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Agent based simulation for C-AGVs at Intermodal Terminal

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ABSTRACT

In recent history there has been a steady increase in container traffic worldwide. As a result modern western Container Terminal ports are turning towards automation to raise their productivity, capacity and reliability. Automated Guided Vehicles (AGVs) are among the most commonly used solutions for horizontal transport within a container terminal. A more recent development in the automated container handling is the use of cassette based or C-AGVs. The latest generation of which provides a zero emission, all electric solution through the use of induction recharge points in the terminal area.

The Multi-Agent System (MAS) based simulation model provides a method for evaluating dispatching strategies for this newest generation of C-AGVs. The location and number of recharge points, cassettes, yard and quay cranes as well as the paths containers have to travel are all included in the model.

The NetLogo based simulator will be used to compare existing dispatching strategies, modified versions of them, or develop and test new ones. The simulator will also simulate different scenarios, which are described in the later chapters, and can thus be used to determine the best configuration and investment plan in a highly complex domain like a Container Terminal.

Keywords: Agents, Automated Container Terminal, C-AGV, MAS, NetLogo.

DUTCH ABSTRACT

De huidige trend in wereldwijd container verkeer laat een continue stijging zien. Om een oplossing te bieden voor deze toenemende vraag naar extra capaciteit kijken de grote Container Terminals in het Westen naar doorgedreven automatisatie om de productiviteit, capaciteit en betrouwbaarheid verder te verhogen. Automated Guided Vehicles (AGVs) behoren tot de meest gebruikte geautomatiseerde oplossingen voor horizontaal transport binnen een container terminal. De recente trend betreft het gebruik van steeds geavanceerdere cassette gebaseerde AGVs (C-AGVs). De nieuwste generatie prototypes offert een uitstootvrije, volledige elektrische oplossing door het gebruik van op inductie gebaseerde contactloze herlaadpunten in de terminal.

Het “Multi-Agent System” (MAS) gebaseerde simulatie model maakt het mogelijk dispatching strategieën voor deze nieuwste generatie C-AGVs te evalueren. Het aantal en de locatie van de herlaad punten, het aantal cassettes, kaai en werfkranen evenals het pad dat een container aflegt zijn allen van belang in het model.

De op NetLogo gebaseerde simulator zal gebruikt kunnen worden om bestaande dispatching strategieën evenals gewijzigde versies ervan te vergelijken en evalueren. De simulator zal gebruikt worden om verschillende scenario’s te simuleren. Met behulp van de resultaten hiervan kan de optimale configuratie en investeringsplan voor dit zeer complexe domain bepaald worden.

Keywords: Agents, Geautomatiseerde Container Terminal, C-AGV, MAS, NetLogo.

"Somewhere, something incredible is waiting to be known."

Dr. Carl Sagan
American Astronomer, Writer and Scientist,
1934-1996

DEDICATIONS

To my father, whose kindness and prayers bring me at this stage and to my mother, who prays putting up with me during the nights and weekends. Also dedicate this achievement to my family and friends by which we were really supported in the way of keeping moral high and always clarify our concepts.

Ali Awais Syed

I want to thank my family for supporting my studies and giving me the opportunity to go to Sweden, on my second Erasmus exchange. Also a lot of thanks to my friends, who helped me through the tougher times of my education… *Dies diem docet!*

Jan Milants

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May, 2009

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ABBREVIATIONS

AGV	Automated Guided Vehicle
ASC	Automated Stacking Crane
C-AGV	Cassette Automated Guided Vehicle
CMS	Crane Management System
CT	Container Terminal
DRMGC	Dual Rail Mounted Gantry Crane
ECT	European Container Terminals, Rotterdam
ETP	Energy Transfer Point
HTS	Horizontal Transportation System
LoLo	Load on Load off
MAS	Multi Agent System
OHBC	Overhead Bridge Crane
QC	Quay Crane
RMGC	Rail Mounted Gantry Crane
RoRo	Roll on Roll off
SC	Straddle Carrier
TC	Transfer Crane
TMS	Traffic Management System
TOS	Terminal Operating System
VTS	Vertical Transportation System
YC	Yard Crane

CHAPTER 1: INTRODUCTION

Modern Containers were first used as a means of transporting goods over sea in 1960s [4] with an intercontinental service between several ports in the Caribbean, Central and South America and the US East Coast. Though not an immediate success, through large investments in specially designed ships and terminals led to economic efficiency and a growing market share of container traffic. Traditionally seaports focussed exclusively on the berth [1].

Nowadays more than 60% of all deep-sea cargo shipping is container based[4]. In the west, most electronics, clothes and other everyday tools have, at one point or another, been transported in a container. Often these products are produced in countries like India and China where labour is cheap and then shipped in containers to their buyers in the rest of the world. As a result of the western addiction to cheap products international and intercontinental container shipping has exploded. Until recently shipping rates increased at almost 10% a year and this growth is expected to continue, although at a slightly slower pace [4].

As a result of this increase ports worldwide, but especially in the west, are turning towards automated solutions to optimize their throughput and efficiency. The high cost associated with port congestion and ship delays pushes terminal operators to implementing new high tech solutions. These are more capable of providing a constant and predictable throughput as well as added flexibility since changes to port operations can now be as simple as a software update.

The goal of this automation is always the same: minimize ship turn-around time. This is the time during which the ship is docked at the port and loading and unloading operations are performed. Because of the high cost associated with keeping an expensive vessel idle ports attempt to minimize this as much as possible.

There are various ways of accomplishing this:

- Deploy more quay cranes per vessel. This is however constrained by the length of the vessels and also the minimum distance required between cranes.
- Improve the handling rate of the individual cranes, by increasing the speeds and semi automation features of the cranes.
- Improve reliability and maintainability of the cranes, so as to minimize the amount of reworks.
- Train and use skilled operators to man the cranes.
- Provide efficient yard handling and horizontal transportation systems for the loading and discharging/unloading operations. [2]

The topic of this thesis falls in the last category: improving the horizontal transportation systems on the yard. Among the solutions currently in use or under consideration are trailers, trucks, Automated Guided Vehicles (AGVs), straddle carriers and overhead bridge cranes. This paper will concentrate on the latest generation of C-AGVs. These will be discussed in a next chapter.

1.1 Background

1.1.1 The Modern Container

Ever since the first container was used in the late 1780s there have been countless variations, each with their own dimensions, form or construction material. It is only since the late 1950s containers were standardized which allowed specific equipment to be build to handle those containers worldwide.

There are 2 main standard sized: 20ft or 6m and the most commonly used 40ft or 12m long containers as shown in figure 1.1 and figure 1.2.

Figure 1.1: 20 Feet Container.

Figure 1.2: 40 Feet Container.

1.1.2 The Container Terminal

Modern container terminals are made up of several independent blocks. The only automated solution in CTs discussed in this thesis is the use of AGVs.

The first, and most expensive unit in a container terminal is the Quay Crane (QC). A large intercontinental container ship is usually unloaded and loaded by up to 5 of these cranes, depending on how many containers need to be moved. The purpose of these cranes is moving containers back and forth between the quay and the ship.

The second unit, the Yard Crane (YC), handles moving containers from a designated buffer zone to the yards stack area where containers are stored until they can be transported outside the terminal to their destination. There are various types of YCs: Transfer Crane (TC), Rail Mounted Gantry Crane (RMGC), Dual RMGC (DRMGC) and Overhead Bridge Crane (OHBC). A number of possible configurations are in use in today's CTs, including the use of 2 YCs for one stack area, however the choice of YCs is not part of the scope of this thesis. Instead we will assume they function according to a specific set of parameters.

Figure 1.3: Container Terminal Quay Cranes.
(Picture taken in Altenwerder, Hamburg, Germany. Courtesy of Google.)

Figure 1.4: Container Terminal Yard Crane. (Courtesy of PACECO Corp.)

The third and cheapest unit is the AGV, whose purpose is to move containers between the quay cranes and the yard cranes through the transport zone. The AGVs ship containers back and forth between the Yard Cranes and the Quay Cranes, or if no ship is being loaded or unloaded to reorganize the yard area by moving containers from one stack to another. This last situation will not be considered in this thesis.

Figure 1.5: AGVs (Courtesy of Container Terminal Altenwerder CTA)

There are a lot of different possible layout for a container yard, however they can all be classified into two major categories: vertical and horizontal storage.

The vertical or perpendicular layout, as shown in the picture below, is the most popular one in Europe and the US.

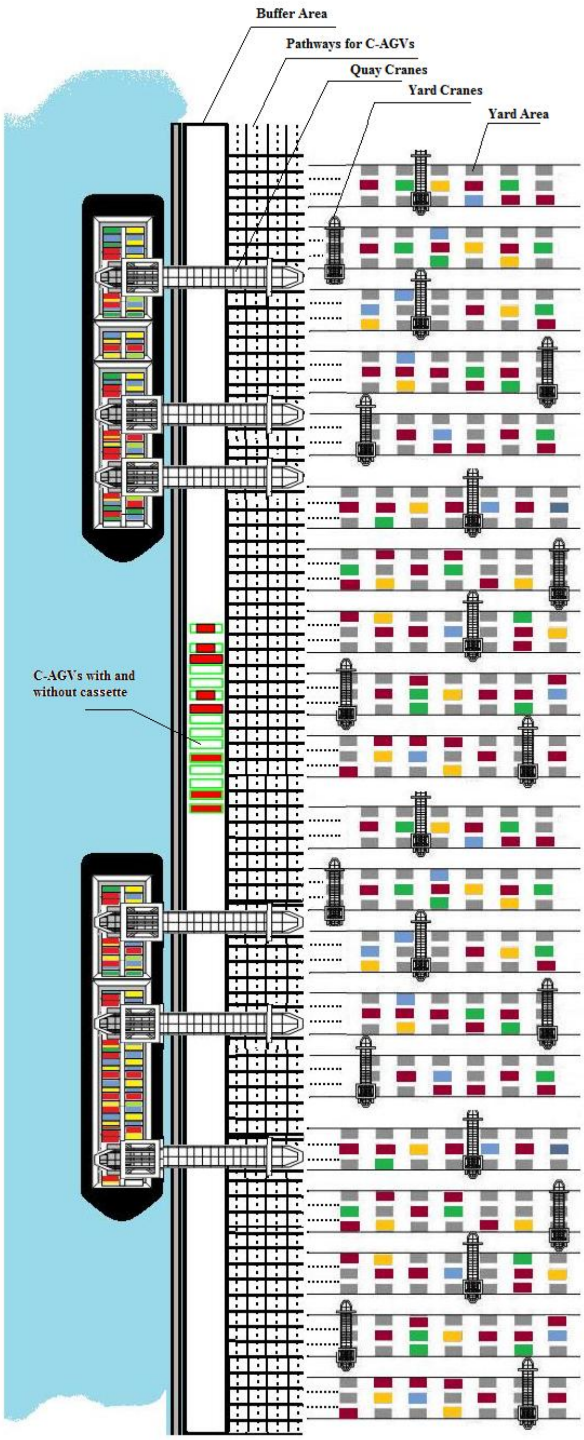


Figure 1.6: Perpendicular or Vertical CT layout.

The second, the horizontal or parallel layout, as shown in the picture below is most commonly used in Asian ports.

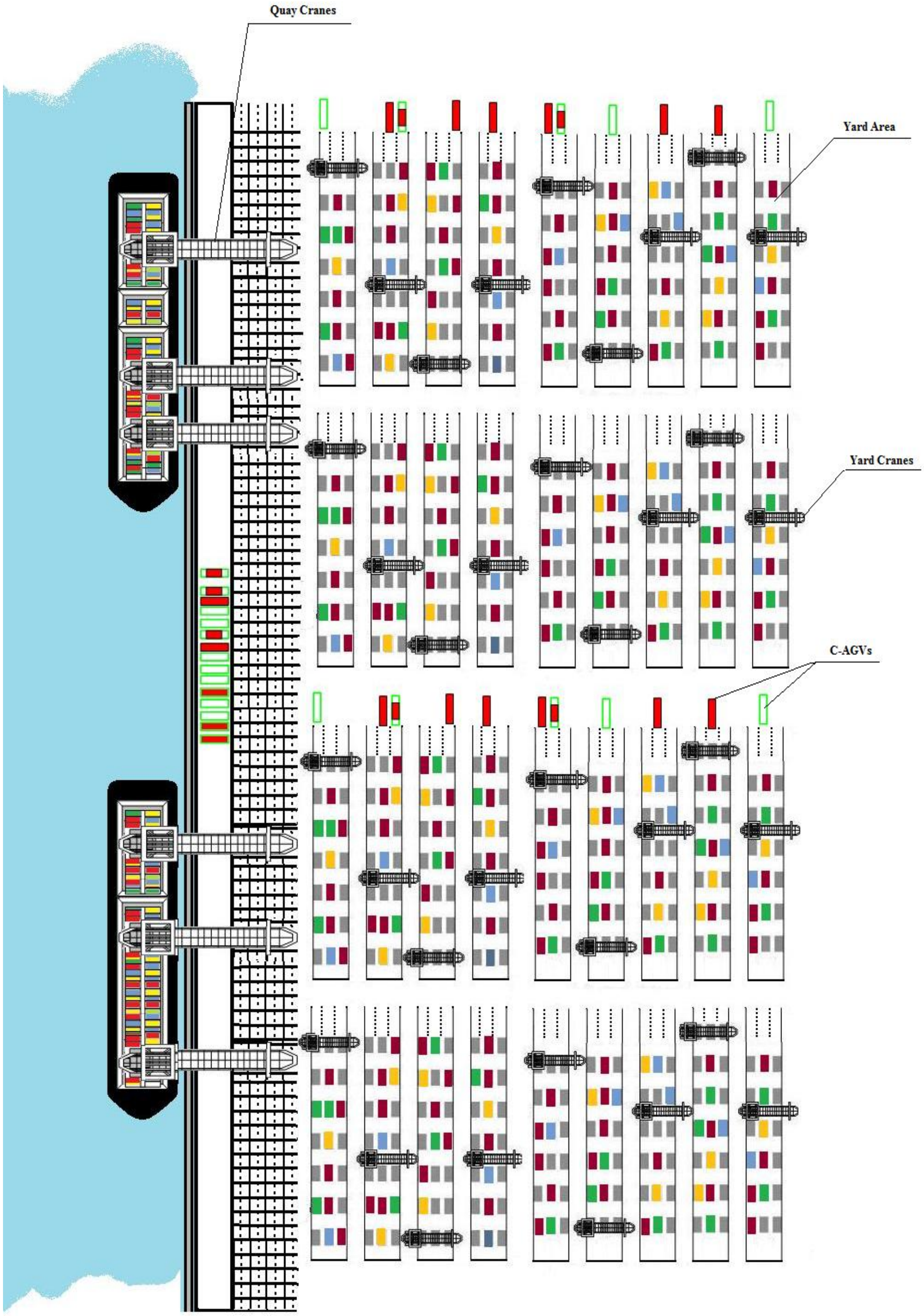


Figure 1.7: Parallel or Horizontal CT layout.

It should be clear that the distance between the QCs and the yard buffer areas is much smaller in a perpendicular layout. Thus AGVs will have to travel much shorter distances between the QC and the YC. Since in most implementations one QC is served by the 2 closest YCs for the majority of all traffic, a single AGV can transfer much more cargo from the QC to the YC buffer area in the same time span. However since this layout can't as easily be expanded as the parallel layout, it is important that the capacity of the YC as well as the throughput required for each block have been accurately estimated in order to prevent congestion in the yard area.

In the horizontal layout on the other hand the distance containers have to spend in the Horizontal Transportation System (HTS) will be much greater than in a perpendicular layout. However YCs can often travel from one block to the next allowing for more YCs to be installed, even when the terminal is already in operation. It is also possible to add new storage capacity farther away from the docks, at the cost of further increasing travel distance.

In general studies have shown the perpendicular design to be the most efficient one, at the cost of being less easily expendable in a later stage.

1.1.3 Automated Guided Vehicles

Although AGVs have been around since the mid 1950s, the first commercial container terminal didn't adopt them until the 1990s. The first to adopt an automated transport system was Europe Container Terminals (ECT) in Rotterdam which used AGVs for horizontal transport and Automated Stacking Cranes (ASCs) for vertical transport. Although during the initial period numerous performance issues were encountered, most of these were caused by faulty software, other operators picked up on the success and started working on their own implementations.

Today Delta Port terminal in Rotterdam is the most technologically advanced port in the world, performing more than 500.000 container lifts a year. [3]

Original AGVs were fixed path AGVs which moved along a predetermined fixed path such as rails or a guidance system build into the roads. Unlike fixed patch AGVs, their free path counterparts, as used in the port of Rotterdam, are much less restricted in their movements, which allows them to follow a much shorter path from their current position to their destination. This however comes at a price: it requires a complex build-in navigation system to guide the AGV.

Among the onboard systems required for this are a propulsion and steering mechanisms, a traffic management system which also handles routing and scheduling and a communication system which allows the AGVs to stay in contact with a central control system.

A more recent development in AGV technology in terminals is the IPSI™ AGV, part of the European Unions' IPSI™ project. These AGVs have been designed to transport containers through the use of and additional buffer in between: cassettes.

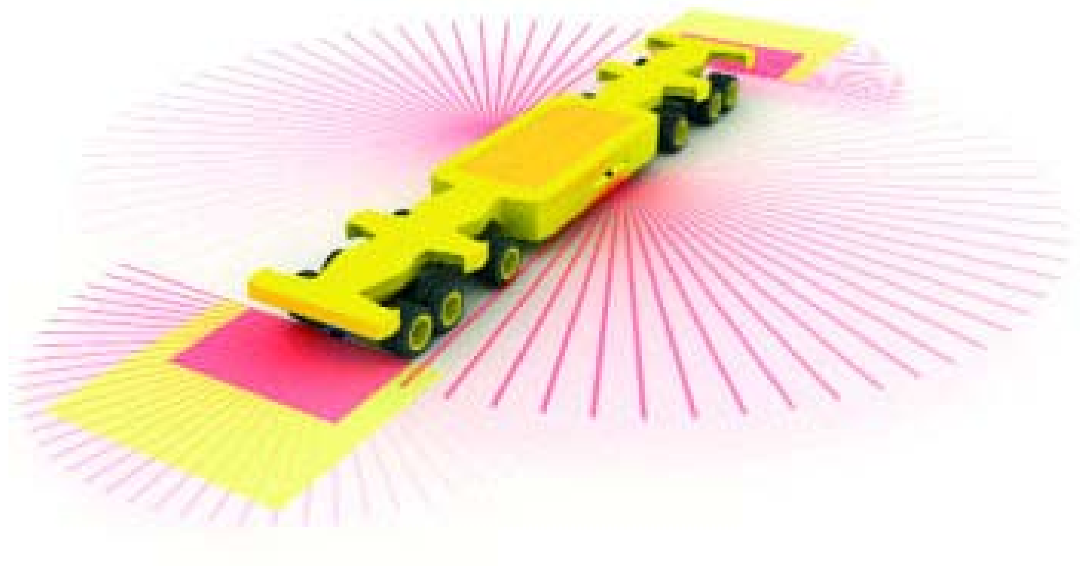


Figure 1.8: IPSI™AGV, Laser Navigation System. (Courtesy of TTS)

These cassette AGVs (C-AGVs) have been designed specifically to transport cassettes with containers on them. Each cassette can carry up to two 40ft or 4 20ft containers.

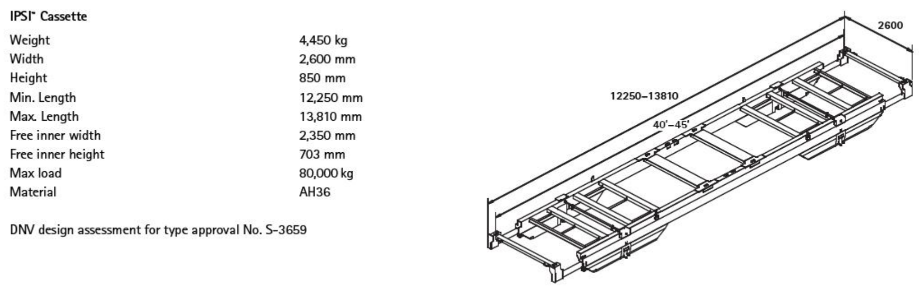


Figure 1.9: IPSI™ Cassette. (courtesy of TTS)

IPSI™ AGVs have been developed to assist in the on-and offloading of two types of ships: LoLo and RoRo. LoLo means Load on Load off and to unload containers from such ships they require the use of quay-cranes. The second type is RoRo stands for Roll on Roll off [6] in which case they drive onto the ships to load the cassettes to unload them in the yard. In this thesis only LoLo operations will be handled.

The AGVs used in this thesis are of a newest generation providing a zero-emission all electric solution. These C-AGV offers several key benefits. The new vehicles have a load capacity of 61 tones, and can carry cassettes with double-stacked 40-foot containers or two 20-foot containers in a single tier. Major improvements to manoeuvrability have been made by incorporating individual electrically driven and steered bogie axles which enable the C-AGVs to be moved in any direction and turn through 360 degrees. This increases the versatility and flexibility of the AGV while minimizing congestion at the quayside. The C-AGV can be steered conventionally or ‘crab’ diagonally, or it can move completely transversally. New cassette designs enable the C-AGV to enter and exit both transversally and longitudinally, which allows decoupling at the quayside that is the key to the system's cargo handling efficiency [4].

The contactless energy transfer technology contains ground-based and vehicle based segments. The two key components to the ground based system are the power electronics element and coils, which enables vehicles such as the C-AGV to receive energy both under the quay crane and the yard cranes areas. In addition to the ground based system, the vehicle based system employs the same technology and uses super capacitors to store the energy, which is then used by the specially designed electric wheel motors [4].

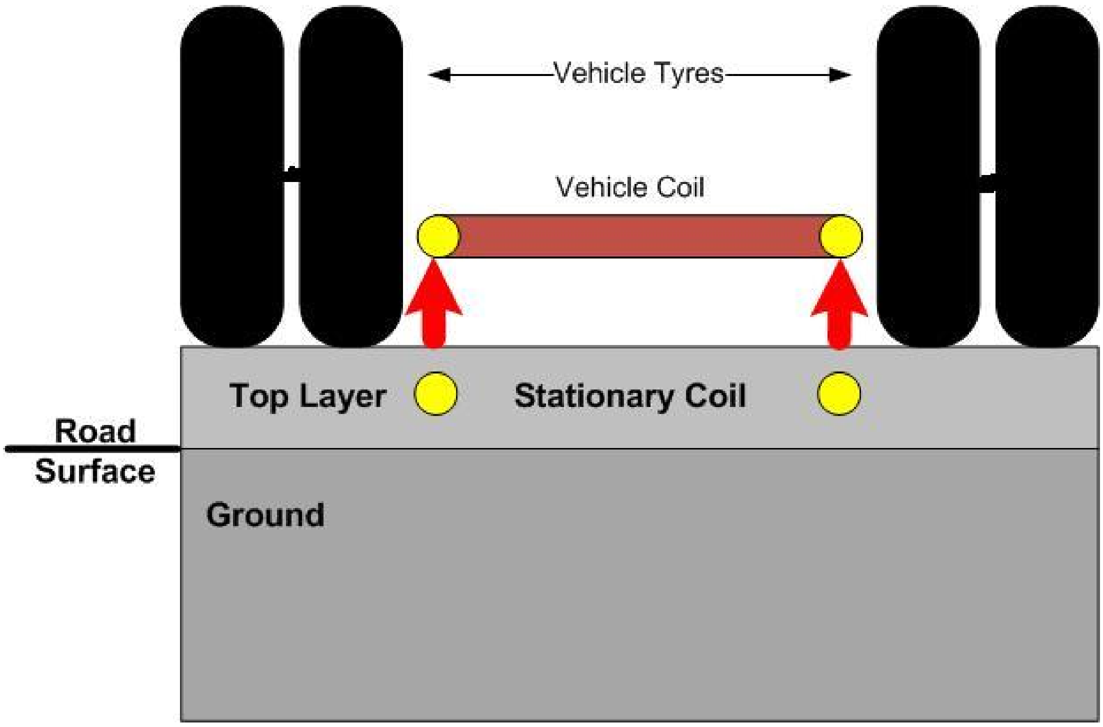


Figure 1.10: Concept of newest C-AGV. [4]

With a full load an AGV can travel around 600m, depending on its load, after which the capacitor needs to be recharged again. The use of capacitors instead of batteries allows for a lighter AGV and even though its range on a single load is limited, the capacitor can be – unlike a battery – recharged within 20 seconds.

