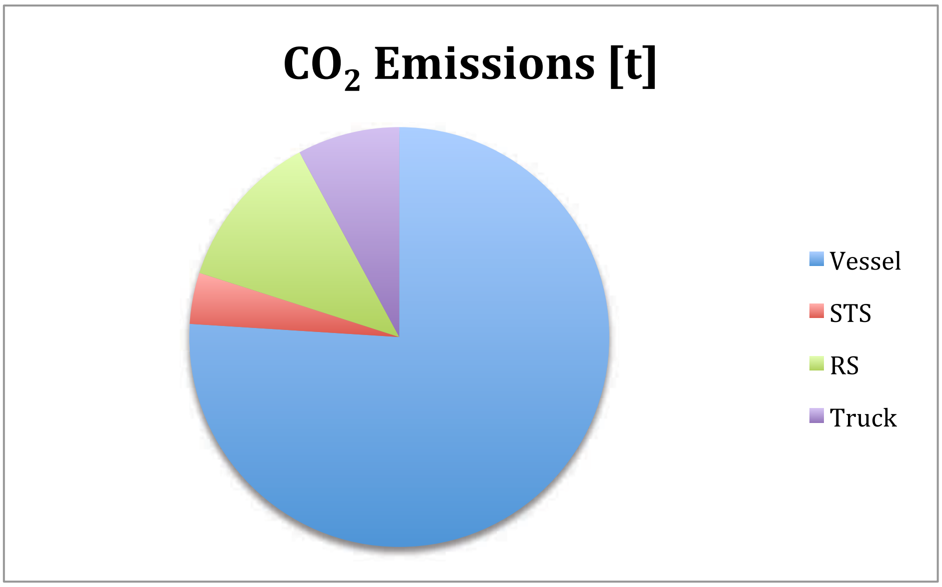

Fig. 4.6.2: Reach Stacker + Tractor Trailer Unit operation system CO_2 emissions graphic

As it can be seen, this operation system shows similar results as the others, the vessel energy and emissions represent about 75% of the total, while the rest of the equipment is around 25%. Again the proportion between energy consumption and CO_2 emissions is not the same due to the different operation of the equipment, STS gantry cranes are fully electrified while TTU and RS work with a diesel engine what means that they have different CO_2 emission factor.

The energy consumption and CO_2 emissions analysis of the different layouts have been calculated without taking into account the consumed energy by the administrations such as buildings and lighting; this consumption is fixed, it is not as dependent on the vessel size and container throughput as the equipment is. Also, the showed result correspond to annual energy consumption and emissions made by the equipment working 312 days per year (6 days a week) and having a container throughput of 2.800 container each day, making a total of 873.600 containers per year.

4.7 Daily Energy Consumption and CO_2 Emissions.

In order to do a deeper analysis of the energy consumption and CO_2 emissions of each layout, a daily study of the consumption and emissions has been made. To do this study it has been taken into account the energy from the vessel, the equipment and the administration. The study consists of analysing each emission per hour, from 8 am to 8 am (of the next day), to make possible the daily analysis; a few assumptions have been made:

- The vessel arrives at 8 am to the port limits.
- The vessel stays 24 hours in the port, leaves at 8 am (2 hours manoeuvre + 20 hours berthing + 2 hours manoeuvre).
- The equipment work during the berthing time, this means from 10 am to 6 am (of the next day).
- The administration, buildings, lights, security, etc. work 24 hours, form 8 am to 8 am.

- The administration energy consumption is 20.000 MWh per year and the CO_2 emissions are 9.220 tonnes per year.