With these new AGVs also come new cassettes. The AGVs are much lighter and slightly smaller thanks to the electric propulsion system. This means they are now smaller then the cassettes they carry. The cassettes have been redesigned so the AGVs can now go below them sideways and pick them up whereas the previous generations of AGVs had to line up with the cassette and pick them up along their length axis.

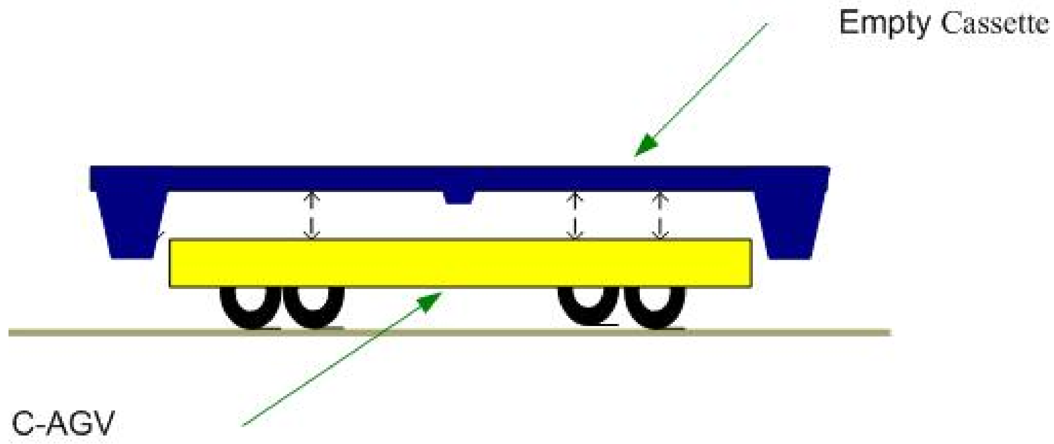


Figure 1.11: C-AGV with empty Cassette.

Even though the use of AGVs in a port environment offers a number of important benefits like continuous and consistent operation, high safety standards and increased accuracy, there is a lot of opposition against the use of AGVs, mainly from unions and local governments fearing possible job losses.

1.2 Motivation

According to Shapiro [25] the concept of logistics can be defined by the seven R's: ensuring the availability of the **R**ight product, in the **R**ight quality, and in the **R**ight condition, at the **R**ight place, at the **R**ight time, for the **R**ight customer, at the **R**ight price. To fulfil the credibility of these 7 R's, the CTs are continuously updating and upgrading their requirement specifications according to the customer demand and supply chain. We think that the new ZERO- Emission AGV technology which is still a prototype will be an important part of this requirement specification.

This thesis will focus on the automated HTS in container terminals using the latest C-AGVs. Because they are so new and there have been few studies that considered the use of cassettes. It seemed like a good idea to look at what has already been done for regular AGVs or older generations of C-AGVs and compare these to the results that would be found when a similar scenario is run using the new C-AGVs.

While there have been a few papers that did take the use of cassettes into account, the use of AGVs quipped with capacitors which require with recharging points, their abilities to turn around their axis and the loading/unloading at the back side of QCs had never been researched. Since it has also not been implemented in a working container terminal yet, it will be interesting to compare the projected results with those of studies on other comparable scenarios and, when finished, with an actual container terminal using these new AGVs.

Thesis report is classified into 10 chapters. Chapter 1 fully describes the backgrounds of the container terminal, horizontal transport system (HTS) and AGVs. Chapter 2 focuses on defining the problems, approaches to solving them and the scope of this thesis. Chapter 3 will explain the research methodology. Chapter 4 is related to the strategy used in this thesis. Simulation tools (NetLogo) and the simulation techniques are discuses in Chapter 5 and Chapter 6. Verification and Validation is done in Chapter 7. Chapter 8th lists the simulation scenarios and results. These results are summarized and discussed in Chapter 9 and in Chapter 10 we draw a final conclusion and propose possible future work that needs to be done on the subject.

CHAPTER 2: PROBLEM DEFINITION

Since the birth of business, sea plays a major and effective role in transportation and shipment of goods as well as travelling. Especially since past 2-3 decades, the decreasing costs, lower rates of transport, rising customer demand, and globalization of trade have caused a steady increase in the use of containers for sea borne cargo. As a result, container terminals have become an important component of logistic networks. To survive and compete with the business competitors in the market and to satisfy customer demand, it is paramount that ships are unloaded and loaded promptly at the quay side. To fulfil and achieve the demand in supply chain , it is necessary to choose the best strategy and transportation system to transfer containers between ships and storage locations on land.

As is already described the intermodal terminal technology has become an important research area capable of boosting a countries economy by increasing ports throughput and efficiency. The use of containers significantly decreases shipping costs and the AGV is the next important step in further lowering the cost.

2.1 Scope of Work

This Multi agent base study is focused on comparing different kinds of dispatching and scheduling algorithm in the horizontal transportation system between the quay crane and yard crane by using the newest version of C-AGVs. It is also necessary to analyze the advantages and disadvantages of each one of the dispatching strategies and to find the ideal ratio of C-AGVs, QC and YC in the ACT. To be precise, we want to find the best configuration studying a particular case. Therefore we needed a concrete scenario in order to decide the most suitable configuration.

We focus on the newest feature: re-charging points for this new type of the C-AGVs make it different from other traditional C-AGVs available. These C-AGVs have a number of new features giving them new capabilities, but also adding constraints to their practical use. Most notable changes are:

- The use of electric motors powered by a capacitor instead of a combustion engine requiring fuel. The use of a capacitor instead of a battery to provide power for the engines means a cost reduction as well as significant shorter load times, however it also means the AGV has to recharge its capacitor every few hundred meters.

- Because the AGV is now powered by much smaller electric engines instead of a heavier combustion engine, it is possible to control each pair of wheels independently allowing the AGV to almost turn around its axis. This results in a much smaller turning radius than the previous generation of AGVs.

What has not changed since the previous generation is the use of cassettes: the AGVs transport cassettes which on their turn can carry up to 2 (40ft) or 4 (20ft) containers. This allows the cranes to continue loading/unloading even when there is no AGV available, as long as enough waiting cassettes are present in the buffer area.

What has changed about the cassettes however is the AGVs ability to pick them up when approaching it from the sides. As mentioned earlier their smaller size allows them to get below the cassette in between its legs at each end, thus eliminating the need for a lengthy line-up operations.

This thesis will attempt to:

- Design and implement an accurate model of basic CT operations taking into account all properties of the latest generation of AGVs.
- Use the model to determine and verify the location of recharge points within the CT.
- Compare AGV scheduling algorithms.
- Determine the most efficient resource usage in multiple CT scenarios.

While there have been studies on the use of C-AGVs before, few took into account that cassettes can carry multiple containers and containers of multiple sizes. Additionally, most previous studies regarding C-AGVs' operation in ports were mathematical models, whereas the model used in this thesis will rely on an actual simulation of a container terminal.

The scope of this thesis is limited to the horizontal container transport by AGVs by the use of cassettes and will assume that both QCs and YQs operate within specified parameters.

2.2 The Problem

Since last two decades the methodological advances regarding container terminal operations have considerably improved. Container transportation has considerably grow in the current decade. This gives a chance to research it and the amount of academic literature as well as case reports are exploding.

According to the recent statistics and research work, ports are gearing up to meet the challenge of handling huge-ships capable of carrying 10,000–12,000 TEU and beyond. To maintain the efficiency and worth of the CT, the terminal operators are giving attention to handling, stacking and transport of large numbers of containers to and from the quayside. High productivity and container throughput from quayside to yard side and vice versa at low cost are vital for a terminal operator in order to compete with other terminals.

2.3 Suggested Approaches

Due to the increase in handling the containers, the competition between container terminals has increased on major seaborne container routes. Terminals are facing more and more containers to be handled in short time at low cost. Therefore, they are forced to improve their handling capacities and strive to achieve gains in productivity. Researchers have different concepts for meeting the current and future demand at CT.

Different kind of revolutionary approaches are considered by CT operators like the design of new terminals with advanced layouts, indented berths and re-engineering from AGVs to C-AGVs. As is mentioned in the above paragraphs researchers give different ideas to handling current situations like changes in CT layout or building new berths, which is more expensive and time consuming and may not be possible at every

CT. On the other hand the replacement of old machinery and equipment with latest alternatives provides more effective results.

In this thesis the latest version of C-AGVs is being studied. It will lead to revolutionary changes in the CT and its daily routines. In our approach every C-AGV is working as an agent. The functions and performance of this new C-AGV are already defined in this and previous chapters. Simulation results prove that this latest version of C-AGVs will lead to remarkable changes in a CT in the near future.

2.4 Operations at ACT

2.4.1 Quay Cranes Operations

All Quay Crane operations in our yard layout will be performed at the back side of the crane, contrary to what is currently customary in ports where containers are now being transferred below the crane. In this new concept all operations are performed at the back sides of the crane, thus decreasing the distance AGVs have to travel, on the other hand increasing the distance the crane has to transport the containers though. An example of this is shown in the figure below.

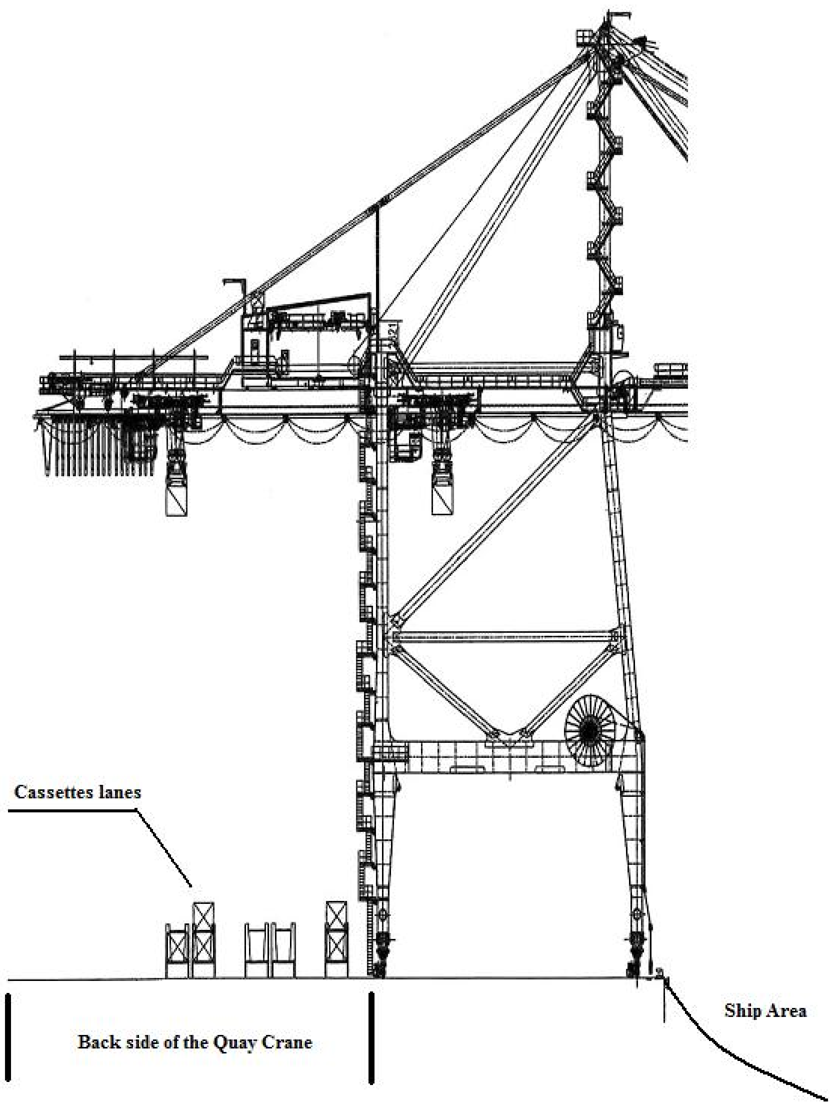


Figure 2.1: Unloading operation at back of Quay Crane.

The space that becomes available below the cranes will be used to store the ship's cargo bay top covers. Additionally this means that the automated area of the yard can be entirely isolated from the areas where humans can come thus decreasing the risk of humans interfering with the system.

As shown in Figure 2.1, there are several lanes behind the crane: 5 of them are cassette lanes on which cassettes wait for containers or to be transported to the yard buffer areas and 3 highways which can be used by AGVs so all locations in the cassette lanes are at all times reachable. As these highways are only wide enough for 1 AGV to fit in them, they are single directional. As we will demonstrate later we will provide points in the highway and cassette lanes where AGVs can leave them in order to proceed to the yard area. This will usually be done on locations where there is more room between 2 successive cranes.

During unloading operations performed by the quay crane enough empty cassettes must be made available to the crane so it may continuously work at its maximum efficiency. Often a number of certain cassettes will be waiting before the crane starts unloading, however if this is not sufficient AGVs must fetch empty cassettes either from a parking zone or cassettes that have already been unloaded by the YCs.

2.4.2 Yard Cranes Operations

Yard crane operations in our layout are also driven by a new buffer system. Instead of having buffer a buffer with room for 4-8 cassettes next to one another, a dual layer approach has been chosen with 4 2-deep cassette lanes where the second in which the second row can be reached through 2 highways leading into the second layer of the buffer.

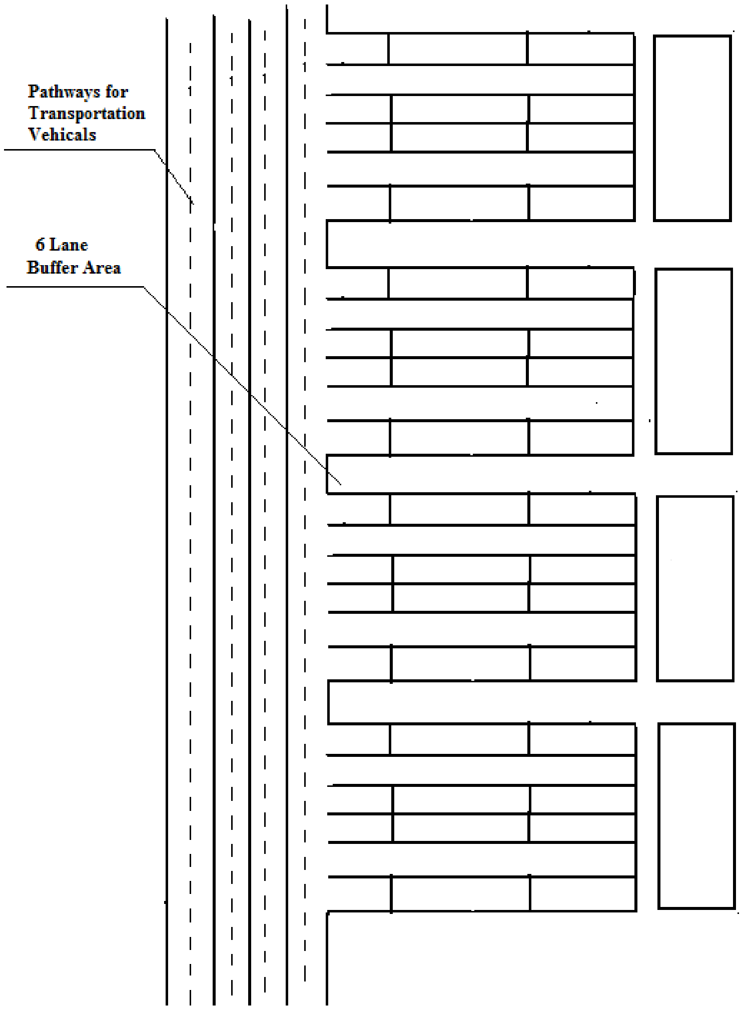


Figure 2.2: Yard Buffer Area.

The layout, as shown in figure 2.2, provides us with 8 places reserved for cassettes using same width a single layer lot with 6 spaces would take. This system is also easily expandable in depth: by adding an additional layer, the buffer capacity is increased by another 4 places. Downside of this approach is that for each extra buffer layer, one layer of storage space in the yard is sacrificed.

2.4.3 C-AGVs Operations

As described earlier, the AGVs used in this thesis are of a new design using an electric propulsion system enabling them to virtually turn around their axis. The independently turning wheels also mean they can go from moving forward or backwards to moving sideways by turning the wheels while standing stationary. However the reason this was made possible, the electric engines, do add an important additional constraint to the traffic management and terminal design: the capacitor fuelling the engines needs to be recharged every 500 to 600 metres, depending on the AGVs load. For this purpose there are specific recharge points build into the road deck on strategic points such as the quay crane and stacking crane areas.

A penalty needs to be taken into account however when the AGVs use their ability to turn around their axis or switch from moving forwards/backwards to moving sideways. During this switching there is no overall movement of the vehicle, however depending on its load it takes a certain amount of time to complete this operation.

Similarly a penalty will need to be given when the AGV switches from "low" or moving mode to "high" or transport mode during the loading of a cassette or vice versa when unloading.

As mentioned in earlier chapters a lot of the functions depend on the AGV's load. Most important of these are speed, acceleration, maximum range on a single charge, raising/lowering speed and turning speed. All of these variables need will need to either taken into account or replaced by averages in the final simulation model.

2.4.3.1 C-AGV Recharging

The biggest advantage of the new generation AGVs, its electrical propulsion, can also potentially be a serious constraint in practical use. The capacitors used by the AGV, while smaller and lighter than batteries need to be recharged very often. To this end recharge segments have to be embedded into the road and when AGVs pass above them they can recharge their capacitors to 100% in approximately 15 seconds, depending on the status of the capacitor before recharging is started.

2.4.3.2 Traffic Management

The Traffic Management System (TMS) controls the flow of traffic throughout the yard area. Most of the TMS is implemented in the AGVs themselves. The sensors present in the AGVs will avoid collisions and handle the flow in the free flow areas as well as in the highways and cassette lanes. Deadlocks are avoided by granting different priorities to different AGV operations.

While much of the traffic management is being handled by the AGVs themselves, the centralized TMS serves to avoid deadlocks and reserve certain cassette places in the buffer areas for a specific AGV. The dispatching of AGVs is also handled by the TMS; this is discussed in the next paragraph.

2.4.4 Dispatching Operations

The dispatching or assignment of jobs to the AGVs is another important part of the TMS. The goal of this system is determine the best job assignment schedule with the least possible the overall cost where cost is determined by a combination of distance to travel, time and priority. There are a number of possible algorithms to allocate jobs to AGVs but these will be discussed in greater detail in later chapters.

CHAPTER 3: METHODOLOGY

Methodology provides tools and techniques that researchers can use for gaining knowledge, firmer understanding and solving problems [5]. Researchers may opt to use more than one methodology approach in answering a question [6]. So, in this thesis, both types of methodology the qualitative and the quantitative are adopted. We followed the concept of *triangulation strategy* [5], which combines quantitative and qualitative approaches:

1. Literature Review
2. Interviews / Field Survey
3. Simulation

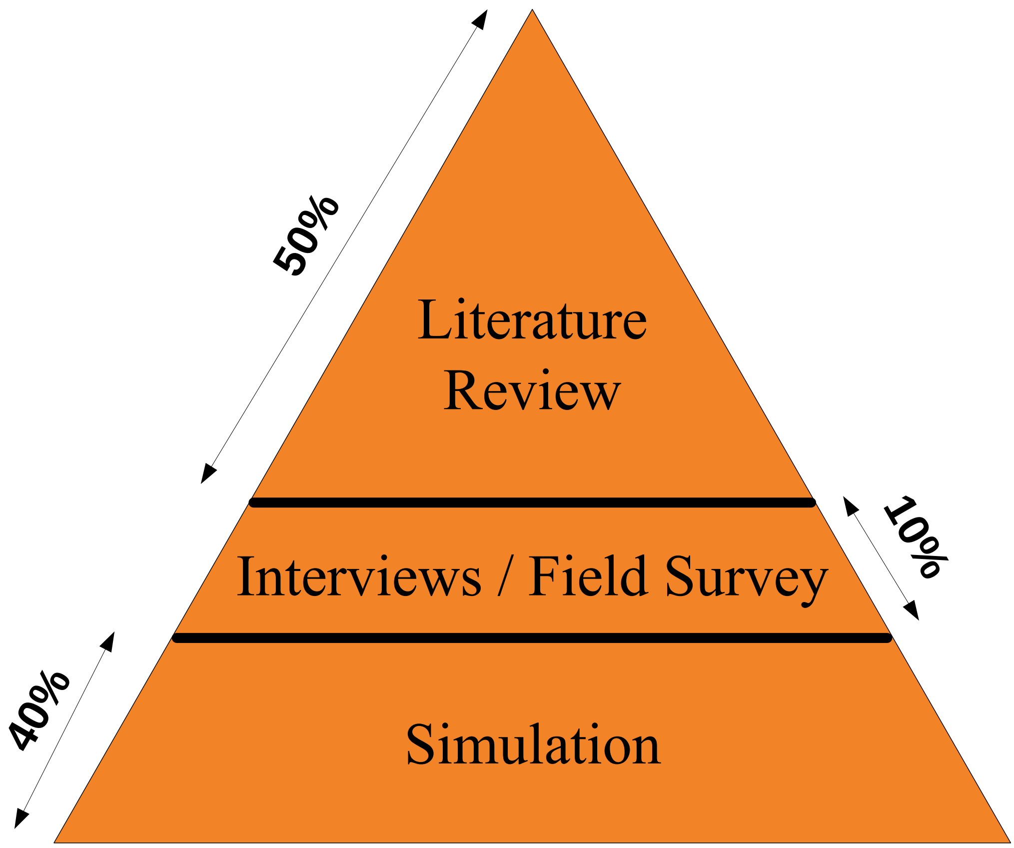


Figure 3.1: Weight distribution of Research work.

The objective of this thesis is to find out a solution for the complex and typical environment at the container terminal which can efficiently fulfil most of the requirements at any ACT.

3.1 Literature Review

Literature review is the method or way to understand and clear your point of views on which your study is based. To completely understand the concept of C-AGVs, Agents, MAS at any ACT our advisor Dr. Lawrence E. Henesey recommended and provided us very helpful material and a list of research papers in this area. This helps us to understand and come to know what has already been done in and what is going in research area.

To completely understand we go through several research papers, magazines, specialized books, conference papers and other journals related to the subjected field. We also concern some of the RFCs but not in that much detail. During literature review we face a lot of problems because almost all the research work is based on traditional AGVs and C-AGVs, where our research is based on new type of C-AGVs which is more capable and has better performance as well as handling.

We hardly found any material or research work related to this type of C-AGV. A few of the research papers and publications are discussed and included here as a literature review in this section.

First of all we build our base and get the core idea form the PhD thesis on Multi-Agent Systems for container terminal by Dr. Henesey [5]. In this remarkable piece of work he explains the actual growth in container traffic in an ACT as well as its negative effects, like congestion. As there is enough space to extend a lot of container terminals, he proposes to increase the productivity in container terminal using a computer-based support for management decision making as well as automation. With the help of the Simport simulation tool he developed a simulation model which is capable to represent the real behaviour of ACT. Finally, this model was used to compare and evaluate two AGVS (Automated Guided Vehicle System) in a container terminal. One of them is a traditional AGV and the other is with C-AGV.

Further more in the same area of interest; Cassette AGV, regular AGV and Shuttle Carrier are discussed and compared by designing a simulation base scenario where the different horizontal transport systems are evaluated by Pascal Bierhuizen and Ivo Saanen [7]. In the end they conclude that C-AGVs travels more than AGVs. However, less C-AGVs are required to reach the same productivity. They also deduce that the cassette system is limited by the absolute number of cassettes, although more cassettes make the YC more efficient.

The dispatching strategies for IPSI ™ are investigated in the master thesis by Kosowski and Persson [3]. They describe the dispatching problem with the flow path layout and the vehicle requirements in order to minimize the cost related to the time, distance and priority.

It's necessary to understand the way of working and performance of any maritime container terminal which was done by the literature reviews of [9, 11, 12, 13, 14, 15, 16, 17, and 18]. After understanding the working and performance of maritime CT its necessary to understand and chose one of the transportation layouts of a CT. There are two types of transportation system layouts in CT which are Horizontal and Vertical. In [8] two designs for optimal AGVs transportation systems are presented which are Horizontal as shown in the figure 3.2 as well as Vertical transportation System as shown in the figure 3.3.

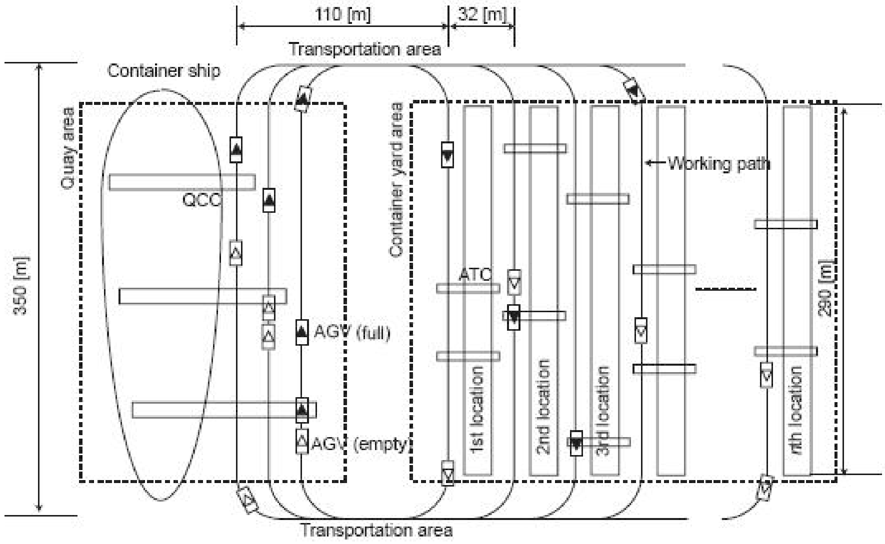


Figure 3.2: Horizontal Transportation System. Curtsey of [8].

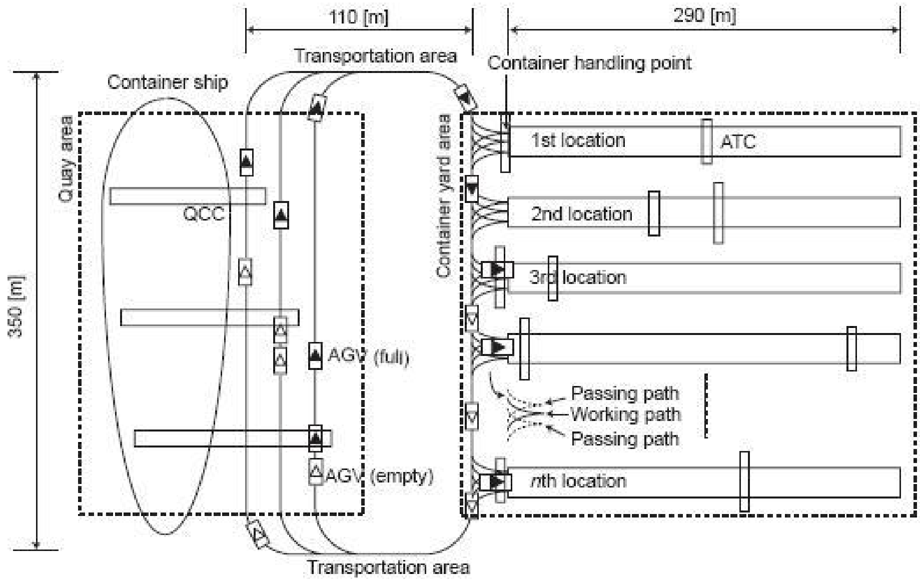


Figure 3.3: Vertical Transportation System. Curtsey of [8].

While reading and reviewing the literatures related to dispatching techniques, Ioannou and Liu [9] discussed multiple techniques. According to their study the minimum queue rule was the best, the random rule was the second best and the shortest distance rule was the third best dispatching rules for the terminal operation to achieve the best throughput performance.

YL Cheng, HC Sen and K Natarajan [2] also discussed how to dispatch AGVs. They proposed a network flow model to solve the AGV dispatching problem. In their study the deployment of the AGVs such that the total waiting time is minimized is found by solving a minimum-cost network flow problem.

An understanding of scheduling of C-AGVs on the bases on OSPF concept was discussed in [10], The results and statistics shows how to fully utilize the C-AGVs, QCs, and YCs in different scenarios while utilizing the maximum capacity of a cassette i.e. 2 X 40 feet or 4 X 20 feet or 2 X 20 and 1 X 40 feet container on a single cassette during the busy operation at CT as shown in the figures: 3.4 & 3.5.

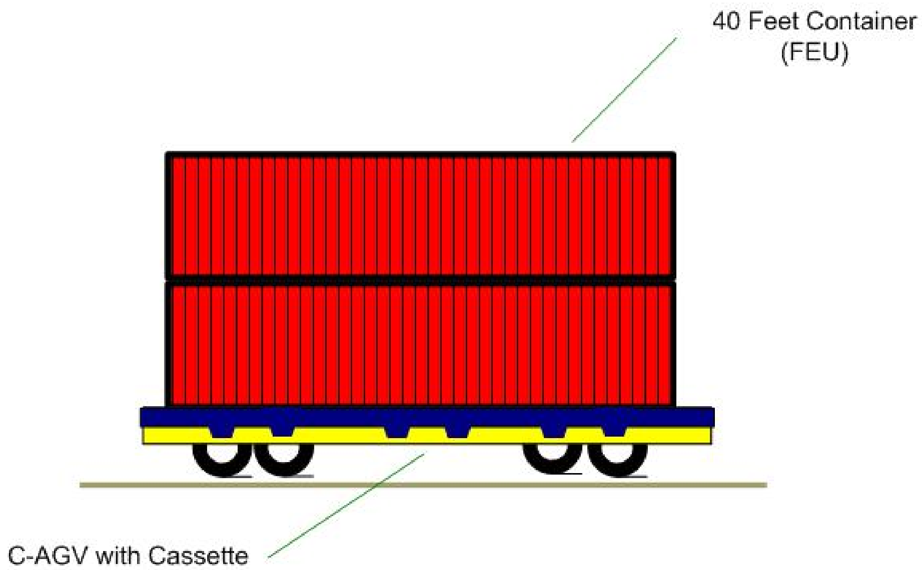


Figure 3.4: 2 x FEU, (Down & UP), this is valid and possible, Courtesy of [10].

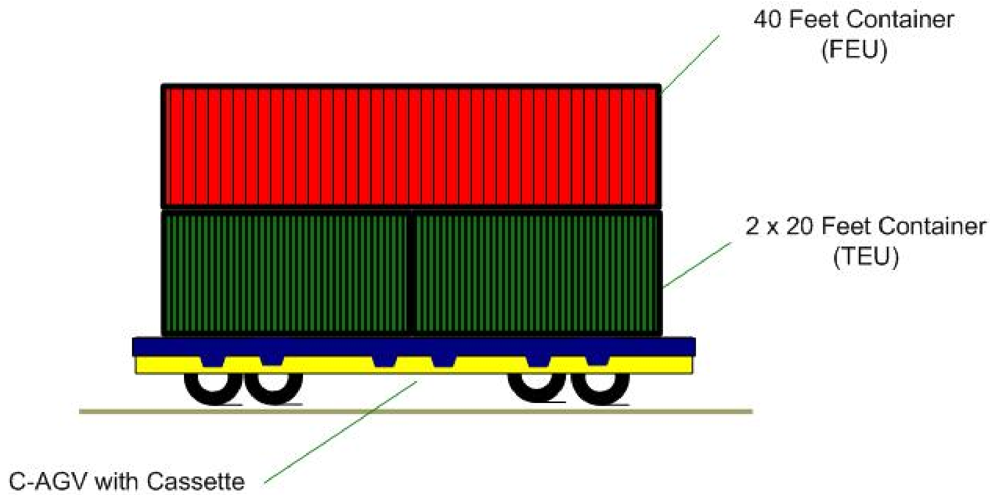


Figure 3.5: 2xTEU & 1xFEU (Down & UP), valid and possible, Courtesy of [10].

In the end, we would like to thanks to the world of Internet and the Google search engine which makes the life easier of every researcher while searching any article and that is why the well known terminology is being used “Google It!!!”.

CHAPTER 4: MODEL STRATEGY

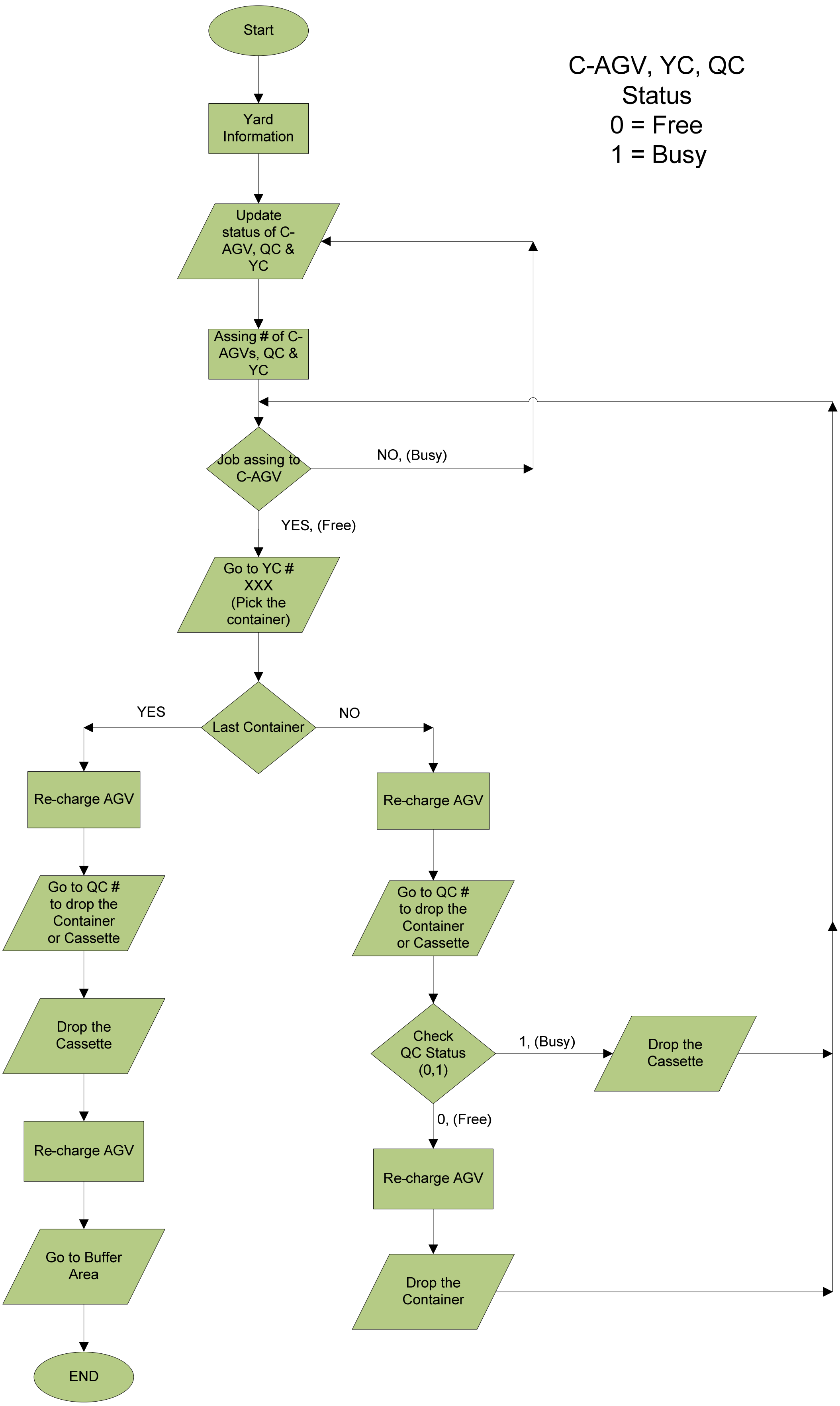
4.1 Model Dispatching Strategies

Defining the dispatching algorithm is a method of assigning job to multi agents in the container model. Three different dispatching algorithms are used in our simulation model which are namely:

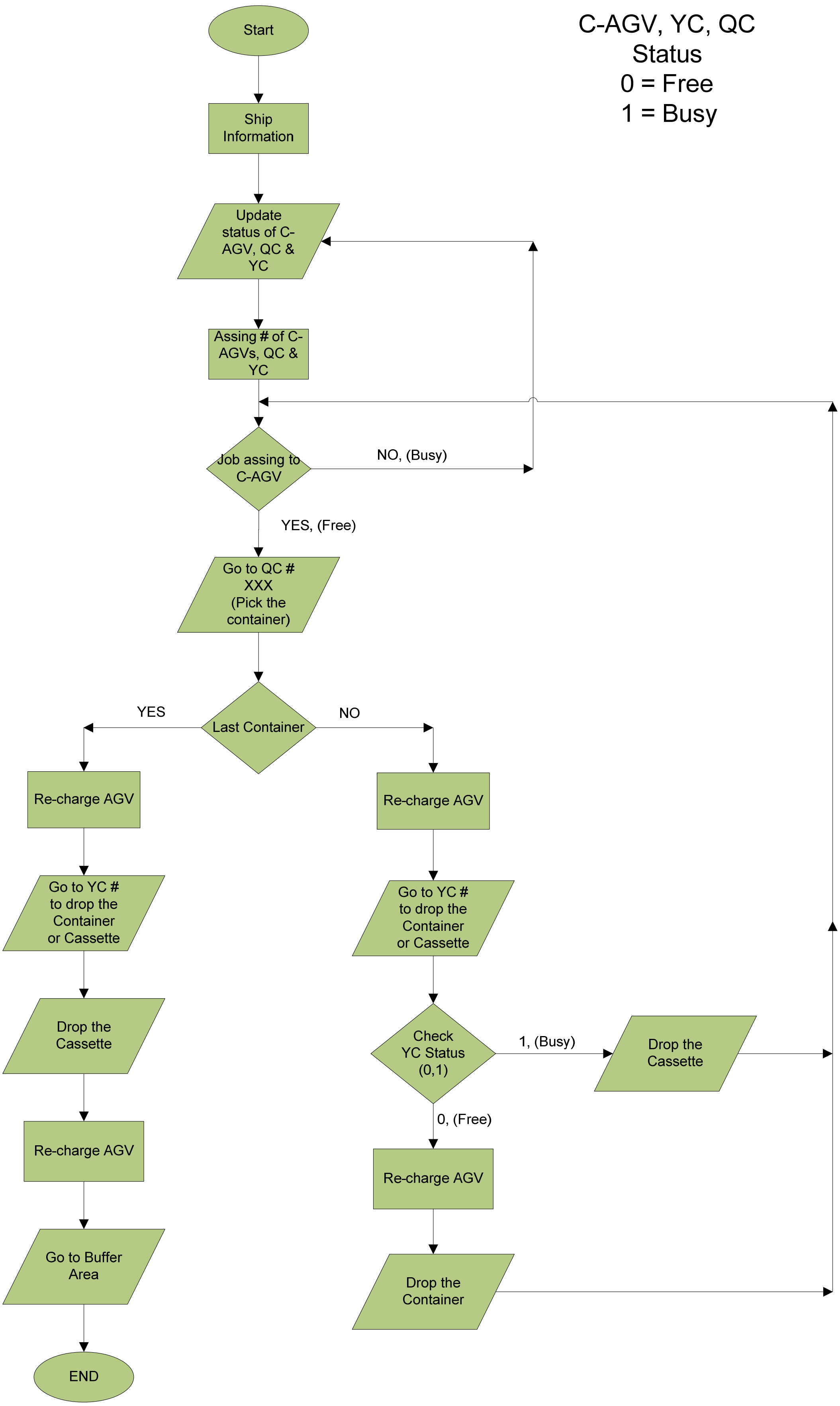
1. Random
2. Closest
3. Furthest

4.1.1 Loading process at ACT in our Model

1) Load program
2) Configure nr of AGVs, cassettes, containers, LOADING, scheduling algorithm
3) Start
4) IF cassette is ready with container(s) on yard
5) THEN go to pick up cassette
6) ELSE remain idle
7) WHEN arrived under designated cassette
8) THEN pick up cassette and reload capacitors
9) WHEN loading ready AND capacitor recharged
10) THEN move to designated destination
11) WHEN arrived on destination
12) THEN unload cassette while recharging capacitor
13) WHEN unloading complete AND capacitor recharged
14) THEN IF new job available THEN go to 5
15) ELSE wait..



Flowchart 4.1: Ship Loading Flowchart.



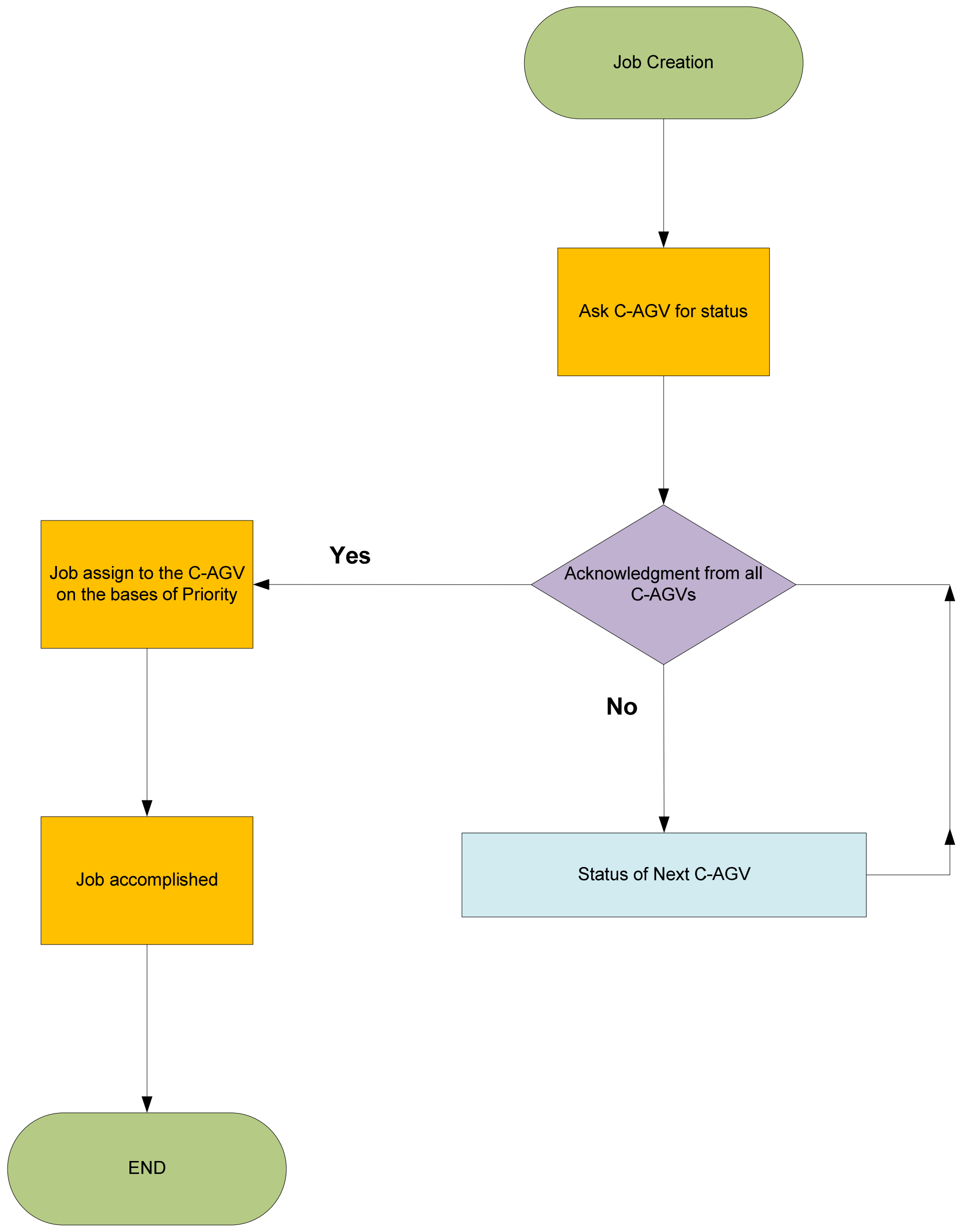
Flowchart 4.2: Ship Unloading Flowchart.

4.1.2 Un-Loading process at ACT in our Model

1) Load program
2) Configure nr of AGVs, cassettes, containers, UNLOADING, scheduling algorithm
3) Start
4) IF cassette is ready with container(s) on quay
5) THEN go to pick up cassette
6) ELSE remain idle
7) WHEN arrived under designated cassette
8) THEN pick up cassette and reload capacitors
9) WHEN loading ready AND capacitor recharged
10) THEN move to designated destination
11) WHEN arrived on destination
12) THEN unload cassette while recharging capacitor
13) WHEN unloading complete AND capacitor recharged
14) THEN IF new job available THEN go to 5
15) ELSE wait..