Having made these assumptions the following is determined:

Table 4.7: Daily container terminal usage

Hour	Energy
8 - 8	Administration
8 - 10	Vessel manoeuvre
10 - 6	Vessel berthing
	Equipment
6 - 8	Vessel manoeuvre

It can be appreciated how the works are also during the night, this is because a container terminal doesn't have a normal operation, it is open and works 24 hours per day 365 days per year. The vessels have to be un/loaded in the shortest time possible independently from the time they arrive at the port. With these assumptions, the daily consumptions and emissions of each operation system have been calculated taking the annual data from each layout and dividing it by 365 days, after that, the hourly consumption has been determined dividing the daily results by the operating hours of each equipment knowing:

- Administration → 24 Hours.
- Manoeuvre time → 4 Hours.
- Berthing time → 20 Hours.
- Equipment → 20 Hours

The results are showed in the following tables and graphics:

Table 4.8: Daily energy consumption

	Energy					
Hour	SC	RMG + AGV	RTG + TTU	RMG + TTU	RMG + ShC	RS + TTU
8	9,79	9,79	9,79	9,79	9,79	9,79
9	9,79	9,79	9,79	9,79	9,79	9,79
10	5,95	6,04	5,50	5,54	5,81	5,69
11	5,95	6,04	5,50	5,54	5,81	5,69
12	5,95	6,04	5,50	5,54	5,81	5,69
13	5,95	6,04	5,50	5,54	5,81	5,69
14	5,95	6,04	5,50	5,54	5,81	5,69
15	5,95	6,04	5,50	5,54	5,81	5,69
16	5,95	6,04	5,50	5,54	5,81	5,69
17	5,95	6,04	5,50	5,54	5,81	5,69
18	5,95	6,04	5,50	5,54	5,81	5,69
19	5,95	6,04	5,50	5,54	5,81	5,69
20	5,95	6,04	5,50	5,54	5,81	5,69
21	5,95	6,04	5,50	5,54	5,81	5,69
22	5,95	6,04	5,50	5,54	5,81	5,69
23	5,95	6,04	5,50	5,54	5,81	5,69
24	5,95	6,04	5,50	5,54	5,81	5,69
1	5,95	6,04	5,50	5,54	5,81	5,69
2	5,95	6,04	5,50	5,54	5,81	5,69
3	5,95	6,04	5,50	5,54	5,81	5,69
4	5,95	6,04	5,50	5,54	5,81	5,69
5	5,95	6,04	5,50	5,54	5,81	5,69
6	9,79	9,79	9,79	9,79	9,79	9,79
7	9,79	9,79	9,79	9,79	9,79	9,79