4.2 Greedy dispatching Algorithm

Greedy heuristic dispatching algorithm is a method of assigning jobs to different AGVs within the container model which is handled by the traffic management system (TMS) that controls the flow of traffic within the yard area. Many AGV dispatching rules adapted to the need of each specific manufacturing system can be found in the literatures. Hodsgson et al. [11] There are many dispatching algorithms used for navigation between multi agents at container terminals, but probably it depends on least possible, in the way of cost, distance and time.



Flowchart 4.3: Concept of a Greedy Model.

The goal of the greedy heuristic is to minimize the total time AGVs spend waiting at the quay crane locations to serve their jobs. The jobs are initially arranged in a First In First out (FIFO) manner based on the earliest quay side appointment time at each quay crane [2].

For example if AGVs are assigned jobs for picking up containers from point A and have to drop them at point B. During this all AGVs are performing the same job in sequence, but the first AGV drops a container first at point (B) and in the mean while this AGV gets another job so, first utilizing AGV will serve first.

This dispatching method is called (FIFO) First In First Out strategy. Another greedy approach is that, if there is no job AGVs will be held on the rest area until they get any job from the controller. How agents will communicate with each other when an operation start at container terminal after arriving ship at the berth area.

This thesis report is also part of those research contributions which is one step forward and based on a new generation of C-AGV at container terminal, which will use recharge points and with lighter and smaller size of capacitor than battery. The simulation part of thesis is consisting of quantitative method and this quantitative work based on Net Logo simulator.

To understand the problem and enhance performance of the system within the CT area, qualitative approaches were adopted. A site survey conducted by our advisor at Karlshamn port was the part of this study. During the survey we observed different operations at CT including the utilization of AGVs, Quay Cranes and Yard Cranes, buffer and storage areas and shipment as well as the rail traffic system in detailed.

4.3 Centralised – Decentralised

The centralised or hierarchical approach in wide scope of information and decision support systems can turn out to be not sufficient or relevant. This is mainly caused by the level and range of the domain complexity, distribution of information sources and destinations. The global outcome of such systems comes from the combination of operations conducted locally or in subsystems. Particularly, subsystems can make a number of autonomous decisions that are not kept under common supervision or management. On the other hand they are subordinated to some relations and make decisions with consideration for the environment conditions, other subsystems or human factor [23].

4.3.1 Disadvantages of decentralised approach

The decentralised information and decision systems are applicable in domains where the problem to solve is described by many parameters and require large amounts of information and are characterised by very complex processes. In such areas the centralised approach encounters the following adverse phenomena [24]:

- The obtained optimal solutions have encountered some difficulties in being acceptable by all sides: especially verification problems are common.

- The autonomy and characteristics of particular subsystems existing in reality has been lost while introducing the centralized system.

- There were difficulties in establishing restrictions and criteria of the system rules and aims.

- The finding solution process has required complex and demanding algorithms compared to the available resources.

- The process of gathering and warehousing information and data were expensive and long-lasting. Because of the data source space distribution and their own autonomy, the data validation and quality control was hard to conduct.

4.3.2 Multi-Agent usage in decentralised simulation model

Decentralized information and decision systems should have the following properties [24]:

- The system architecture should reflect the decentralized way of decision making.

- The system architecture should be consistent with the decentralized nature of the problem taking into account distribution of particular subsystems.

- The system construction should model the relations and dependencies between subsystems without trammel their autonomies.

- The system should implement and support the information gathering, exchanging, warehousing and accessing in the application scope.

These basic points are support to multi agents' usage technology in decentralized system.

4.3.3 Advantages of Multi-Agent usage in decentralised model

The decentralised model implementation with the multi agent technology according to [25] can provide the following advantages:

- The possibility of the computerization of the problem as a whole with the maintenance of existing organizational relations but without forcing autonomous subsystems to disclose confidential information or to deliver data that are difficult or impossible to estimate on the appropriate reliability level.

- The negotiation platform which provides attainment of the solution acceptable by all of the subsystems.

- The increase of subsystems ability to adapt to requirements change or to environment evolution.

- The improvement of distributed knowledge bases reliability.

- The decrease of distributed knowledge bases maintenance costs. The data are warehoused in or close to their actual sources.

- The natural distribution of computational problem. Partial algorithms are simultaneously implemented by particular agents.

- The easiness of modifications. Structural or parametric changes do not destroy obtained solution. During communication and negotiation procedure the acceptable solution can be found again with small costs of resources. The autonomy of particular agents decreases computational costs needed for modifications.

- The openness – the easiness of introducing new agents and removing the existing agents (subsystems) – the changes will be noticed only by interested in that agents.

4.4 Agents

The terms autonomous agent and multi-agent system started to appear in literature in late 80s. Till now the domain remains under development, mainly because of the new hardware capacity, especially in the computer networks field. The appearance of new technology assets – for example development of distributed systems - creates huge possibilities of gaining quick access to remote information sources, which gives some bases of the approach[23].

Nowadays the agent approach finds its application in the wide scope of computer systems, for example:

- Personal digital assistants – which belong to such applications as for example Microsoft Word
- Intelligent electronic mail filters
- Cooperative team of robots software
- Distributed air traffic management systems

The agent and multi agent system domain is derived from artificial intelligence research. Its influence originates from other domains such as object-oriented programming and development, distributed and concurrent systems and human-computer interfaces. To a greater or lesser degree the approach constitutes the subject of interest not only in the computer science domain – but also by biologists, sociologists or economists. Nevertheless this indicates the approach universality, this also leads to interpretations diversity and some notions ambiguities [23].

4.4.1 Agents in a Modern ACT

These are the active agents in a modern Automated Container Terminal, the whole operation of loading and unloading containers is being done by these active members.

- Ship
- Containers
- Quay Crane
- IPSI Cassette
- IPSI AGV
- AGV (Automated guided vehicle)
- Yard Crane
- Straddle Carrier

In this thesis the most important agent is the latest and newest version of C-AGV. On the other hand QC and YC are also active agents. All the above important agents are already discussed in the previous pages.

4.4.2 How an C-AGV agent works?

- Each C-AGV agent is assigned to one automated guided vehicle and is responsible for the transportation between quay cranes to yard cranes in yard area.

- C-AGV decision layer allows C-AGV to know its location, avoid and go around some obstacles as well as recharge at recharge points while moving, tells when to stop if destination point is reached.

- C-AGV Functional Layer define as:

  - Start moving: C-AGV agent orders vehicle to start moving
  - Stop moving: C-AGV agent orders vehicle to stop moving
  - Start receiving container: AGV agent orders vehicle to move just under quay crane holder
  - End receiving container: C-AGV agent orders vehicle to drive off from place under quay crane holder
  - Start leaving container: C-AGV agent orders vehicle to move just under stacking crane holder
  - Stop leaving container: C-AGV agent orders vehicle to drive off from the place under stacking crane holder
  - Recharging: C-AGV agent orders to vehicle every time the battery is lower than the threshold level.

Each C-AGV has the following main attributes:

- C-AGV Number: Unique C-AGV number which represent the C-AGV
- Current Status: Free, Idle, Sleeping, Busy
- Next Job: The next job assign to a C-AGV
- Current Location: place and location of C-AGV which use to assign the next job.
- Decision making: on the basis of current situation, it will take some decision

CHAPTER 5: NETLOGO

5.1 Introduction

Netlogo is a multi-agent programmable modelling environment. There are two main elements in NetLogo model: patches and turtles. Patches are square background tiles with a configurable display size and a model s layout is build with any number of patches making up the background of the display. Besides being the base for the simulations' display, patches are also agents in the simulation. The other element is the turtle. A turtle is an agent occupying a single patch on the simulation field. Subtypes of turtles can be created, if needed and can either all operate independently and concurrently or be programmed to react to each other.

5.2 NetLogo Model

A simulation run of a model consists of a sequence of ticks, comparable to time passing in the model. Whatever happens during a tick is entirely up to the programmer, however usually each tick can be associated with a new status of the system, defined by the actions the turtles take or how the programmer changed the environment.

NetLogo is especially well suited to model complex systems, such as a CT over time and explore both the connection between the micro-level behaviour of individuals and the macro-level patterns that emerge from the interaction of many individuals. However, there are also a number of downsides to implementing a model using NetLogo. While NetLogo itself is written in Java and Scala, the model programmer is bound to a limited set of programming commands in a NetLogo specific language.

Furthermore, this language is entirely procedural whereas most common languages nowadays evolve to an Object Oriented (OO)or Aspect Oriented (AO) design. Global variable names can only be used once, either if a path or in a turtle which on the longer run leads to ever more complex naming and confusing code.

The main reason for using NetLogo to build our model is because it is entirely agent based yet still allows for some things to be handled centralized. Additionally, it was a tool recommended by our supervisor and a lot of example simulation models were available as well as good documentation on the API. The fact that NetLogo has a limited set of commands can also be advantageous: it is fairly easy to learn.

5.3 CT Model

In our model AGVs are implemented as turtles, everything else, cassettes, containers, QCs and YCs are patches and controlled by a centralized scheduling system that updates statuses every tick. A single tick in the model represents a single second. So the model is capable is simulation the CT operations second by second.

As seen in the screenshot of the main model interface, figure 5.1, the user has a number of configurable options after which setup will initialize the model into the configured initial state, in this case Unloading with 50 cassettes and 20 AGVs. Once initialized the model can either be updated step by step or second by second or run at a NetLogo controlled interval. The end-user can follow the utilization on the given graph and textual statistics are also shown at the completion of the run.

A number of not so commonly needed configuration options have due to lack of space in the main interface tab been put in a configuration file in the models source code.

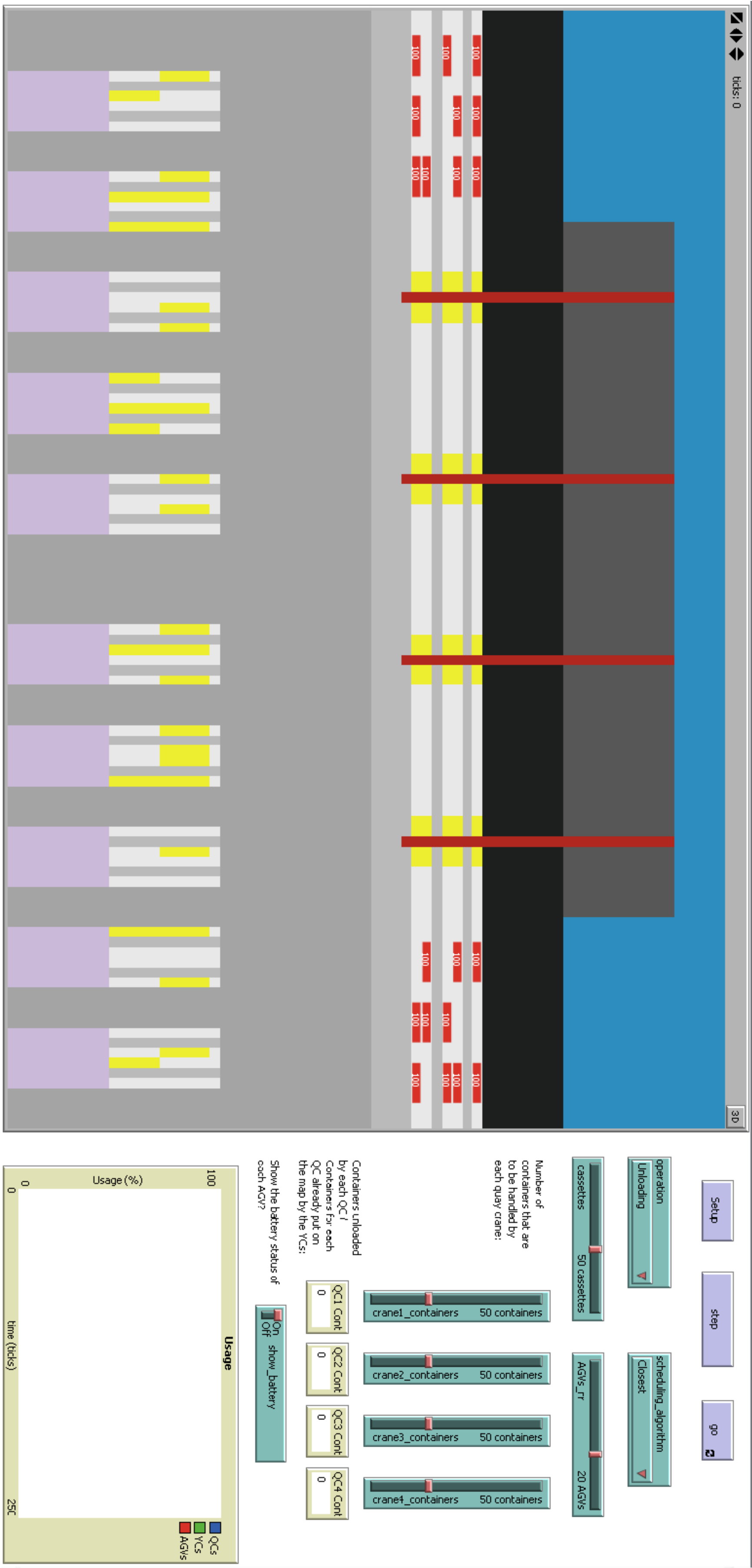


Figure 5.1: Screenshot of the Simulation Model.

In order to minimize the number of possible states each AGV can be in and to avoid having to implement a highly sophisticated routing and traffic management system in NetLogo AGVs have only a few possible states and movement options which combined should still allow them to move around the terminal as naturally as possible. Each AGV can assume one of following states:

- **Sleeping:** Long term idling on a recharge point in the unused Quay area. This is also the state in which AGVs spawn and to which they will return if they haven't had a job for a certain amount of time.

- **Idling:** Short term idling on any recharge point on the map. This is meanly used between different jobs and usually does not last long. If the AGV remains idle for more than a set amount of time they will go to a parking spot on the quay and switch to sleeping mode to avoid having too many .idle objects on the map.

- **Recharging:** Usually this mode is entered if an AGV reaches its destination and finishes loading or unloading. If the capacitor hasn't reached a pre-defined capacity yet, the AGV remains in recharge mode until a minimum capacity is reached. After which the AGV will switch back to either idling or moving mode if a job has been assigned to it. In rare occasions if an AGV's capacitor gets below 10% it will reroute itself to the closest recharge point until sufficiently recharged. This however is depending on the scheduling algorithm quite rare considering the AGV has a long range compared to the average distance it has to travel to complete a job.

- **Enroute:** AGVs are in this mode while travelling from one point to another.

- **Turning:** This is a substate of 'Enroute' mainly meant to simplify the AGV operations. When travelling from the yard to the quay or vice versa, an AGV has to rotate 90° around its axis. Because this would introduce a number of problems regarding routing the turning mode was introduced. When an AGV passes a turning point (located between the quay and yard) it enters turning mode and a few ticks later is turned 90° and moved out of the turning zone. This way turning is a single uninterruptable process.

- **Rotating:** Also a substate of 'Enroute', this state indicates the AGV is stationary and rotating its wheels 90° in order to go from moving along the x-axis to moving along the y-axis or vice versa. This state was added in version 1.2 of the model and does not exist in the original 1.0 version.

- **Loading/Unloading:** This is the process during which the AGV raises or lowers itself in order to pick up or drop off a cassette. This takes a certain amount of time, during which the AGV can also recharge its capacitors.

Of all these states, only the 'Enroute' (as well as its substates Turning and Rotating) and the Loading/Unloading states perform useful work. The time spend by AGVs in the other states should therefore always be minimized by the scheduling algorithms.

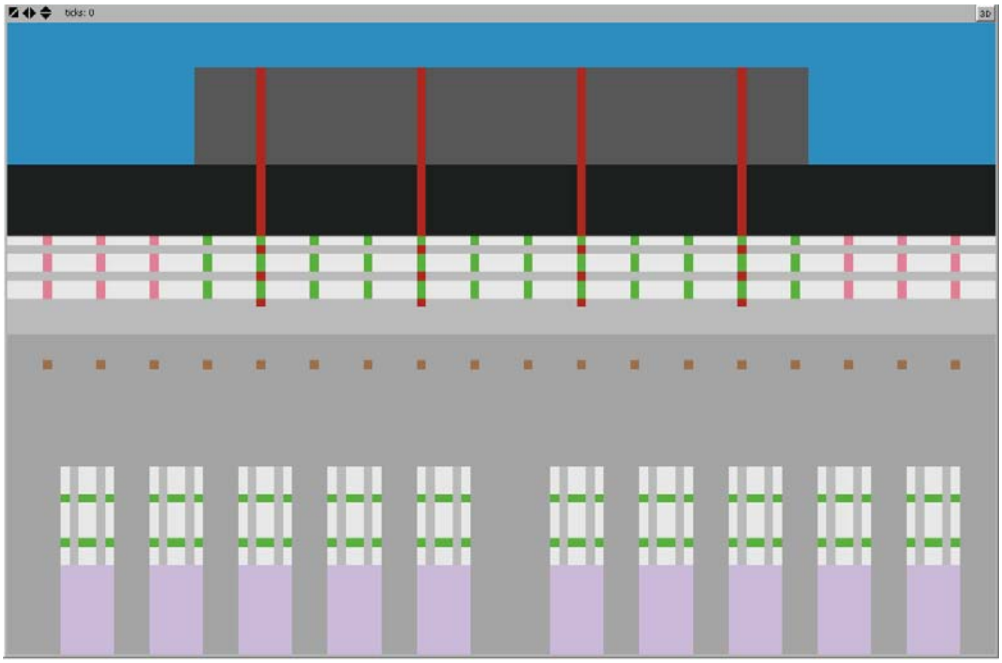


Figure 5.2: Screenshot of the CT Layout.

The recharge points are shown in green on figure 5.2. The pink dots represent the parking spots for the AGVs and are also equipped with recharge points. A destination of an AGV should always coincide with a recharge points as these have been strategically located below the spaces reserved for cassettes. This way the AGVs almost never need to use the recharge mode with most scheduling algorithms.

The brown dots represent the turning points. Each dot is at the centre of a single directional corridor in which the C-AGV can turn when going from the quay to the yard or vice versa.

Although the main scheduling algorithm is implemented in a centralised fashion in the model, most of the functionality is implemented in each agent. The agents will navigate on their own towards the destination assigned to them by the scheduling algorithm. Furthermore, the AGV agents are programmed to handle the cassette supply automatically without intervention of the scheduling algorithm. During unloading after the AGV has moved a cassette from the AC to a yard, it will automatically look if it needs and can return an empty cassette to the QC it is closest to. Once finished with that it will be available to the main scheduling algorithm again.

However this agent based scheduling does not provide a 100% guaranteed way of making sure enough cassettes get to all the cranes, especially if there are fewer AGVs, not all cranes may have a steady supply, more specifically those further away from the AGVs. To solve this a secondary centralised scheduling algorithm – which operates independently from the one assign AGVs to move offloaded containers – is used to ensure a steady supply of cassettes to all cranes.

This secondary algorithm only intervenes when it detects that for some reason the agent based scheduling isn't sufficient and unlike the agent based algorithm can assign an AGV from anywhere on the map to a job. A similar system is present when Loading the ship.

Chapter 6: Simulation Techniques

6.1 Multi Agent System (MAS)

The terms autonomous agent and multi-agent system start to appear in literature in the late 80s [23]. The concept of agents comes from the OOP (Object Oriented Programming). In reality it's a computer system that is capable of independent action on behalf of its user or owner. MAS (Multi-agent system) is a system described in terms of aggregations of goal-oriented, interacting and autonomous entities, placed in a shared environment. [12]. It's a system having a number of agents interacting with each other by sharing and exchanging the information. The agents do not solely react to the environment, but may act proactively as well as be able to respond to the changes in their environment.

Simulation is the imitation of some real thing, state of affairs, or process. This chapter is a broad collection of methods used to study and analyze the behaviour and performance of the newest version of C-AGVs which are still not in use at any CT.

The results will help CT operators, who can try out new designs, layouts and systems before committing resources to acquisition or implementation. This simulation is based on different scenarios, which are based on different phenomena that occur in the operations at an ACT. It allows users to compress and expand time and gain insight about which agents are the most important to the overall performance and how these agents interact. It will help to identify bottlenecks in ACT operations, information, and operational flow; better understand how the system really operates (as opposed to how everyone thinks it operates); and will help to compare alternatives and reduce the risks of decisions.

In our simulation we decided to use a MAS because it is closest to the situation in reality where you will have very autonomous and intelligent AGVs operating next to each other, cooperating with each other and only minimal centralized control.

The communication between the different agents in the NetLogo based model is query based: each agent has access to its own data and other agents, as well as the centralised system can at any time ask another agent for specific data.

6.2 List of Assumptions

Because these new C-AGV's are still mainly theoretical and few prototypes are available yet, no exact specifications of it are available. For this reason, and for further simplifying the problem, a number of assumptions have been made while developing the model.

- The distance between the quay area and the yard areas is 54 metres. The Distance includes: 1 vertical highway on the yard, 3 horizontal highways on the quay and an area in between which is used in the model for turning the AGVs.

- The QCs in the model have fixed positions. This means that the cassettes and containers on the quay also always have to be moved between a fixed set of coordinates.

- There is enough room on each side of each QC for an AGV to move vertically down to the yard area or highways.

- There is enough distance between 2 AGVs, based on the size the model assumes for each cassette or AGV. Both are assumed to be 5 patches, or 15 metres long, longer then the AGV and cassette will be. This means that no free patch has to be left open between two AGVs.

- While in reality the AGVs can move along any vector, in the model AGVs cannot. Instead they move either along the x-axis or along the y-axis. Additionally the AGVs move from hop to hop and thus two consecutive hop share the coordinates of either axis.

- AGVs do not need any time to accelerate or decelerate: AGVs move at a preset speed per tick **or less**.

- The AGVs recharge contactless while loading, unloading or resting on a recharge point, however they do not recharge when simply passing over one. Firstly, this simplifies the recharging procedure and secondly, this means that all recharge points in the yard and quay mustn't be constantly powered on – wasting power – while power efficiency is one of the highlights of this new AGV generation.

- The AGVs have a range of 500 meters – which translates in a battery capacity of 500. Certain penalties are imposed on the battery status for each AGV operation. All of these figures are variable and can be easily changed, as listed in the next section.

- During loading of a ship all containers for a QC will be supplied by the 2 closest yards.

- During unloading the majority of all containers will be send to the closest 2 yards. Percentage is configurable.

6.3 Default settings

The model has a number of configuration settings that are not visible on the model main window. A number of more technical and rarely used settings can be modified by editing the config.nls file. The following list gives an overview of these options with some explanation[1].

General Configuration Settings		
show_stats	This optional allows the running of the model to be speed up significantly by disabling user output. When set to *false* statistics will not be printed to the console. This should be enabled when running the model within *BehaviorSpace*.	true
enable_validation	When set to *true* the normal functionality of the model is disabled and only a pre-programmed setup is run.	false
Container and Crane Settings		
cassette_distribution	This option allows the configuration of the percentage of empty cassettes to be placed on the quay when unloading a ship.	100/100
QC_load_interval	Minimum number of ticks/seconds between QC container load operations.	16
QC_unload_interval	Minimum number of ticks/seconds between QC container unload operations.	16
YC_store_interval	Minimum number of ticks/seconds between YC container storing operations.	35
YC_unstore_interval	Minimum number of ticks/seconds between YC container retrieval operations.	35
allow_container _stacking	When set to *true* up to 2 40ft containers may be loaded onto a cassette. When set to *false*, a cassette may only contain a single container.	true
initialise_ready	Defines whether cranes are initialised in the ready position. When set to *true* a container will ready can be handled by the crane on the first tick. When set to *false* the cranes have to wait for the interval to complete before they can complete an operation. This option creates nicer graphs because it avoids the long idle time at the beginning.	true

[1] This are the default settings for model version 1.2.

AGV Configuration Settings		
agv_speed	Maximum number of patches an AGV can advance per tick or second. (1 patch = 3 on 3 metres).	2
agv_loading	Number of ticks/seconds the AGVs need to load a cassette. (Raise themselves)	5
agv_unloading	Number of ticks/seconds the AGVs need to unload a cassette. (Lower themselves)	5
agv_turning	Number of ticks/seconds the AGVs need to pass through the turning zone and thus turn 90° from horizontal to parallel orientation.	3
agv_rotate	Number of ticks/seconds the AGVs need to rotate their wheels 90°.	3
agv_delay_sleep	Number of ticks/seconds after which an idle AGV will return to the parking spots on the quay and enter sleep mode.	120
agv_batt_capacity	Total capacity of the AGV's capacitor.	500
agv_batt_loading	Units per second the capacitor reloads while the AGV is holding stationary above a recharge point.	30
agv_batt_pen_mov	Battery penalty from battery when moving 1 patch ahead (3m).	3
agv_bat_pen_turning	Battery penalty for turning the AGV 90° while moving from the yard to the quay or vice versa.	6
agv_bat_pen_rot	Battery penalty for turning wheels 90° This is deducted every time a new hop in the path to the final destination is set, so may not be 100% accurate as there is a chance the next hop is reachable along the current axis. (Estimated 85% accuracy.)	1
agv_bat_threshold	Minimum capacitor charge required before the AGV leaves a recharge point.	250
agv_bat_thresh_rech	When an AGV is in recharge mode, this sets until what level the capacitor should be recharged before resuming normal operations.	375
Scheduling Configuration Settings		
distr_unloading_local	Defines how many of the containers during unloading are destined for the local (the 2 closest) yards.	90/100
show_supply_cassette_msgs	When set to *true* the model shows notices when the secondary scheduling algorithm controlling the supply of empty cassettes issues an order to an AGV. Most of the empty cassette movements should be automatically handled by the idle AGVs themselves. This algorithm only intervenes when it detects a lack or surplus of empty cassettes.	true

supply_cassettes _threshold	Defines how many empty spaces are allowed at a QC – during unloading – before the secondary scheduling algorithm will assign an AGV to bring a cassette to it by the secondary scheduling algorithm.	1
remove_cassettes _threshold	Defines how many empty cassettes are tolerated at a QC – during loading – before the secondary scheduling algorithm will assign an AGV to remove a cassette in order to free space.	1
supply_cassettes_min	Defines how many cassettes must be present at the very least in every operational yard while loading the ship.	2
loading_free_agvs	Defines how many of the AGVs during loading will be kept in reserve for the secondary scheduling algorithm.	20/100
sec_sched_mode[1]	Defines the algorithm used by the secondary scheduling system. This only intervenes when it detects a lack or surplus of empty cassettes. It will ensure the removal of empty cassettes from the quay during loading and a steady supply of them during loading. When set to "Pri", the same algorithm will be used as is being used by the primary scheduling algorithm. Possible values: “Pri”, "Random", "Closest" and "Furthest".	Pri

In this thesis we will always be using these default setting unless mentioned otherwise.

[1] “Pri” did not exist in version 1.0 of the model, but was added in version 1.2 and was made the new default setting.

CHAPTER 7: VERIFICATION AND VALIDATION

7.1 The Method

Because the subject of this thesis – the new type of C-AGV's – is still a prototype and no reference data or previous studies are available regarding its turnaround time and operation, the model has to be validated against a theoretical mathematical model instead. In order to verify and validate the results produced by the model, the model was equipped with a specific pre-programmed scenario to complete. The results for this scenario can then be calculated manually and compared to the results produced by the model.

The verification scenario consist of the following:

- A loaded cassette will be placed on map at the most inland position below QC1.
- At start-up the AGV will be placed on the map at the same location.
- The AGV will load the cassette.
- Once loaded, the AGV will transport the cassette to the yard buffer position on the first level in yard 2, directly opposite of QC1.
- Once arrived at its destination, the AGV unloads the cassette which is immediately removed from the map. Simultaneously a new cassette is spawned at the same position below QC1 and the AGV is instructed to go pick it up.

From the number of patches the AGV moved during a single move in the simulation we can calculate the distance with which this would correspond in reality. Using this distance and the average speed of the AVG we are able to manually calculate how long it should take the model to move 10 cassettes from the quay to the yard area. We can then compare the results of the model with the result reached by manually calculating the time required.

7.2 The Results[1]

Except for the validation variable which is set to true, all settings in the model's configuration file are left at their default settings. The settings in the configuration panel on the model's main window do not affect the outcome of the results of a validation test run.

The following are the times used by the model and the distance travelled by the AGV:

Top Speed	2 patchs / tick (6 m/s)
Rotating wheels 90°	3s
Loading	5s
Unloading	5s
Distance from quay to yard	33 patches (99m)
Distance from yard to quay	35 patches (105m)

[1] Results of the verification and validation process are valid only for version 1.2 of the model.

With above values we can calculate the time it should take the AGV. However for the speed we will be using an average of 5m/s since in the model does the AGV does not continuously travel at its top speed.

Speed	5m/s
Distance:	
10 x quay to yard	990m
9 x yard to quay	945m
+ = Total distance travelled	+ = 1935m
Time spend rotating:	
10 x quay to yard	10 x 3 x 3s
9 x yard to quay	9 x 3 x 3s
+ = Total time spend rotating	+ = 171s
Time spend travelling	1935m / 5m/s + 171s = 558s
Time spend loading	10 x 5s = 50s
Time spend unloading	10 x 5s = 50s
Total Time	**658s**

The result of the models' validation test run however is **655** ticks or seconds.

As we can see the model produces a result very close to the one produced by the calculations, even though we assumed an average speed of 5m/s for the AGV in the theoretical calculations to compensate for the AGV not always travelling at its optimal speed.

In version 1.0 of the model, the difference was slightly larger: up to 6%. The difference in this later version of the module is much smaller because the model now accurately simulates the turning of the AGV wheels.

Finally, the model was also verified and validated by industry expert Dr. Lawrence E Henesey by setting it up to run a number of scenarios using actual industry data and comparing the result with the time it should have taken on paper.

CHAPTER 8: SIMULATION RESULTS

To verify the credibility of the model we created 6 scenarios. These scenarios are based on different dispatching algorithms. Three of these scenarios are related to loading process, using three different scheduling algorithms and three are related to unloading process of the ship. The model itself is very user friendly. The C-AGVs are the only real agents in the model. The QC and YC are handled by Crane Management System (CMS) and number of Cargos and Cassettes are variable. All the results mentioned in the scenarios are in tics or seconds, else specified.

Every scenarios has 6 inputs. These inputs are:

1. **Operation**
   a. Loading
   b. Unloading

2. **Scheduling Algorithm**
   a. Random
   b. Closest
   c. Furthest

3. **# of Cassettes**
   a. Minimum 10
   b. Maximum 80

4. **# of C-AGVs**
   a. Minimum 3
   b. Maximum 30

5. **# of QCs**
   a. Minimum 1
   b. Maximum 4

6. **# of Containers**
   a. Minimum 1
   b. Maximum 150

All results listed in this chapter are based on runs of version 1.0 of the model. These results are based on approximately 400 simulations runs. The next chapter also includes summary results for data produced by version 1.2 of the model. However because of the quantity of data produced by the 15.000 version 1.2 simulation runs, the raw data itself has not been included in this thesis.

8.1 Scenario 1(a)

In the first part of the first scenario we used the following settings

- Operation = Loading,
- Scheduling Algorithm = Random,
- # of Containers per QC = 100
- # of AGVs = 5, 10, 15, 20 & 25 respectively
- # of Cassettes = 12, 24, 36, 48 & 60 respectively
- # of QC 2

With the above mentioned inputs we run 35 simulations . In the end we calculate the mean to get more accurate results. The results also include three different overall activity percentages related to C-AGV, QC and YC of every run.

Operation = Loading, Scheduling Algorithm = Random, # of Cassettes per QC = 100					
# of QC = 2	# C-AGV= 5	# C-AGV = 10	# C-AGV= 15	# C-AGV= 20	# C-AGV= 25
	# Cass = 12	# Cass = 24	# Cass = 36	# Cass = 48	# Cass = 60
# of QC = 2	3102	1761	1684	1663	1709
Over all Activity of C-AGV	85.70%	69.00%	49.60%	38.10%	29.90%
Over all Activity of QC	25.50%	45.20%	47.10%	47.80%	46.60%
Over all Activity of YC	26.00%	42.70%	44.20%	41.60%	35.80%
# of QC = 2	3166	1877	1695	1680	1691
Over all Activity of C-AGV	86.20%	66.00%	50.30%	37.30%	29.30%
Over all Activity of QC	25.10%	42.40%	47.00%	47.40%	47.10%
Over all Activity of YC	25.70%	41.50%	41.80%	39.60%	36.20%
# of QC = 2	3059	1783	1743	1710	1728
Over all Activity of C-AGV	85.50%	68.60%	50.50%	36.70%	30.10%
Over all Activity of QC	26.00%	44.70%	45.70%	46.60%	46.10%
Over all Activity of YC	26.00%	42.70%	42.70%	38.40%	36.00%
# of QC = 2	3200	1784	1713	1662	1714
Over all Activity of C-AGV	83.40%	68.30%	50.70%	39.50%	30.40%
Over all Activity of QC	24.90%	44.60%	46.50%	47.90%	46.50%
Over all Activity of YC	25.40%	43.70%	44.40%	41.10%	35.70%
# of QC = 2	3167	1752	1678	1703	1763
Over all Activity of C-AGV	85.40%	72.30%	49.00%	38.90%	29.50%
Over all Activity of QC	25.10%	45.40%	47.50%	46.80%	45.20%
Over all Activity of YC	26.00%	43.90%	42.80%	38.00%	34.70%
# of QC = 2	3185	1736	1717	1661	1744
Over all Activity of C-AGV	85.50%	69.60%	48.30%	38.30%	29.50%
Over all Activity of QC	25.00%	45.90%	46.40%	47.90%	45.70%
Over all Activity of YC	25.50%	43.90%	42.80%	40.00%	35.60%
# of QC = 2	3220	1830	1685	1751	1687
Over all Activity of C-AGV	84.70%	68.60%	48.20%	36.90%	30.30%
Over all Activity of QC	24.70%	43.50%	47.30%	45.50%	47.20%
Over all Activity of YC	25.80%	43.00%	41.50%	38.50%	36.30%
Average	3157.00	1789.00	1702.14	1690.00	1719.43
Avg. C-AGV Activity	85.20%	68.91%	49.51%	37.96%	29.86%
Avg. QC Activity	25.19%	44.53%	46.79%	47.13%	46.34%
Avg. YC Activity	25.77%	43.06%	42.89%	39.60%	35.76%

Table 8.1: Scenario 1a, Loading, Random, QC= 2

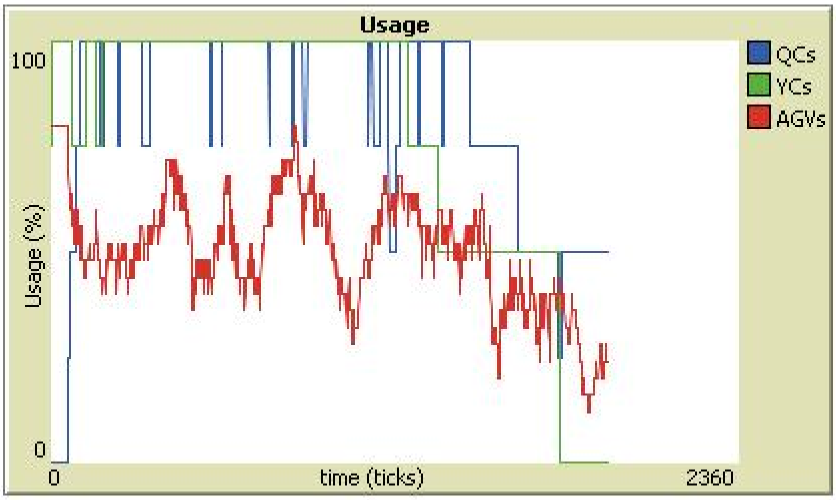


Figure 8.1: Simulation result for simulation run # 1a.34

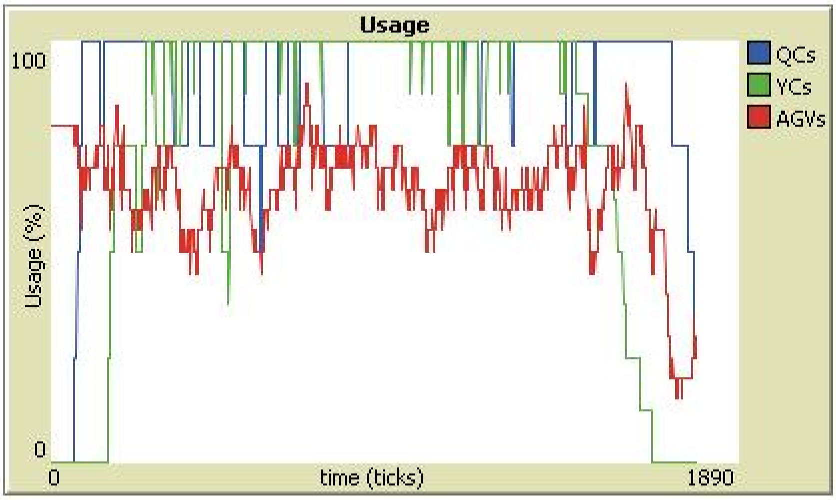


Figure 8.2: Simulation result for simulation run # 1a.35

8.2 Scenario 1(b)

In the 2nd part of the first scenario we used the following settings

- Operation = Loading,
- Scheduling Algorithm = Random,
- # of Containers per QC = 100
- # of AGVs = 5, 10, 15, 20 & 25 respectively
- # of Cassettes = 12, 24, 36, 48 & 60 respectively
- # of QC 4

With the above mentioned inputs we run 35 simulations . In the end we calculate the mean to get more accurate results. The results also include three different overall activity percentages related to C-AGV, QC and YC of every run.

Operation = Loading, Scheduling Algorithm = Random, # of Cassettes per QC = 100					
	# C-AGV= 5 # Cass = 12	# C-AGV = 10 # Cass = 24	# C-AGV= 15 # Cass = 36	# C-AGV= 20 # Cass = 48	# C-AGV= 25 # Cass = 60
# of QC = 4	6208	3475	2167	1785	1727
Over all Activity of C-AGV	84.80%	81.60%	79.00%	66.00%	54.50%
Over all Activity of QC	25.70%	45.90%	73.70%	89.40%	92.30%
Over all Activity of YC	26.50%	44.30%	66.20%	74.50%	70.90%
# of QC = 4	5972	3377	2202	1774	1803
Over all Activity of C-AGV	85.20%	84.30%	78.30%	65.90%	53.10%
Over all Activity of QC	26.70%	47.20%	72.50%	89.80%	88.80%
Over all Activity of YC	27.50%	45.60%	65.20%	75.00%	68.20%
# of QC = 4	6032	3428	2200	1780	1781
Over all Activity of C-AGV	84.60%	82.90%	78.50%	66.40%	54.10%
Over all Activity of QC	26.50%	46.60%	72.40%	89.70%	89.60%
Over all Activity of YC	27.30%	44.90%	65.20%	74.70%	68.80%
# of QC = 4	6087	3491	2235	1816	1734
Over all Activity of C-AGV	85.50%	80.70%	78.60%	65.10%	54.10%
Over all Activity of QC	26.20%	45.70%	71.30%	87.90%	91.90%
Over all Activity of YC	27.00%	44.10%	64.20%	73.20%	70.60%
# of QC = 4	6103	3516	2265	1805	1750
Over all Activity of C-AGV	84.40%	80.90%	77.90%	65.50%	54.30%
Over all Activity of QC	26.20%	45.40%	70.50%	88.40%	91.20%
Over all Activity of YC	27.00%	43.80%	63.40%	73.70%	70.00%
# of QC = 4	6245	3419	2203	1791	1769
Over all Activity of C-AGV	83.40%	84.10%	78.90%	66.40%	53.90%
Over all Activity of QC	25.60%	46.60%	72.50%	89.10%	90.20%
Over all Activity of YC	26.30%	45.00%	65.10%	74.30%	69.20%
# of QC = 4	6101	3488	2237	2039	1781
Over all Activity of C-AGV	85.20%	81.80%	79.30%	61.50%	54.00%
Over all Activity of QC	26.20%	45.80%	71.30%	78.30%	89.60%
Over all Activity of YC	37.00%	44.20%	64.10%	65.20%	68.80%
Average	6106.86	3456.29	2215.57	1827.14	1763.57
Avg. C-AGV Activity	84.73%	82.33%	78.64%	65.26%	54.00%
Avg. QC Activity	26.16%	46.17%	72.03%	87.51%	90.51%
Avg. YC Activity	28.37%	44.56%	64.77%	72.94%	69.50%

Table 8.2: Scenario 1b, Loading, Random, QC= 4

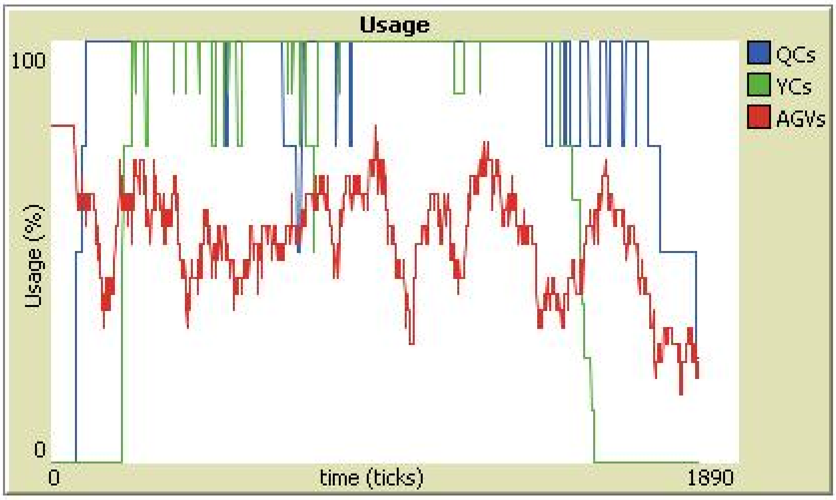


Figure 8.3: Simulation result for simulation run # 1b.66

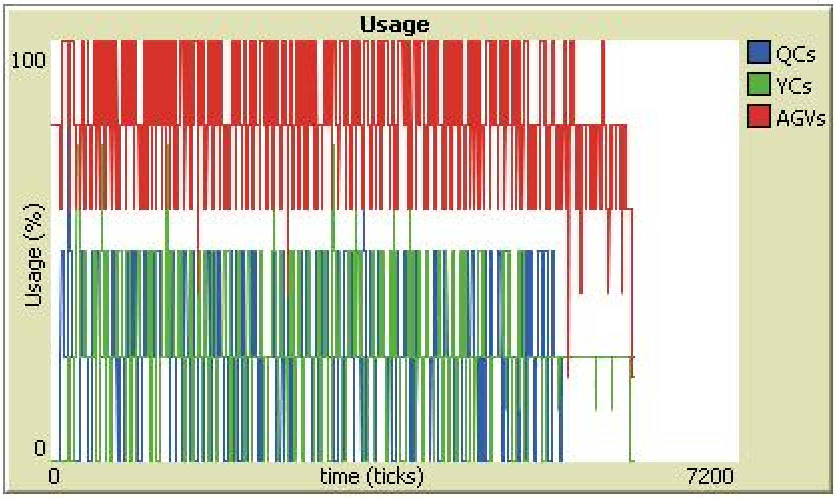


Figure 8.4: Simulation result for simulation run # 1b.70

8.3 Scenario 2(a)

In the first part of the 2nd scenario we used the following settings

- Operation = Loading,
- Scheduling Algorithm = Closest,
- # of Containers per QC = 100
- # of AGVs = 5, 10, 15, 20 & 25 respectively
- # of Cassettes = 12, 24, 36, 48 & 60 respectively
- # of QC 2

With the above mentioned inputs we run 35 simulations . In the end we calculate the mean to get more accurate results. The results also include three different overall activity percentages related to C-AGV, QC and YC of every run.