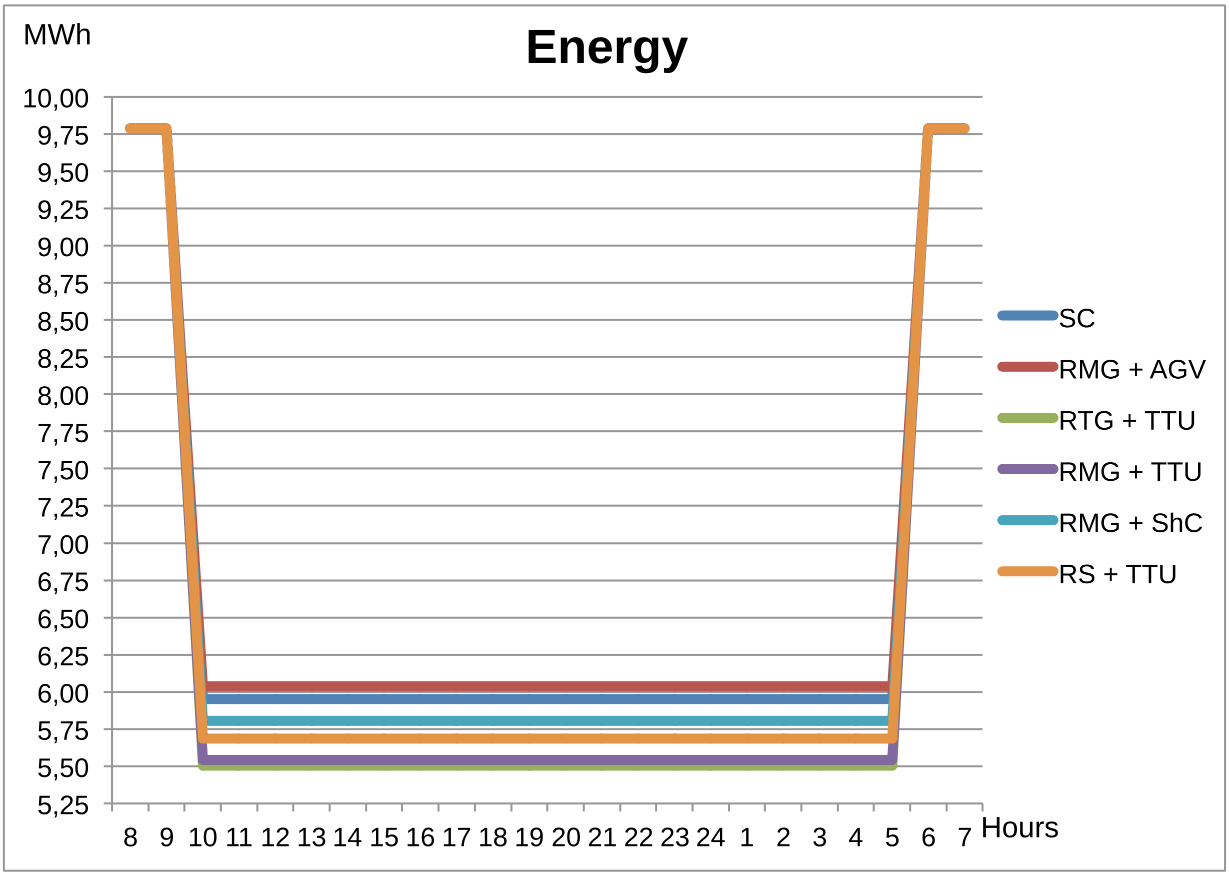

Fig. 4.7.1: Daily energy consumption graphic

Table 4.9: Daily CO_2 emissions

	CO_2 Emissions					
Hour	SC	RMG + AGV	RTG + TTU	RMG + TTU	RMG + ShC	RS + TTU
8	6,02	6,02	6,02	6,02	6,02	6,02
9	6,02	6,02	6,02	6,02	6,02	6,02
10	3,58	3,51	3,26	3,15	3,32	3,41
11	3,58	3,51	3,26	3,15	3,32	3,41
12	3,58	3,51	3,26	3,15	3,32	3,41
13	3,58	3,51	3,26	3,15	3,32	3,41
14	3,58	3,51	3,26	3,15	3,32	3,41
15	3,58	3,51	3,26	3,15	3,32	3,41
16	3,58	3,51	3,26	3,15	3,32	3,41
17	3,58	3,51	3,26	3,15	3,32	3,41
18	3,58	3,51	3,26	3,15	3,32	3,41
19	3,58	3,51	3,26	3,15	3,32	3,41
20	3,58	3,51	3,26	3,15	3,32	3,41
21	3,58	3,51	3,26	3,15	3,32	3,41
22	3,58	3,51	3,26	3,15	3,32	3,41
23	3,58	3,51	3,26	3,15	3,32	3,41
24	3,58	3,51	3,26	3,15	3,32	3,41
1	3,58	3,51	3,26	3,15	3,32	3,41
2	3,58	3,51	3,26	3,15	3,32	3,41
3	3,58	3,51	3,26	3,15	3,32	3,41
4	3,58	3,51	3,26	3,15	3,32	3,41
5	3,58	3,51	3,26	3,15	3,32	3,41
6	6,02	6,02	6,02	6,02	6,02	6,02
7	6,02	6,02	6,02	6,02	6,02	6,02

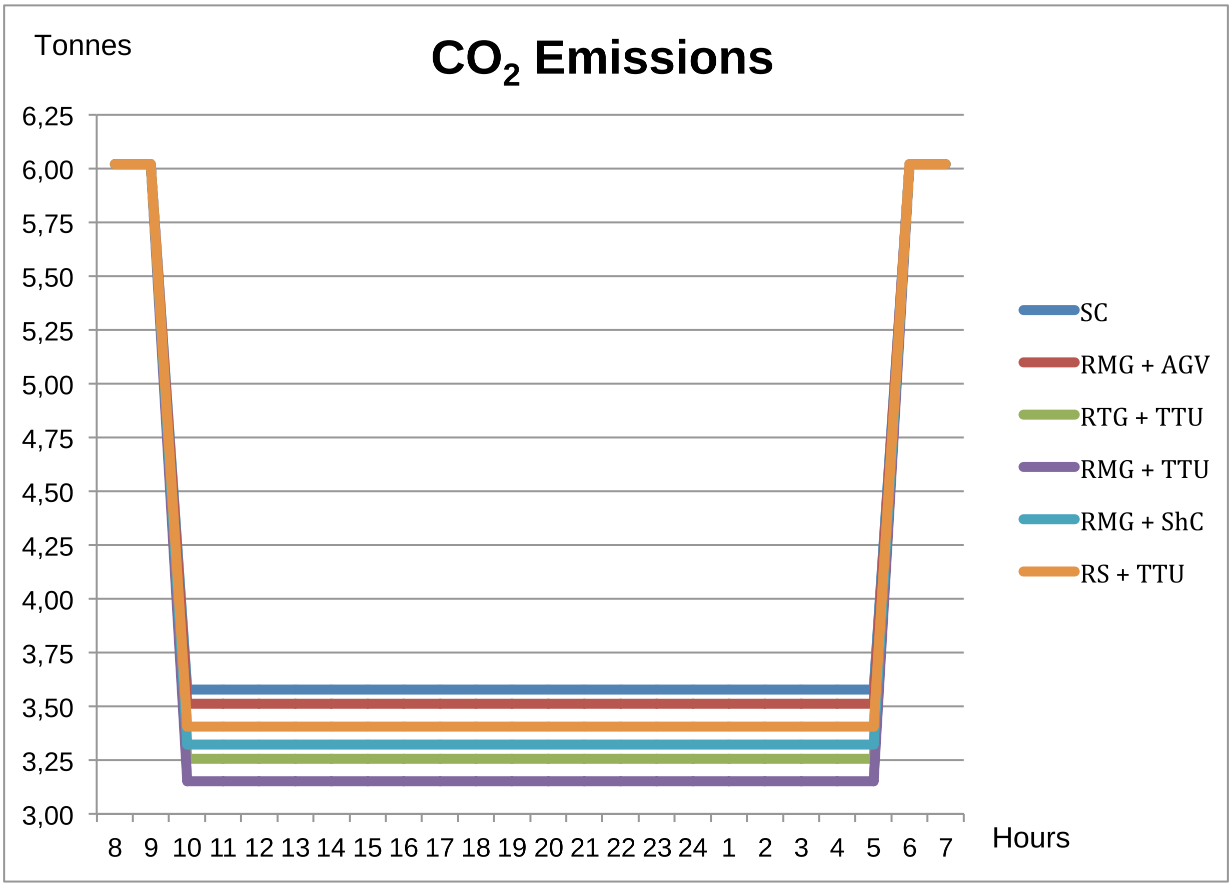

Fig. 4.7.2: Daily CO_2 emissions

It can be clearly appreciated that the consumption as well as the emissions are very linear; this is due to the already explained fact that there is no difference between day and night since all the equipment work independently from the hour to lower the berthing time of the vessel. Also, it is seen that the different layouts have similar consumption and emissions; this result was something expected since at was already seen with the study of the consumption and emissions from each layout. The first 2 hours (from 8 am to 10 am) and the last 2 (from 6 am to 8 am) are the same in all the operation systems since it only involves the vessel manoeuvre time consumption and emissions; no equipment is used in that time. During this time the consumption is higher than in the berthing time, this is mainly because in the manoeuvre time the principal engine of the vessel is working, and as it has been said this engine has a power around 30.000 kW, which is a much bigger power than the rest of the used equipment power.

5. Real Port Model

In this chapter it is going to be built a real port model to make possible the calculations of the energy consumption and the CO_2 emissions. To build this model, the results of each operation system are going to be adapted to real port characteristics. After this, the energy consumption per container is going to be calculated in each layout as well as in HHLA port and to conclude it is going to be compared the energy consumption of HHLA with a port model with the same number of equipment as in HHLA but with the calculated results for energy consumption and CO_2 emissions.