Operation = Loading, Scheduling Algorithm = Closest, # of Cassettes per QC = 100					
	# C-AGV= 5	# C-AGV = 10	# C-AGV= 15	# C-AGV= 20	# C-AGV= 25
	# Cass = 12	# Cass = 24	# Cass = 36	# Cass = 48	# Cass = 60
# of QC = 2	2962	1757	1714	1677	1665
Over all Activity of C-AGV	84.80%	67.30%	47.40%	36.40%	26.70%
Over all Activity of QC	26.90%	48.30%	46.50%	47.50%	47.80%
Over all Activity of YC	27.50%	44.30%	43.40%	41.20%	36.30%
# of QC = 2	2994	1810	1658	1681	1724
Over all Activity of C-AGV	85.30%	65.10%	47.30%	34.80%	26.70%
Over all Activity of QC	26.60%	44.00%	47.90%	47.40%	47.20%
Over all Activity of YC	27.20%	44.50%	43.80%	38.50%	35.00%
# of QC = 2	2966	1738	1688	1690	1681
Over all Activity of C-AGV	85.80%	67.40%	46.60%	33.10%	28.00%
Over all Activity of QC	26.80%	45.80%	47.20%	47.10%	47.40%
Over all Activity of YC	28.00%	45.30%	42.50%	39.30%	37.50%
# of QC = 2	2908	1711	1717	1644	1693
Over all Activity of C-AGV	85.70%	71.10%	44.80%	34.30%	27.70%
Over all Activity of QC	27.40%	46.40%	46.40%	47.90%	47.00%
Over all Activity of YC	27.70%	45.00%	42.30%	40.50%	35.70%
# of QC = 2	3053	1735	1753	1660	1656
Over all Activity of C-AGV	83.60%	68.40%	45.60%	35.60%	26.90%
Over all Activity of QC	26.10%	45.90%	45.40%	47.90%	48.10%
Over all Activity of YC	26.70%	44.40%	40.90%	40.10%	36.50%
# of QC = 2	3042	1745	1710	1669	1705
Over all Activity of C-AGV	85.50%	63.40%	46.30%	35.10%	27.80%
Over all Activity of QC	26.20%	45.60%	46.60%	47.70%	46.70%
Over all Activity of YC	27.90%	43.10%	42.00%	40.40%	36.40%
# of QC = 2	3093	1844	1693	1773	1738
Over all Activity of C-AGV	85.40%	64.30%	44.70%	34.50%	27.50%
Over all Activity of QC	25.70%	43.20%	47.00%	45.90%	45.80%
Over all Activity of YC	26.60%	42.20%	42.40%	38.40%	35.20%
Average	3002.57	1762.86	1704.71	1684.86	1694.57
Avg. C-AGV Activity	85.16%	66.71%	46.10%	34.83%	27.33%
Avg. QC Activity	26.53%	45.60%	46.71%	47.34%	47.14%
Avg. YC Activity	27.37%	44.11%	42.47%	39.77%	36.09%

Table 8.3: Scenario 2a, Loading, Closest, QC= 2

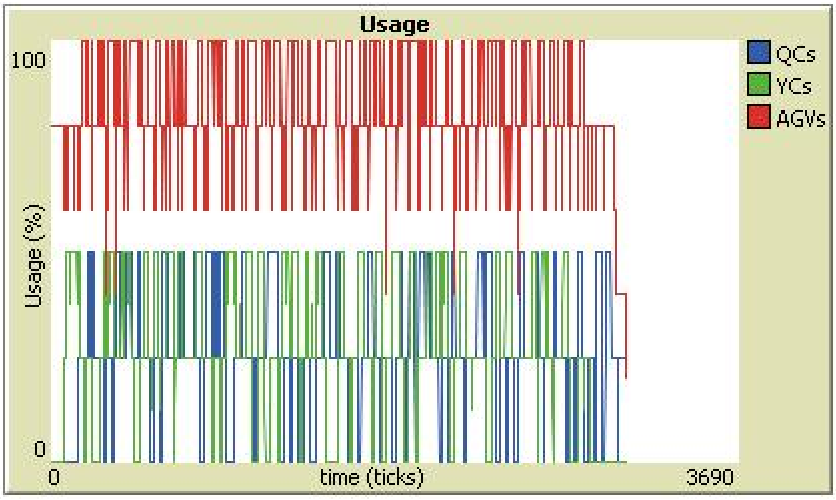


Figure 8.5: Simulation result for simulation run # 2a.31

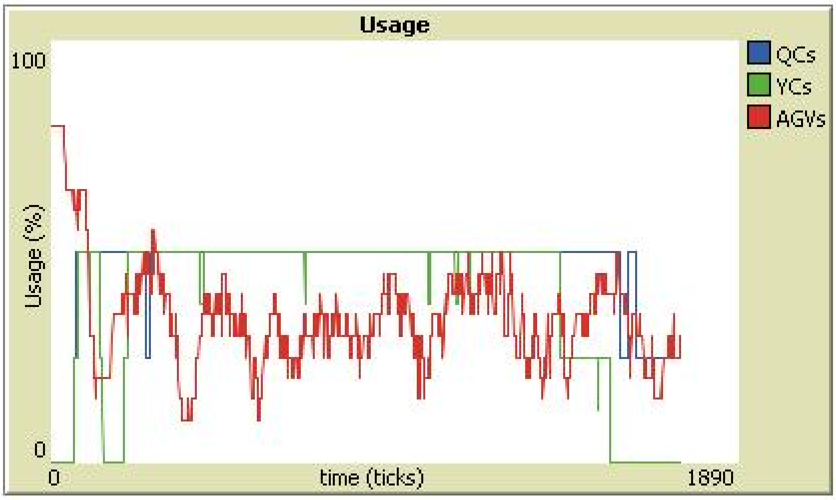


Figure 8.6: Simulation result for simulation run # 2a.35

8.4 Scenario 2(b)

In the 2nd part of the 2nd scenario we used the following settings

- Operation = Loading,
- Scheduling Algorithm = Closest,
- # of Containers per QC = 100
- # of AGVs = 5, 10, 15, 20 & 25 respectively
- # of Cassettes = 12, 24, 36, 48 & 60 respectively
- # of QC 4

With the above mentioned inputs we run 35 simulations . In the end we calculate the mean to get more accurate results. The results also include three different overall activity percentages related to C-AGV, QC and YC of every run.

Operation = Loading, Scheduling Algorithm = Closest, # of Cassettes per QC = 100					
	# C-AGV= 5	# C-AGV = 10	# C-AGV= 15	# C-AGV= 20	# C-AGV= 25
	# Cass = 12	# Cass = 24	# Cass = 36	# Cass = 48	# Cass = 60
# of QC = 4	5625	3267	2014	1750	1659
Over all Activity of C-AGV	83.50%	82.20%	77.10%	61.30%	51.90%
Over all Activity of QC	28.40%	48.90%	79.30%	91.20%	96.00%
Over all Activity of YC	29.20%	47.10%	71.30%	76.00%	73.80%
# of QC = 4	5606	3182	2022	1708	1707
Over all Activity of C-AGV	85.50%	83.40%	75.10%	61.50%	50.20%
Over all Activity of QC	28.50%	50.10%	78.80%	93.40%	93.50%
Over all Activity of YC	29.30%	48.40%	71.00%	77.90%	71.80%
# of QC = 4	5748	3262	1979	1835	1730
Over all Activity of C-AGV	83.90%	80.00%	75.30%	59.40%	50.50%
Over all Activity of QC	27.80%	48.90%	80.70%	87.00%	92.30%
Over all Activity of YC	28.60%	47.20%	72.50%	72.50%	70.80%
# of QC = 4	5826	3197	1954	1761	1724
Over all Activity of C-AGV	84.00%	82.70%	76.50%	59.80%	49.00%
Over all Activity of QC	27.40%	49.90%	87.70%	90.60%	92.50%
Over all Activity of YC	28.20%	48.20%	73.40%	75.50%	71.10%
# of QC = 4	5763	3266	1978	1688	1720
Over all Activity of C-AGV	85.10%	81.10%	78.20%	62.20%	49.90%
Over all Activity of QC	27.70%	48.90%	80.70%	94.50%	92.80%
Over all Activity of YC	28.50%	47.20%	72.50%	78.80%	71.20%
# of QC = 4	5794	3134	2012	1774	1713
Over all Activity of C-AGV	83.90%	82.90%	74.40%	59.90%	50.00%
Over all Activity of QC	27.90%	50.90%	79.30%	90.00%	93.20%
Over all Activity of YC	28.40%	49.10%	71.30%	75.00%	71.50%
# of QC = 4	5583	3164	1955	1917	1750
Over all Activity of C-AGV	84.00%	82.90%	76.00%	57.60%	49.20%
Over all Activity of QC	28.60%	50.50%	81.60%	83.30%	91.20%
Over all Activity of YC	29.50%	48.70%	73.40%	69.40%	70.00%
Average	5706.43	3210.29	1987.71	1776.14	1714.71
Avg. C-AGV Activity	84.27%	82.17%	76.09%	60.24%	50.10%
Avg. QC Activity	28.04%	49.73%	81.16%	90.00%	93.07%
Avg. YC Activity	28.81%	47.99%	72.20%	75.01%	71.46%

Table 8.4: Scenario 2b, Loading, Closest, QC= 4

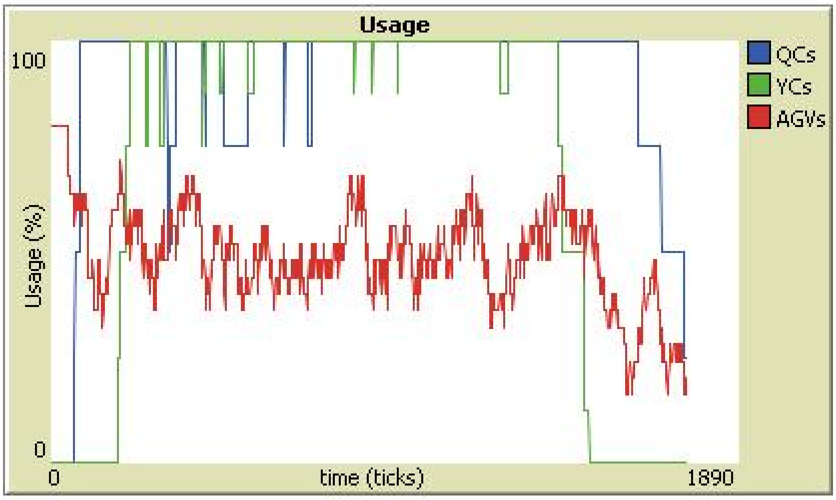


Figure 8.7: Simulation result for simulation run # 2a.66

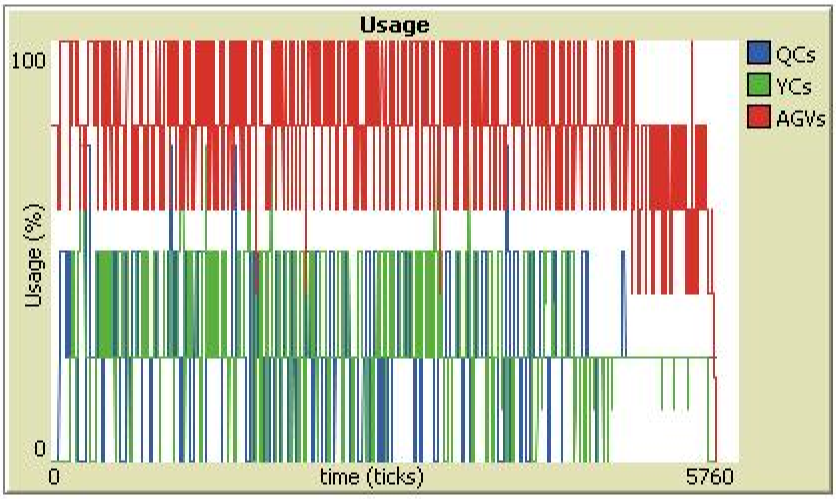


Figure 8.8: Simulation result for simulation run # 2a.70

8.5 Scenario 3(a)

In the first part of the 3rd scenario we used the following settings

- Operation = Loading,
- Scheduling Algorithm = Furthest,
- # of Containers per QC = 100
- # of AGVs = 5, 10, 15, 20 & 25 respectively
- # of Cassettes = 12, 24, 36, 48 & 60 respectively
- # of QC 2

With the above mentioned inputs we run 35 simulations . In the end we calculate the mean to get more accurate results. The results also include three different overall activity percentages related to C-AGV, QC and YC of every run.

Operation = Loading, Scheduling Algorithm = Furthest, # of Cassettes per QC = 100					
	# C-AGV= 5	# C-AGV = 10	# C-AGV= 15	# C-AGV= 20	# C-AGV= 25
	# Cass = 12	# Cass = 24	# Cass = 36	# Cass = 48	# Cass = 60
# of QC = 2	3444	1849	1734	1740	1674
Over all Activity of C-AGV	84.70%	69.10%	51.40%	40.00%	31.70%
Over all Activity of QC	23.10%	42.90%	45.90%	45.80%	47.60%
Over all Activity of YC	23.40%	41.20%	42.90%	38.20%	36.60%
# of QC = 2	3418	1803	1727	1760	1698
Over all Activity of C-AGV	86.30%	72.00%	51.60%	38.90%	31.50%
Over all Activity of QC	23.30%	44.20%	46.10%	45.20%	46.90%
Over all Activity of YC	24.60%	42.70%	40.50%	37.30%	36.10%
# of QC = 2	3516	1813	1802	1713	1709
Over all Activity of C-AGV	85.80%	70.50%	47.90%	41.40%	31.30%
Over all Activity of QC	22.60%	43.90%	44.20%	46.50%	46.60%
Over all Activity of YC	23.40%	44.40%	39.30%	38.30%	35.30%
# of QC = 2	3461	1809	1735	1724	1685
Over all Activity of C-AGV	84.30%	70.70%	53.40%	40.60%	32.10%
Over all Activity of QC	23.00%	44.00%	45.90%	46.20%	47.10%
Over all Activity of YC	23.00%	42.60%	42.90%	37.10%	35.80%
# of QC = 2	3345	1805	1709	1711	1758
Over all Activity of C-AGV	86.50%	71.20%	51.50%	39.20%	31.60%
Over all Activity of QC	23.80%	44.10%	46.60%	46.50%	45.30%
Over all Activity of YC	24.60%	42.70%	41.50%	39.40%	34.30%
# of QC = 2	3329	1866	1821	1815	1706
Over all Activity of C-AGV	85.70%	68.10%	46.70%	37.50%	32.20%
Over all Activity of QC	23.90%	42.70%	43.70%	43.90%	46.70%
Over all Activity of YC	24.70%	41.30%	41.30%	37.60%	35.40%
# of QC = 2	3448	1805	1767	1726	1712
Over all Activity of C-AGV	64.70%	70.90%	50.40%	39.30%	31.30%
Over all Activity of QC	23.10%	44.10%	45.10%	46.10%	46.50%
Over all Activity of YC	23.90%	42.20%	40.60%	38.50%	35.30%
Average	3423.00	1821.43	1756.43	1741.29	1706.00
Avg. C-AGV Activity	82.57%	70.36%	50.41%	39.56%	31.67%
Avg. QC Activity	23.26%	43.70%	45.36%	45.74%	46.67%
Avg. YC Activity	23.94%	42.44%	41.29%	38.06%	35.54%

Table 8.5: Scenario 3a, Loading, Furthest, QC= 2

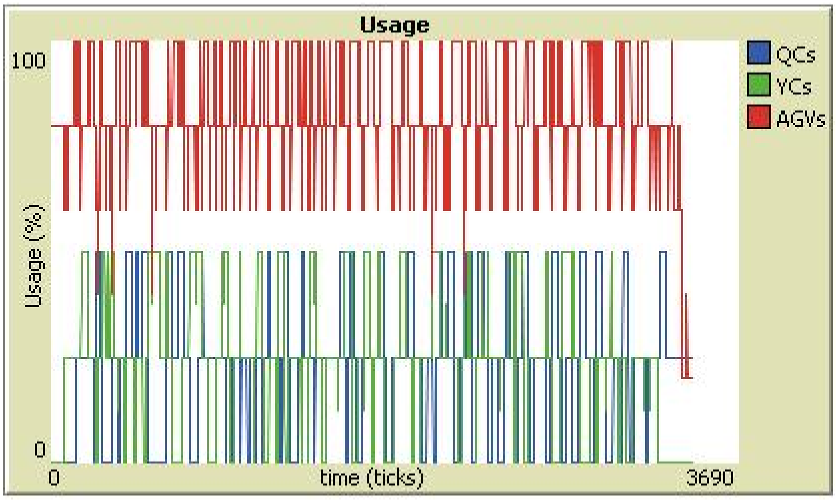


Figure 8.9: Simulation result for simulation run # 3a.31

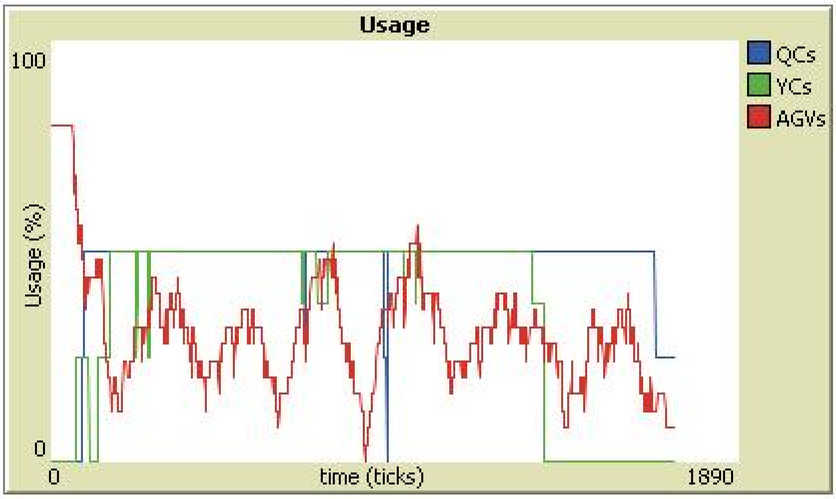


Figure 8.10: Simulation result for simulation run # 3a.35

8.6 Scenario 3(b)

In the 2nd part of the 3rd scenario we used the following settings

- Operation = Loading,
- Scheduling Algorithm = Furthest,
- # of Containers per QC = 100
- # of AGVs = 5, 10, 15, 20 & 25 respectively
- # of Cassettes = 12, 24, 36, 48 & 60 respectively
- # of QC 4

With the above mentioned inputs we run 35 simulations . In the end we calculate the mean to get more accurate results. The results also include three different overall activity percentages related to C-AGV, QC and YC of every run.

Operation = Loading, Scheduling Algorithm = Furthest, # of Cassettes per QC = 100					
	# C-AGV= 5	# C-AGV = 10	# C-AGV= 15	# C-AGV= 20	# C-AGV= 25
	# Cass = 12	# Cass = 24	# Cass = 36	# Cass = 48	# Cass = 60
# of QC = 4	6379	3592	2454	1839	1727
Over all Activity of C-AGV	85.20%	84.80%	76.70%	66.70%	59.50%
Over all Activity of QC	25.00%	44.40%	65.00%	86.60%	92.40%
Over all Activity of YC	25.80%	42.90%	58.50%	72.30%	70.90%
# of QC = 4	6530	3671	2380	1969	1794
Over all Activity of C-AGV	85.30%	82.10%	79.80%	66.00%	57.00%
Over all Activity of QC	24.40%	43.50%	67.10%	81.10%	89.00%
Over all Activity of YC	25.20%	42.00%	60.30%	67.50%	68.30%
# of QC = 4	6567	3574	2438	1859	1930
Over all Activity of C-AGV	85.70%	84.20%	76.70%	66.80%	54.40%
Over all Activity of QC	24.30%	44.60%	65.50%	85.70%	82.70%
Over all Activity of YC	25.00%	43.10%	58.90%	71.50%	63.50%
# of QC = 4	6694	3634	2328	1852	1891
Over all Activity of C-AGV	85.40%	82.50%	78.50%	67.70%	54.20%
Over all Activity of QC	23.80%	43.90%	68.60%	86.20%	84.40%
Over all Activity of YC	24.60%	42.40%	61.60%	71.80%	64.80%
# of QC = 4	6466	3555	2350	1863	1768
Over all Activity of C-AGV	84.90%	84.40%	79.40%	68.80%	58.00%
Over all Activity of QC	24.70%	44.80%	67.90%	85.70%	90.30%
Over all Activity of YC	25.40%	43.30%	61.10%	71.40%	69.30%
# of QC = 4	6499	3696	2402	1935	1798
Over all Activity of C-AGV	85.20%	82.50%	77.10%	66.30%	56.90%
Over all Activity of QC	24.60%	43.20%	66.50%	82.50%	88.80%
Over all Activity of YC	25.30%	41.70%	59.70%	68.70%	68.10%
# of QC = 4	6421	3608	2410	1840	1800
Over all Activity of C-AGV	85.40%	83.20%	76.60%	68.50%	57.40%
Over all Activity of QC	24.90%	44.20%	66.20%	86.80%	88.70%
Over all Activity of YC	25.60%	42.70%	59.50%	72.30%	68.10%
Average	6508.00	3618.57	2394.57	1879.57	1815.43
Avg. C-AGV Activity	85.30%	83.39%	77.83%	67.26%	56.77%
Avg. QC Activity	24.53%	44.09%	66.69%	84.94%	88.04%
Avg. YC Activity	25.27%	42.59%	59.94%	70.79%	67.57%

Table 8.6: Scenario 3b, Loading, Furthest, QC= 4

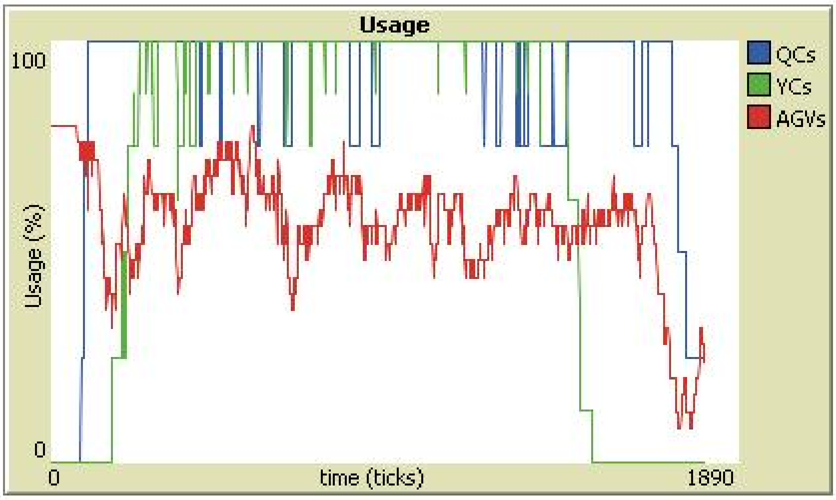


Figure 8.11: Simulation result for simulation run # 3b.66

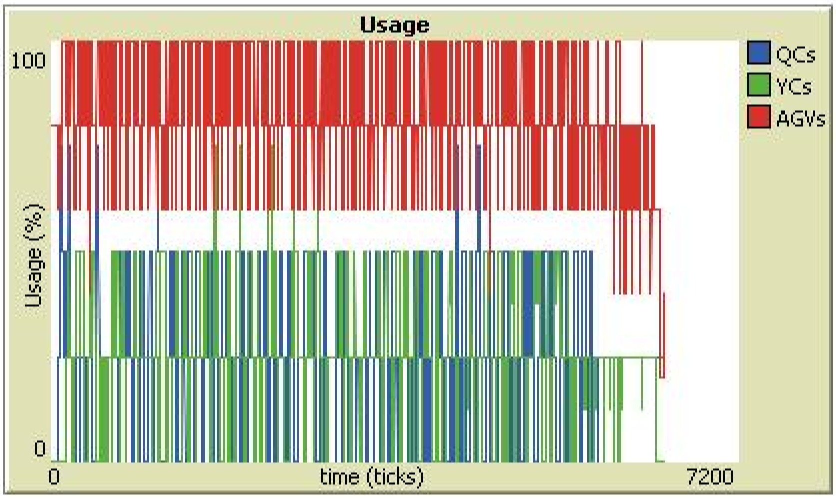


Figure 8.12: Simulation result for simulation run # 3b.70

8.7 Scenario 4(a)

In the first part of the 4th scenario we used the following settings

- Operation = Unloading,
- Scheduling Algorithm = Random,
- # of Containers per QC = 100
- # of AGVs = 5, 10, 15, 20 & 25 respectively
- # of Cassettes = 12, 24, 36, 48 & 60 respectively
- # of QC 2

With the above mentioned inputs we run 35 simulations . In the end we calculate the mean to get more accurate results. The results also include three different overall activity percentages related to C-AGV, QC and YC of every run.