5.1 Real Port Model

To adapt the results to real port characteristics, it has been taken HHLA port characteristics and based on them the model has been made.

HHLA had a container throughput of 7 millions of containers in 2012 [12], knowing this fact the model has been made aiming to have a similar container throughput, also, HHLA has 52 STS gantry cranes, making different assumptions:

- 5 STS gantry crane needed per vessel.
- STS gantry cranes work 16 hours per day, 312 days per year (6 days a week).
- A STS gantry crane un/loads and average of 35 containers per hour

With these assumptions the container throughput per day of a vessel can be calculated:

Container throughput = STS number x STS working hours x STS containers per hour;

Container throughput = 5 x 16 x 35 = 2.800 containers

Knowing this value it can be now calculated the average number of vessel per day needed to achieve an annual container throughput of 7 mill. of containers.

$$\text{Vessel Number} = \frac{annual\ throughput}{days\ x\ daily\ throughput} = \frac{7\ mill.\ container}{365\ x\ 2800} \approx 7\ \text{vessel per day}$$

Having 7 vessels per day means that 35 STS gantry cranes and the correspondent equipment work each day, but there has to be more than 35 STS cranes since each crane work only 6 days per week but the vessels arrive and have to be un/loaded every day of the week. To make a successful operation with these values, the container terminal should have at least 37 STS gantry cranes whit its correspondent equipment.

It is not easy to do an accurate model of a container terminal since many assumptions have to be made and each terminal is different, uses different layouts with specific parameters for each layout or can combine two or more operation systems, as it has been said, there is not an ideal container terminal, or a general container terminal. Since an individual analysis of the consumption and emissions have been made in this project, it is possible to do an approximate study of different operation systems combining each equipment and knowing the needed quantity of the machinery used.

To do a comparative analysis between the general layouts that have been explained and a real port like HHLA, the energy consumption of each operation system as well as HHLA per container has been calculated in kWh per container.

5.2 kWh per container

The calculations of this factor are based on the already calculated energy of the different operation systems without taking into account the vessel energy consumption. To do the calculations the annual container throughput had to be determined and the annual energy consumption has already been calculated in chapter 4. To obtain the annual container throughput, the same assumptions as in the chapter 4 and in section 5.1 have been made:

- 5 STS gantry cranes per container.
- STS work 16 hours per day and 6 days a week, making 312 days each year.
- An STS has an average productivity of 35 containers per hour.

With these assumptions it is determined that the container throughput of 2.800 containers per vessel and day. This means the annual container throughput is:

Annual Container Throughput = Daily Container Throughput x Working Days

Annual Container Throughput = 2.800 x 312 = 873.600 containers

Taking the equipment energy of each operation system:

Table 5.1: Operation systems energy consumption

	Energy [MWh]					
	SC	RMG + AGV	RTG + TTU	RMG + TTU	RMG + ShC	RS + TTU
5 STS	2201,54	2201,54	2201,54	2201,54	2201,54	2201,54
20 SC	7792,52					
10 RMG		2750		2750	2750	
20 AGV		5667,29				
10 RTG			2474,6			
20 TTU			2058,9	2058,9		2058,9
15 ShC					3984,81	
15 RS						3803,68
Total	9994,06	10618,83	6735,04	7010,44	8936,35	8064,12

Knowing the annual energy of the equipment and the annual container throughput made with this equipment and energy, the needed energy per container was calculated.

$$\text{Energy per Container} = \frac{Annual\ Energy}{Annual\ Container\ Throughput}$$

With this it was determined:

Table 5.2: Model annual container throughput

Annual Container
873600

Table 5.3: Operation systems energy consumption per container

Energy per Container [kWh/cont]					
SC	RMG + AGV	RTG + TTU	RMG + TTU	RMG + ShC	RS + TTU
11,44	12,16	7,71	8,02	10,23	9,23

It is seen how these values are in the same range and that the operation systems using TTUs have a lower energy consumption per container, however the difference is not very high.