Operation = Unloading, Scheduling Algorithm = Random, # of Cassettes per QC = 100					
	# C-AGV = 10	# C-AGV= 15	# C-AGV= 20	# C-AGV= 25	# C-AGV= 30
	# Cass = 24	# Cass = 36	# Cass = 48	# Cass = 60	# Cass = 72
# of QC = 2	2109	1762	1835	1931	1789
Over all Activity of C-AGV	83.40%	69.40%	46.80%	35.80%	31.10%
Over all Activity of QC	37.90%	45.40%	43.60%	41.40%	44.70%
Over all Activity of YC	32.70%	39.50%	37.80%	36.00%	38.70%
# of QC = 2	2128	1865	1740	1936	1910
Over all Activity of C-AGV	83.00%	60.90%	47.70%	34.40%	28.10%
Over all Activity of QC	37.60%	42.90%	46.00%	41.30%	41.90%
Over all Activity of YC	32.50%	37.30%	40.00%	36.00%	36.40%
# of QC = 2	2068	1949	1901	1807	1904
Over all Activity of C-AGV	85.60%	56.90%	44.10%	37.10%	29.40%
Over all Activity of QC	38.70%	41.00%	42.10%	44.30%	42.00%
Over all Activity of YC	33.50%	35.70%	36.60%	38.50%	36.20%
# of QC = 2	2129	1997	1824	1817	1921
Over all Activity of C-AGV	82.80%	57.80%	46.40%	35.70%	28.60%
Over all Activity of QC	37.60%	40.10%	43.90%	44.00%	41.60%
Over all Activity of YC	32.60%	34.70%	38.10%	38.30%	36.20%
# of QC = 2	2092	1874	1843	1862	1833
Over all Activity of C-AGV	84.90%	58.70%	45.80%	36.10%	30.50%
Over all Activity of QC	38.20%	42.70%	43.40%	43.00%	43.60%
Over all Activity of YC	33.30%	37.20%	37.80%	37.40%	37.90%
# of QC = 2	2101	1834	1750	1807	1992
Over all Activity of C-AGV	83.40%	61.90%	46.40%	36.90%	27.70%
Over all Activity of QC	38.10%	43.60%	45.70%	44.30%	40.20%
Over all Activity of YC	33.10%	37.80%	39.50%	38.50%	34.90%
# of QC = 2	2025	1847	1793	1844	1842
Over all Activity of C-AGV	89.20%	61.80%	46.90%	36.50%	30.70%
Over all Activity of QC	39.50%	43.30%	44.60%	43.40%	43.40%
Over all Activity of YC	34.10%	37.70%	38.60%	37.70%	37.80%
Average	2093.14	1875.43	1812.29	1857.71	1884.43
Avg. C-AGV Activity	84.61%	61.06%	46.30%	36.07%	29.44%
Avg. QC Activity	38.23%	42.71%	44.19%	43.10%	42.49%
Avg. YC Activity	33.11%	37.13%	38.34%	37.49%	36.87%

Table 8.7: Scenario 4a, Unloading, Random, QC= 2

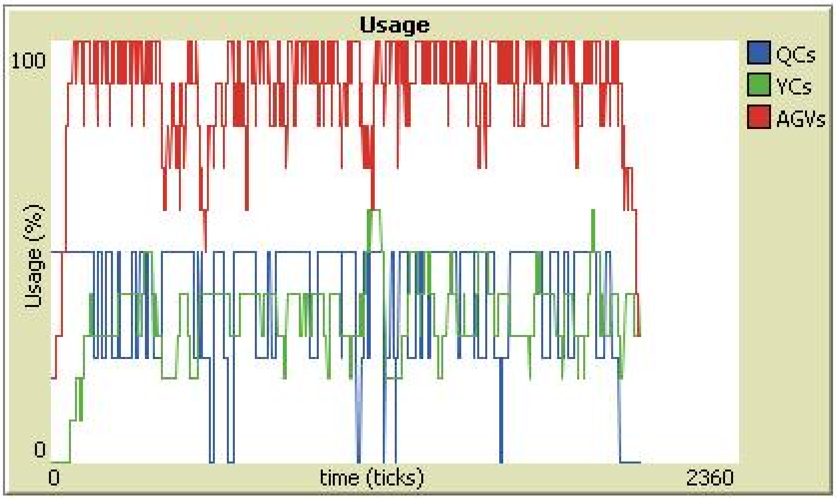


Figure 8.13: Simulation result for simulation run # 4a.31

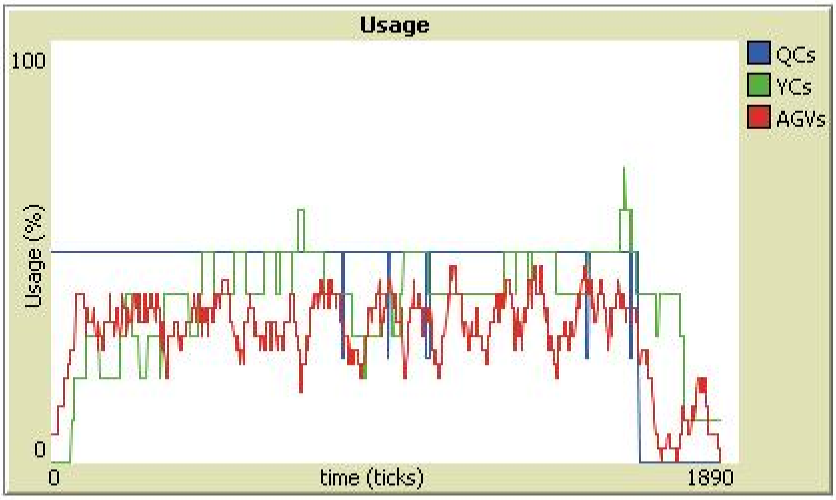


Figure 8.14: Simulation result for simulation run # 4a.35

8.8 Scenario 4(b)

In the 2nd part of the 4th scenario we used the following settings

- Operation = Unloading,
- Scheduling Algorithm = Random,
- # of Containers per QC = 100
- # of AGVs = 5, 10, 15, 20 & 25 respectively
- # of Cassettes = 12, 24, 36, 48 & 60 respectively
- # of QC 4

With the above mentioned inputs we run 35 simulations . In the end we calculate the mean to get more accurate results. The results also include three different overall activity percentages related to C-AGV, QC and YC of every run.

Operation = Unloading, Scheduling Algorithm = Random, # of Cassettes per QC = 100					
	# C-AGV = 10	# C-AGV= 15	# C-AGV= 20	# C-AGV= 25	# C-AGV= 30
	# Cass = 24	# Cass = 36	# Cass = 48	# Cass = 60	# Cass = 72
# of QC = 4	3361	2135	1934	1893	1935
Over all Activity of C-AGV	90.30%	91.20%	83.50%	69.50%	56.70%
Over all Activity of QC	47.60%	74.90%	82.70%	84.50%	82.70%
Over all Activity of YC	41.50%	65.20%	72.20%	73.70%	72.00%
# of QC = 4	3277	2310	2023	1939	1949
Over all Activity of C-AGV	91.30%	89.60%	80.60%	68.40%	56.00%
Over all Activity of QC	48.80%	69.30%	79.10%	82.50%	82.10%
Over all Activity of YC	42.60%	60.40%	67.00%	71.80%	71.60%
# of QC = 4	3492	2246	1914	1930	1925
Over all Activity of C-AGV	89.20%	87.20%	83.60%	67.10%	56.90%
Over all Activity of QC	45.80%	71.20%	83.60%	82.90%	83.10%
Over all Activity of YC	40.00%	62.10%	72.70%	72.30%	72.40%
# of QC = 4	3391	2285	1880	1967	1952
Over all Activity of C-AGV	91.50%	87.90%	85.30%	68.40%	55.10%
Over all Activity of QC	47.20%	70.00%	85.10%	81.30%	81.80%
Over all Activity of YC	41.20%	61.00%	73.90%	70.90%	71.30%
# of QC = 4	3439	2285	2035	1916	1956
Over all Activity of C-AGV	89.40%	87.60%	81.70%	70.70%	55.80%
Over all Activity of QC	46.50%	70.00%	78.60%	83.50%	82.00%
Over all Activity of YC	40.60%	61.00%	68.60%	72.60%	71.40%
# of QC = 4	3365	2198	1974	1904	1930
Over all Activity of C-AGV	92.10%	91.00%	85.30%	68.10%	55.00%
Over all Activity of QC	47.50%	72.80%	81.10%	84.00%	82.90%
Over all Activity of YC	41.50%	63.50%	70.70%	73.30%	72.30%
# of QC = 4	3300	2206	1898	1971	1937
Over all Activity of C-AGV	91.20%	90.80%	84.80%	70.20%	58.20%
Over all Activity of QC	48.50%	72.50%	84.30%	81.20%	82.60%
Over all Activity of YC	42.20%	63.30%	73.10%	70.70%	71.90%
Average	3375.00	2237.86	1951.14	1931.43	1940.57
Avg. C-AGV Activity	90.71%	89.33%	83.54%	68.91%	56.24%
Avg. QC Activity	47.41%	71.53%	82.07%	82.84%	82.46%
Avg. YC Activity	41.37%	62.36%	71.17%	72.19%	71.84%

Table 8.8: Scenario 4b, Unloading, Random, QC= 4

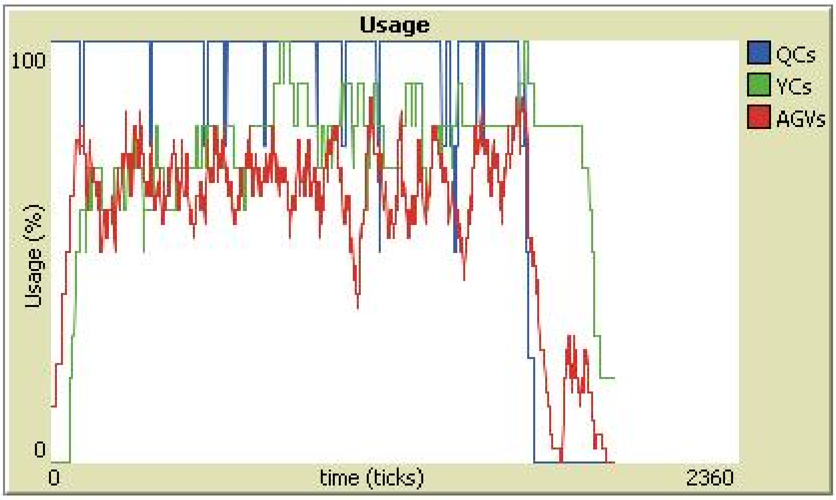


Figure 8.15: Simulation result for simulation run # 4b.66

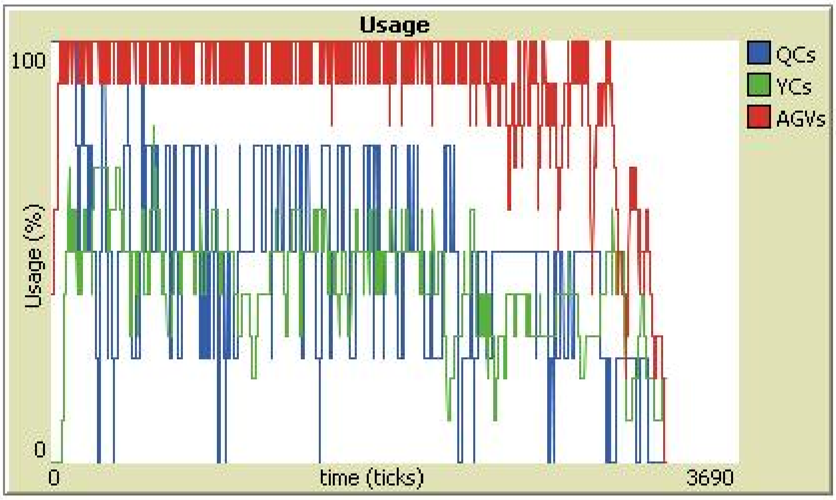


Figure 8.16: Simulation result for simulation run # 4b.70

8.9 Scenario 5(a)

In the 1st part of the 5th scenario we used the following settings

- Operation = Unloading,
- Scheduling Algorithm = Closest,
- # of Containers per QC = 100
- # of AGVs = 5, 10, 15, 20 & 25 respectively
- # of Cassettes = 12, 24, 36, 48 & 60 respectively
- # of QC 2

With the above mentioned inputs we run 35 simulations . In the end we calculate the mean to get more accurate results. The results also include three different overall activity percentages related to C-AGV, QC and YC of every run.

Operation = Unloading, Scheduling Algorithm = Closest, # of Cassettes per QC = 100					
	# C-AGV = 10	# C-AGV= 15	# C-AGV= 20	# C-AGV= 25	# C-AGV= 30
	# Cass = 24	# Cass = 36	# Cass = 48	# Cass = 60	# Cass = 72
# of QC = 2	2138	1771	1829	1801	1847
Over all Activity of C-AGV	85.50%	66.90%	48.40%	39.50%	31.60%
Over all Activity of QC	37.40%	45.20%	43.70%	44.40%	43.30%
Over all Activity of YC	32.60%	39.10%	38.10%	38.60%	37.60%
# of QC = 2	2283	1801	1847	1888	1876
Over all Activity of C-AGV	81.10%	65.50%	47.60%	37.20%	31.30%
Over all Activity of QC	35.00%	44.40%	43.30%	42.40%	42.60%
Over all Activity of YC	30.50%	38.60%	37.70%	36.90%	37.10%
# of QC = 2	2331	1822	1775	1808	1805
Over all Activity of C-AGV	81.10%	64.40%	47.10%	38.00%	31.60%
Over all Activity of QC	34.30%	43.90%	45.10%	44.20%	44.30%
Over all Activity of YC	29.90%	38.10%	39.10%	38.30%	38.40%
# of QC = 2	2323	1737	1793	1850	1782
Over all Activity of C-AGV	80.60%	66.30%	48.20%	36.90%	32,9%
Over all Activity of QC	34.40%	46.10%	44.60%	43.20%	44.90%
Over all Activity of YC	30.00%	39.90%	38.80%	37.60%	38.80%
# of QC = 2	2110	1794	1758	1810	1763
Over all Activity of C-AGV	87.50%	66.20%	49.10%	38.10%	32.00%
Over all Activity of QC	37.90%	44.60%	45.50%	44.20%	45.40%
Over all Activity of YC	30.00%	38.80%	39.40%	38.40%	39.20%
# of QC = 2	2262	1813	1816	1807	1815
Over all Activity of C-AGV	81.90%	63.80%	48.40%	38.60%	32.20%
Over all Activity of QC	35.40%	44.10%	44.90%	44.30%	44.10%
Over all Activity of YC	30.80%	38.40%	38.30%	38.50%	38.20%
# of QC = 2	2248	1836	1771	1790	1818
Over all Activity of C-AGV	84.10%	65.40%	48.70%	39.00%	31.80%
Over all Activity of QC	35.60%	43.50%	45.20%	44.70%	44.00%
Over all Activity of YC	31.00%	37.90%	39.10%	38.90%	38.10%
Average	2242.14	1796.29	1798.43	1822.00	1815.14
Avg. C-AGV Activity	83.11%	65.50%	48.21%	38.19%	#VALUE!
Avg. QC Activity	35.71%	44.54%	44.61%	43.91%	44.09%
Avg. YC Activity	30.69%	38.69%	38.64%	38.17%	38.20%

Table 8.9: Scenario 5a, Unloading, Closest, QC= 2

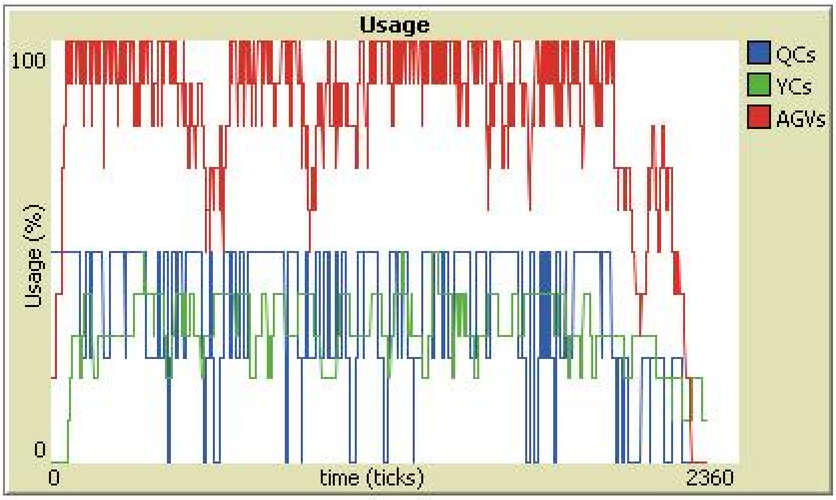


Figure 8.17: Simulation result for simulation run # 5a.31

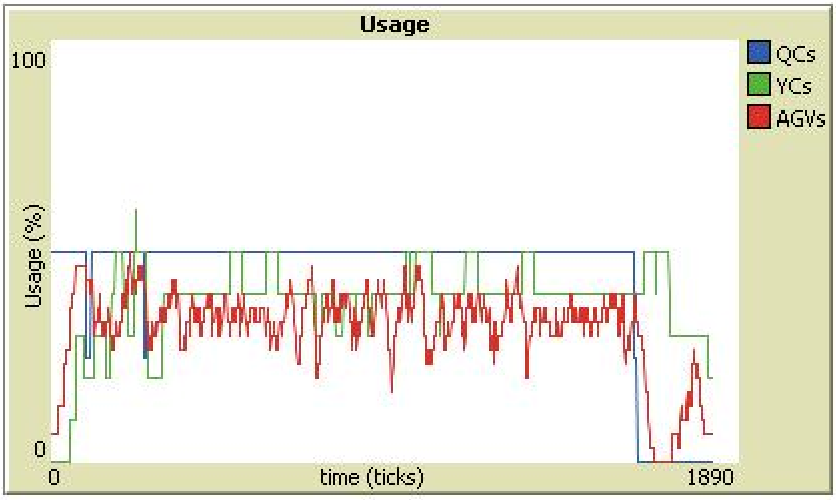


Figure 8.18: Simulation result for simulation run # 5a.35

8.10 Scenario 5(b)

In the 2nd part of the 5th scenario we used the following settings

- Operation = Unloading,
- Scheduling Algorithm = Closest,
- # of Containers per QC = 100
- # of AGVs = 5, 10, 15, 20 & 25 respectively
- # of Cassettes = 12, 24, 36, 48 & 60 respectively
- # of QC 4

With the above mentioned inputs we run 35 simulations . In the end we calculate the mean to get more accurate results. The results also include three different overall activity percentages related to C-AGV, QC and YC of every run.

Operation = Unloading, Scheduling Algorithm = Closest, # of Cassettes per QC = 100					
	# C-AGV = 10	# C-AGV= 15	# C-AGV= 20	# C-AGV= 25	# C-AGV= 30
	# Cass = 24	# Cass = 36	# Cass = 48	# Cass = 60	# Cass = 72
# of QC = 4	3210	2208	1929	1868	1836
Over all Activity of C-AGV	93.60%	92.40%	84.90%	44.10%	62.20%
Over all Activity of QC	49.80%	72.50%	82.90%	85.70%	87.10%
Over all Activity of YC	43.50%	63.20%	72.30%	74.50%	75.70%
# of QC = 4	3410	2357	1969	1845	1916
Over all Activity of C-AGV	92.90%	85.60%	83.20%	73.40%	60.50%
Over all Activity of QC	46.90%	67.90%	81.30%	86.70%	83.50%
Over all Activity of YC	40.90%	59.20%	70.90%	75.50%	72.80%
# of QC = 4	3180	2146	1937	1864	1898
Over all Activity of C-AGV	94.50%	91.40%	84.00%	72.70%	59.60%
Over all Activity of QC	50.30%	74.60%	82.60%	85.80%	84.30%
Over all Activity of YC	43.90%	64.50%	72.00%	74.90%	73.50%
# of QC = 4	3240	2170	1905	1907	1874
Over all Activity of C-AGV	94.00%	89.20%	85.80%	73.00%	61.00%
Over all Activity of QC	49.40%	73.30%	84.00%	83.90%	85.40%
Over all Activity of YC	43.10%	64.20%	73.10%	73.20%	74.40%
# of QC = 4	3328	2356	1935	1948	1912
Over all Activity of C-AGV	94.30%	85.90%	84.20%	71.80%	59.20%
Over all Activity of QC	48.10%	67.90%	82.70%	81.10%	83.70%
Over all Activity of YC	41.90%	59.20%	72.10%	71.60%	73.00%
# of QC = 4	3832	2139	1912	1832	1871
Over all Activity of C-AGV	85.70%	91.80%	87.30%	74.50%	61.70%
Over all Activity of QC	41.80%	74.80%	83.70%	87.30%	85.50%
Over all Activity of YC	36.40%	65.00%	72.90%	75.90%	74.50%
# of QC = 4	3537	2234	1969	1935	1875
Over all Activity of C-AGV	89.60%	91.00%	84.40%	71.60%	60.60%
Over all Activity of QC	45.20%	71.60%	81.30%	82.70%	85.30%
Over all Activity of YC	39.50%	62.40%	70.90%	72.10%	74.20%
Average	3391.00	2230.00	1936.57	1885.57	1883.14
Avg. C-AGV Activity	92.09%	89.61%	84.83%	68.73%	60.69%
Avg. QC Activity	47.36%	71.80%	82.64%	84.74%	84.97%
Avg. YC Activity	41.31%	62.53%	72.03%	73.96%	74.01%

Table 8.10: Scenario 5b, Unloading, Closest, QC= 4

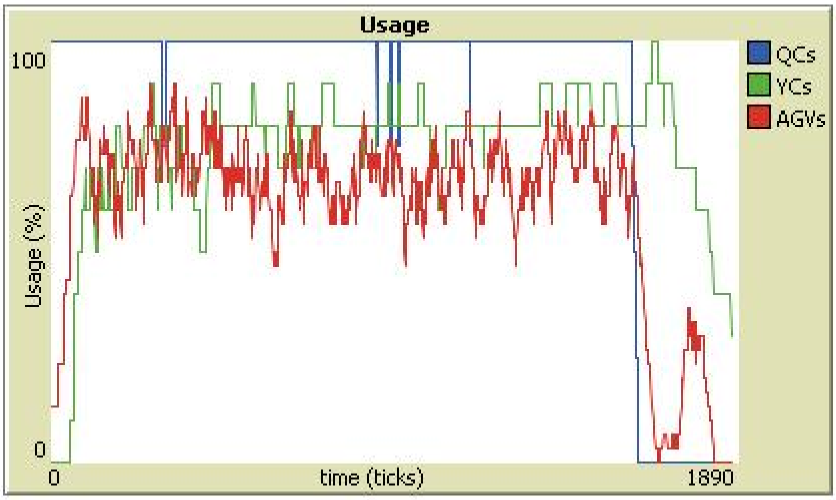


Figure 8.19: Simulation result for simulation run # 5b.66

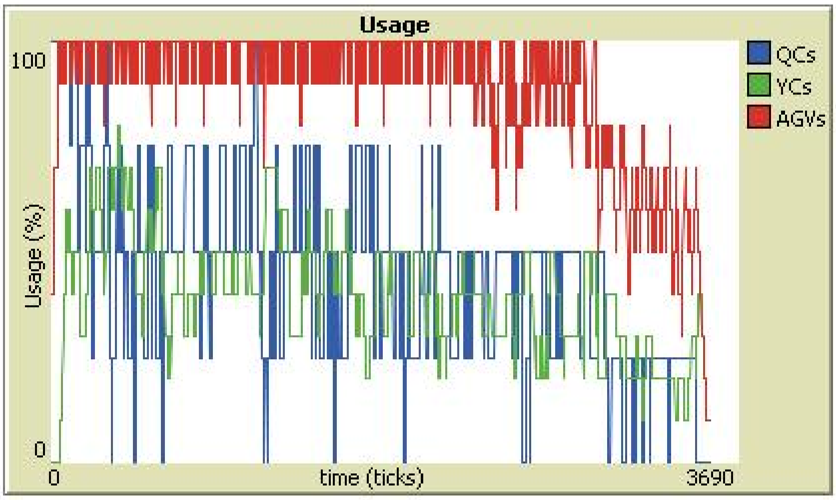


Figure 8.20: Simulation result for simulation run # 5b.70

8.11 Scenario 6(a)

In the 1st part of the 6th scenario we used the following settings

- Operation = Unloading,
- Scheduling Algorithm = Furthest,
- # of Containers per QC = 100
- # of AGVs = 5, 10, 15, 20 & 25 respectively
- # of Cassettes = 12, 24, 36, 48 & 60 respectively
- # of QC 2

With the above mentioned inputs we run 35 simulations . In the end we calculate the mean to get more accurate results. The results also include three different overall activity percentages related to C-AGV, QC and YC of every run.