It has also been calculated the needed energy consumption per container from a real port like HHLA. The calculations are based on the information given in HHLA Sustainability Report from 2012 [8]; there they state that 52% of the emissions were made by the SCs, 18% by the AGVs and 11% by the container and rail gantry cranes (STS and RMG). HHLA also informs that the total emissions in 2012 were 112.000 CO_2 tonnes. Knowing that SCs and AGVs work with diesel engines and STS and RMGs are fully electrified the needed energy is determined using the correspondent CO_2 emission factor for each operation ($2{,}65\,\frac{kg\ CO_2}{Diesel\ litre}$; $461\,\frac{CO_2\ gr}{kWh}$). The SCs and AGVs energy consumption was calculated with Eq.2 and Eq.3 and the cranes energy consumption with Eq.5; with these calculations it was determined:

Table 5.4: HHLA container handling equipment CO_2 emissions

CO_2 Emissions [t]		
SC	AGV	STS + RMG
58240	20160	12320

Table 5.5: HHLA container handling equipment energy consumption

Energy [MWh]			
SC	AGV	STS + RMG	Total
70768,19	24496,68	26724,51	121989,38

Knowing that with this energy consumption the HHLA port had a container throughput of 7 mill. containers in 2012 [12], it can be easily obtained the needed energy per container:

Table 5.6: HHLA energy consumption per container

Energy per Container [kWh/cont]
17,43

Having determined these values, a comparison between the researched results in this project and the obtained results from HHLA has been made.

5.3 Comparison with HHLA port

If the obtained results from section 5.2 are compared:

Table 5.7: HHLA and operation systems energy consumption per container comparison

Energy per Container [kWh/cont]						
SC	RMG + AGV	RTG + TTU	RMG + TTU	RMG + ShC	RS + TTU	HHLA
11,44	12,16	7,71	8,02	10,23	9,23	17,43

It is clearly seen that despite they are all values on the same range; the HHLA port shows higher energy consumption than the rest of the operation systems, this may be due to several factors. To explain these factors, the equipment from HHLA has to be reminded:

Table 5.8: HHLA container handling equipment

	CTA	CTB	CTT
STS	15	25	12
SC		120	59
AGV	86		
RMG	4	5	3

Seeing the equipment it can be seen how different operation systems are used in the terminals. In CTA it is used the RMG + AGV operation system, however the proportion of the used equipment is not the same as it has been assumed in this project to do the energy consumption calculations of this layout, while CTA terminal uses 5,7 AGV per STS crane and 0,2 RMG per STS; to do the calculations of the RMG + AGV layout it was assumed 4 AGV per STS and 2 RMG per STS. The CTB and CTT terminals combine a pure Straddle Carrier system with the use of RMG cranes, this operation system has not been studied, also, comparing the equipment proportion with the one used to study the pure SC operation system it is appreciated that in CTB terminal they use 4,8 SC per STS gantry crane and CTT terminal uses 4,9 SC per STS gantry crane, they have similar proportion, however, in this study the used proportion to analyse the energy consumption was 4 SC per STS gantry crane and no RMG cranes were considered since it is a pure Straddle Carrier operation system.

These differences between the real operation of HHLA and the analysed operation systems make the deviation of the energy consumption per container obtained results. There are also other important factors that affect to this energy consumption, in this project it has been assumed that 5 STS per vessel are needed but some vessels might need a higher or a lower number of STS to be un/loaded; also, the assumed working hours of each equipment can differ from the real working hours in a container terminal and the container throughput per vessel has been estimated but it is different in each vessel. As it has been said, the studied results can differ from real energy consumption but the give an accurate estimation of it.

To validate the calculated energy from each process, a container terminal model has been made using the same equipment and having the same annual container throughput as HHLA port.

Table 5.9: Model energy consumption with the same equipment as HHLA

	Model		
	Number	Individual Energy [MWh]	Total Energy [MWh]
STS	52	440,31	22896,12
SC	179	389,63	69743,77
AGV	86	283,36	24368,96
RMG	12	275	3300
Total			120308,85

Taking the total energy consumption and an annual container throughput of 7 mill. containers:

Table 5.10: Energy consumption per container comparison between HHLA and model with the same equipment

Energy Consumption per container [kWh/cont]	
HHLA	Model
17,41	17,19

If both results are compared it can be appreciated that are very similar, this means that the obtained values of each individual process in this project are very similar to real operation, however the different operation systems that have been analysed can differ from real operations due to the assumed proportions of the equipment used, yet, some of these layouts might be used in various real container terminals, as the container terminals have different operations and requirements.

To do another verification of the calculated results from the energy consumptions of the individual processes such as SC and AGV, the determined diesel consumption has been compared with the value given by HHLA Sustainability Report of 2012 [8]. In this report HHLA port informs that the diesel consumption in 2012 was 26,5 mill. litres of diesel. Calculating the diesel consumption of 86 AGV and 179 SC, as they are the only machinery operating with diesel engines, based on the research that had been made:

Table 5.11: Model diesel consumption with the same equipment as HHLA

	Model		
	Number	Individial Diesel Consumption [l]	Total Diesel Consumption [mill. l]
SC	179	121000	21,659
AGV	86	88000	7,568
Total			29,227

Comparing the total diesel consumption of HHLA and of the model:

Table 5.12: Diesel consumption comparison between HHLA and model with the same equipment

Annual Diesel Consumption [mill. l]	
HHLA	Model
26,5	29,2

It is observed how both results are very similar, the small difference between both numbers can be because of the assumed diesel consumption in litres per hour of the SC and the AGV and the assumed annual operating hours, despite this small difference, it can be said that both assumptions, litres per hour and annual operating hours, are very accurate as the calculated result is very similar to the value given by HHLA port.

6. Conclusions

Since the importance of shipping transport for the world's goods, the harbours play a central role related to this subject. In this project have been investigated and analysed the energy consumption and CO_2 emissions of standard container terminals.

To achieve this analysis, first it had to be determined how does a container terminal work and which processes are involved in the un/loading and storing of the containers. Knowing the main processes that are carried out in a container terminal, the individual consumption and CO_2 emissions of each one have been calculated and when possible, compared with the values obtained from a real port. To do a deeper study of the energy consumption in a container terminal, it has been also determined the consumed energy by the administration facilities such as buildings, lighting or security, as well as the consumed energy made by the vessel in the port limits, to make possible these calculations different assumptions had to be made.

As in a standard container terminal different processes are combined in order to make the terminal work, in this study have been analysed some possible combinations obtaining the energy consumption and CO_2 emissions of each one. Despite the fact that each container terminal works with different operation systems, the calculations made in this project make possible to obtain the energy and emissions of a layout that hasn't been taken into account in this paper, this is due to the obtained individual energy and emissions of each different process.

In chapter 5 have been compared the consumed energy per container from each layout and from HHLA, it is appreciated that HHLA energy consumption is much higher compared to the other operation systems, however, if a model is built with the same used equipment as the used in HHLA, the obtained results are very similar. This fact means that the operation systems may not be used in a container terminal as they have been studied in this project but if different layouts are made with the calculated individual energy consumption, it can be determined an accurate estimation of the energy consumption from a real port as it has been made with HHLA port.

In the future, the tendency is that the energy consumption and the CO_2 emissions are going to be lowered due the different advances in each process, hybrid operation, higher efficiency, different used fuel, etc. However, this project gives a good energy consumption and CO_2 emissions estimation of a standard container terminal, being able to calculate different layouts possibilities that can be used in a terminal. Also, the container terminals tend to be more automatized being less needed the manned vehicles, this tendency gives special importance to the AGV and RMG and Lift Automated Guided Vehicle (LAGV), this vehicle is not mentioned in this project since it is barely used, however it will be used in the future since it is an unmanned automated vehicle that has the ability to lift the containers from the ground, giving the STS gantry crane a higher productivity.

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