Operation = Unloading, Scheduling Algorithm = Furthest, # of Cassettes per QC = 100					
	# C-AGV = 10	# C-AGV= 15	# C-AGV= 20	# C-AGV= 25	# C-AGV= 30
	# Cass = 24	# Cass = 36	# Cass = 48	# Cass = 60	# Cass = 72
# of QC = 2	2200	1858	1861	1919	2009
Over all Activity of C-AGV	78.70%	57.90%	44.40%	33.60%	27.50%
Over all Activity of QC	36.40%	43.10%	43.00%	41.70%	39.80%
Over all Activity of YC	31.70%	37.40%	37.40%	36.20%	34.70%
# of QC = 2	2138	1875	1931	1903	1797
Over all Activity of C-AGV	81.80%	59.90%	44.70%	34.90%	29.70%
Over all Activity of QC	37.40%	42.70%	41.40%	42.00%	44.50%
Over all Activity of YC	32.50%	37.00%	36.10%	36.60%	38.60%
# of QC = 2	2176	1831	1839	1853	1868
Over all Activity of C-AGV	78.30%	60.20%	45.40%	34.60%	29.60%
Over all Activity of QC	36.80%	43.70%	43.50%	43.20%	42.80%
Over all Activity of YC	32.00%	37.70%	37.90%	37.60%	37.30%
# of QC = 2	2040	1884	1883	1912	1946
Over all Activity of C-AGV	85.20%	60.30%	42.30%	34.30%	27.00%
Over all Activity of QC	36.20%	42.50%	42.50%	41.80%	41.10%
Over all Activity of YC	34.10%	37.00%	36.80%	36.40%	35.80%
# of QC = 2	2108	1936	1944	1927	1837
Over all Activity of C-AGV	82.30%	57.80%	42.00%	34.30%	29.20%
Over all Activity of QC	38.00%	41.30%	41.20%	42.50%	43.50%
Over all Activity of YC	33.00%	36.50%	35.80%	36.10%	37.90%
# of QC = 2	2211	1763	1851	1846	1943
Over all Activity of C-AGV	78.50%	59.40%	44.30%	35.40%	27.90%
Over all Activity of QC	36.20%	45.40%	43.30%	43.30%	41.20%
Over all Activity of YC	31.50%	39.30%	37.60%	37.70%	35.80%
# of QC = 2	2205	1888	1766	1914	1919
Over all Activity of C-AGV	77.90%	55.90%	46.10%	33.90%	27.50%
Over all Activity of QC	36.30%	42.40%	45.30%	41.80%	41.70%
Over all Activity of YC	31.60%	36.90%	39.20%	36.30%	63.30%
Average	2154.00	1862.14	1867.86	1896.29	1902.71
Avg. C-AGV Activity	80.39%	58.77%	44.17%	34.43%	28.34%
Avg. QC Activity	36.76%	43.01%	42.89%	42.33%	42.09%
Avg. YC Activity	32.34%	37.40%	37.26%	36.70%	40.49%

Table 8.11: Scenario 6a, Unloading, Furthest, QC= 2

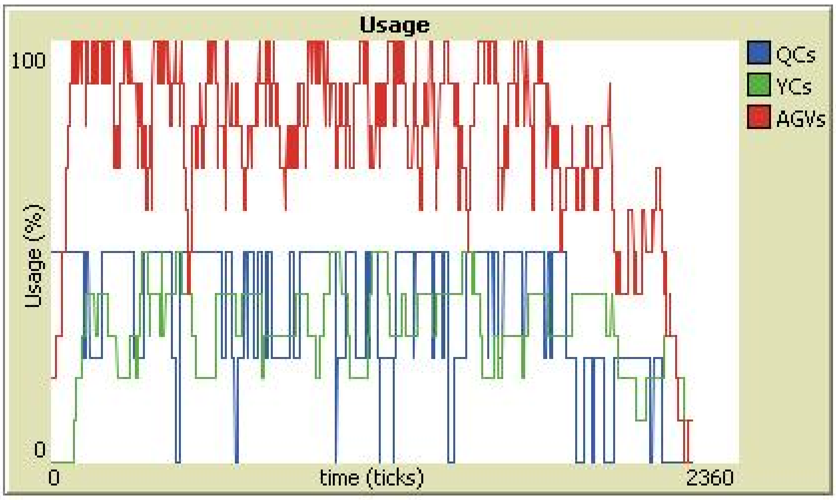


Figure 8.21: Simulation result for simulation run # 6a.31

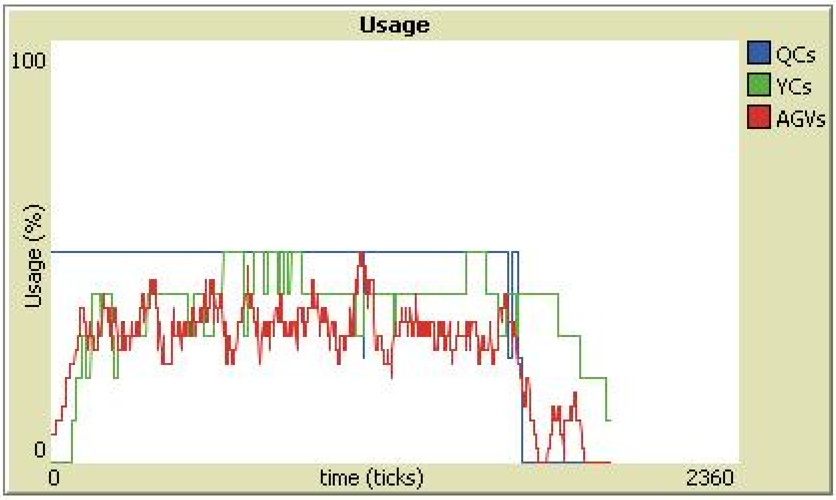


Figure 8.22: Simulation result for simulation run # 6a.35

8.12 Scenario 6(b)

In the 2nd part of the 6th scenario we used the following settings

- Operation = Unloading,
- Scheduling Algorithm = Furthest,
- # of Containers per QC = 100
- # of AGVs = 5, 10, 15, 20 & 25 respectively
- # of Cassettes = 12, 24, 36, 48 & 60 respectively
- # of QC 4

With the above mentioned inputs we run 35 simulations . In the end we calculate the mean to get more accurate results. The results also include three different overall activity percentages related to C-AGV, QC and YC of every run.

Operation = Unloading, Scheduling Algorithm = Furthest, # of Cassettes per QC = 100					
	# C-AGV = 10	# C-AGV= 15	# C-AGV= 20	# C-AGV= 25	# C-AGV= 30
	# Cass = 24	# Cass = 36	# Cass = 48	# Cass = 60	# Cass = 72
# of QC = 4	3532	2290	2014	1961	2100
Over all Activity of C-AGV	88.90%	87.80%	80.40%	67.50%	52.10%
Over all Activity of QC	45.30%	69.90%	79.40%	81.60%	76.20%
Over all Activity of YC	39.50%	60.90%	69.30%	71.10%	66.40%
# of QC = 4	3274	2638	1947	1990	1975
Over all Activity of C-AGV	92.40%	78.90%	84.20%	67.60%	54.70%
Over all Activity of QC	48.90%	60.70%	82.20%	80.40%	61.00%
Over all Activity of YC	42.50%	52.90%	71.70%	70.20%	70.60%
# of QC = 4	3502	2464	2043	2000	1933
Over all Activity of C-AGV	86.80%	82.60%	79.30%	65.70%	57.10%
Over all Activity of QC	45.70%	64.90%	78.30%	80.00%	82.80%
Over all Activity of YC	39.90%	56.70%	68.30%	69.80%	72.10%
# of QC = 4	3628	2211	1906	1963	1949
Over all Activity of C-AGV	87.10%	91.90%	86.80%	66.10%	56.20%
Over all Activity of QC	44.10%	72.40%	83.90%	81.50%	82.10%
Over all Activity of YC	38.50%	63.00%	72.90%	71.10%	71.40%
# of QC = 4	3615	2397	1948	1937	2035
Over all Activity of C-AGV	83.90%	85.40%	84.10%	66.10%	51.90%
Over all Activity of QC	44.30%	66.40%	82.10%	82.60%	78.60%
Over all Activity of YC	38.60%	58.20%	77.60%	71.90%	68.60%
# of QC = 4	3612	2185	1863	2018	1960
Over all Activity of C-AGV	86.70%	89.10%	86.10%	63.60%	56.00%
Over all Activity of QC	44.30%	73.20%	85.90%	79.30%	81.60%
Over all Activity of YC	38.60%	63.80%	74.80%	69.10%	71.10%
# of QC = 4	3612	2360	1920	1944	2030
Over all Activity of C-AGV	84.50%	84.20%	83.10%	68.00%	53.40%
Over all Activity of QC	44.30%	67.80%	83.30%	82.30%	78.80%
Over all Activity of YC	38.60%	59.10%	72.70%	71.10%	68.70%
Average	3539.29	2363.57	1948.71	1973.29	1997.43
Avg. C-AGV Activity	87.19%	85.70%	83.43%	66.37%	54.49%
Avg. QC Activity	45.27%	67.90%	82.16%	81.10%	77.30%
Avg. YC Activity	39.46%	59.23%	72.47%	70.61%	69.84%

Table 8.12: Scenario 6b, Unloading, Furthest, QC= 4

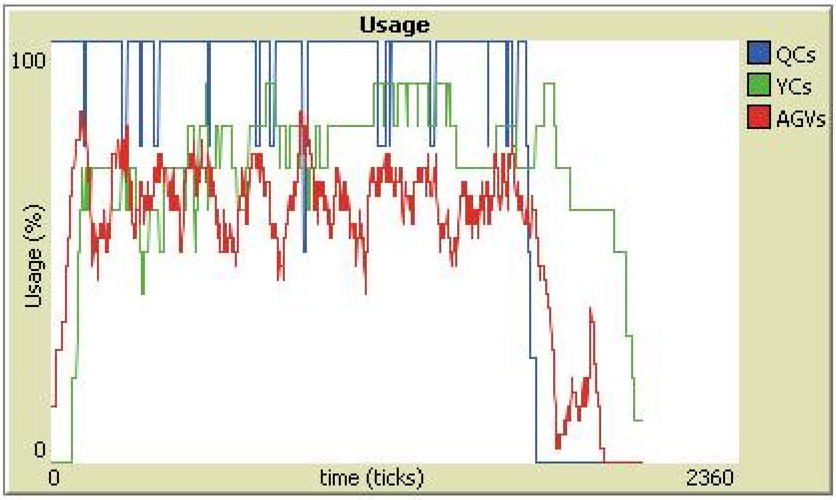


Figure 8.23: Simulation result for simulation run # 6b.66

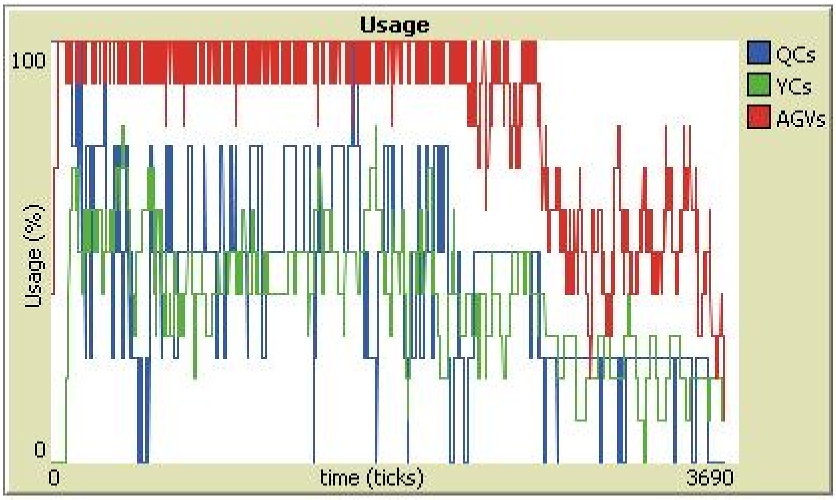


Figure 8.24: Simulation result for simulation run # 6b.70

CHAPTER 9: EXECUTIVE SUMMARY

This summary is based on data obtained from both version 1.0 and version 1.2 of the model which was used during the last review of this thesis. In most cases there should not be a significant difference in the results output by both versions. However if version 1.2 was used and the results differ significantly from those obtained from the previous version of the model, the version used will be mentioned the below the graph.

Figures 9.1, 9.2, 9.3 and 9.4 show the time it took the AGVs to complete the scenarios with the different scheduling algorithms. From these we can conclude that the choice of the scheduling algorithm is more important, the smaller the number of AGVs gets and is eventually almost negligible with a large number of AGVs and cassettes. With a sufficient large number of these, it is even possible for the normally worst scheduling algorithms “furthest” and “random” to outperform the “closest” scheduling algorithm. This can be explained by the activity statistics of the AGVs. The less efficient scheduling algorithm is compensated by the abundance of AGVs which are now simply being utilized more efficiently.

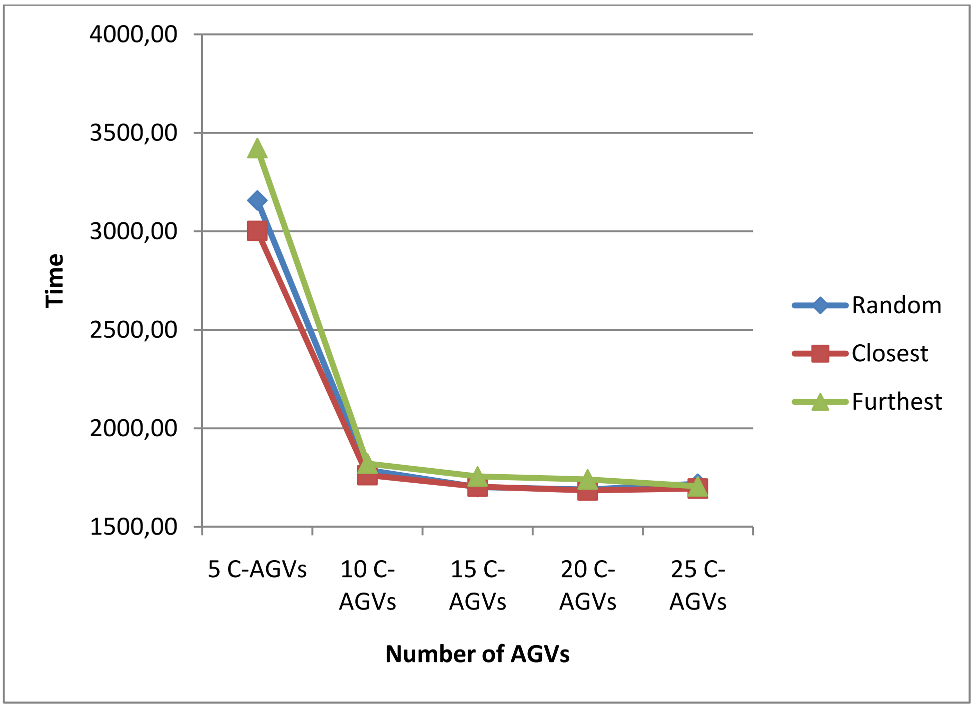


Figure 9.1: Comparison of scheduling algorithms during the loading process with 2 QCs

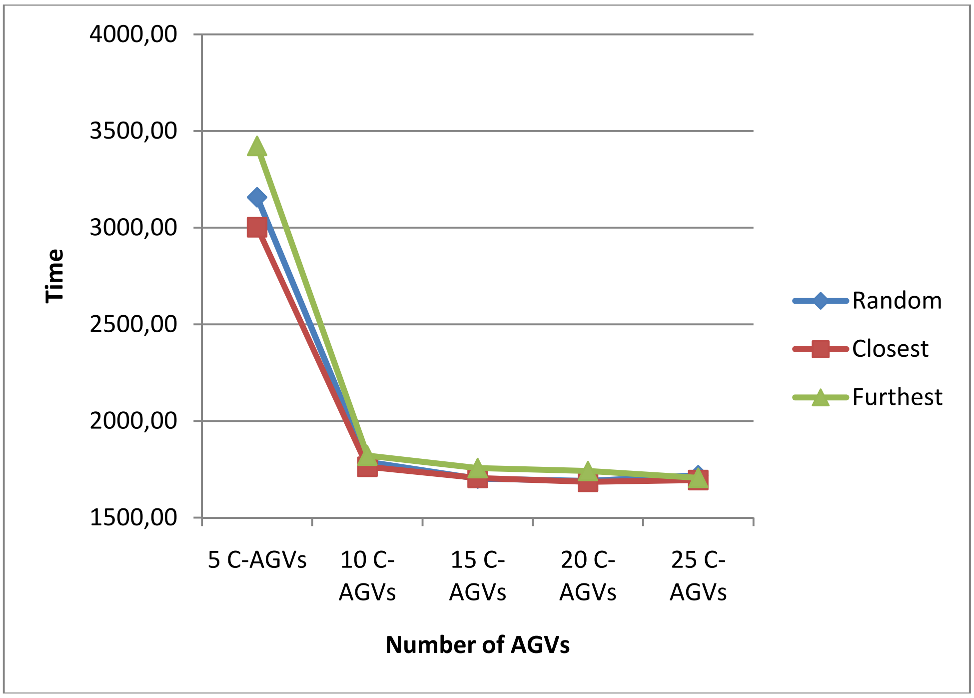


Figure 9.2: Comparison of scheduling algorithms during the loading process with 4 QCs

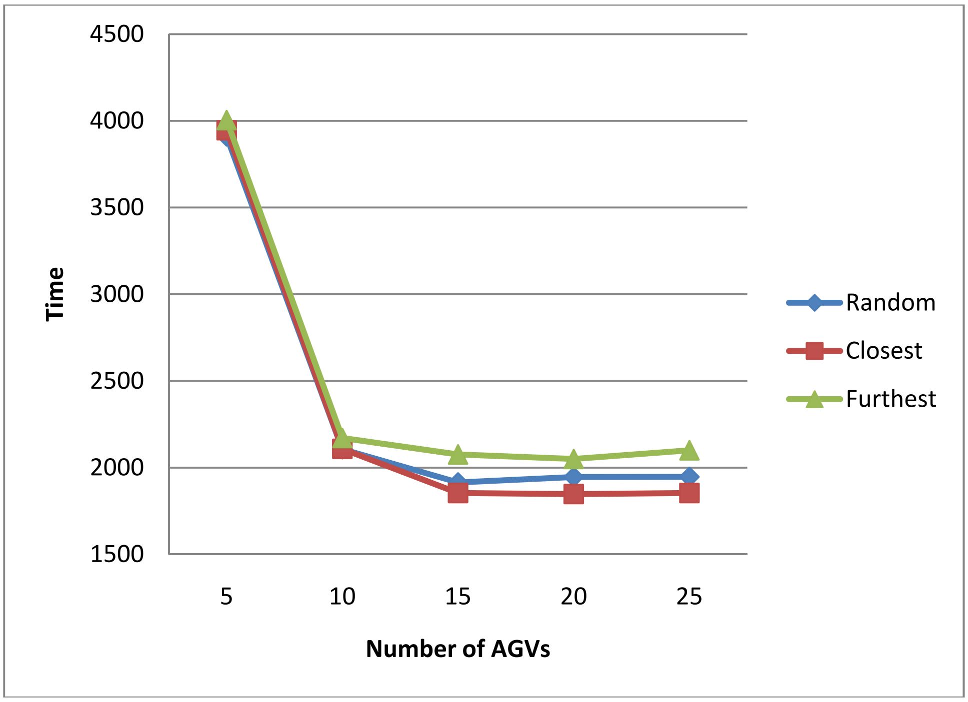


Figure 9.3: Comparison of scheduling algorithms during the Unloading process with 2 QCs[1]

[1] Graph created with data from model version 1.2.

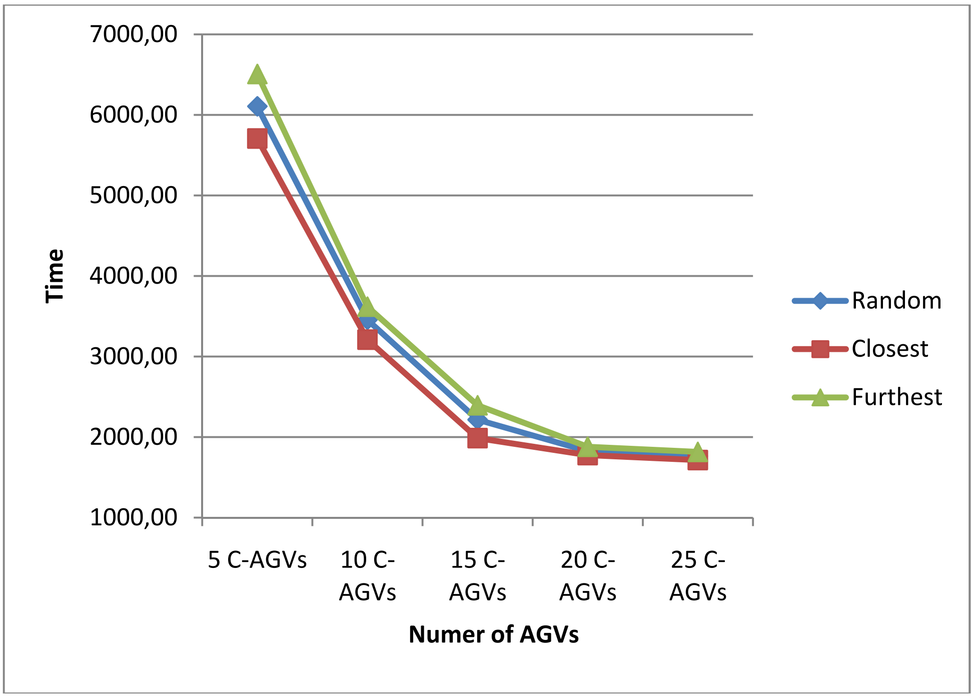


Figure 9.4: Comparison of scheduling algorithms during the Unloading process with 4 QCs

The graphs figure 9.5 and 9.6 show the time it takes to load and unload with the random scheduling algorithm and a fixed number of containers being handled by each QC. So when going from 2 QCs to 4QCs, the traffic to be handled is also doubled. This way the effect of the number of AGVs and cassettes is enlarged.

We can clearly see that while for loading the number of AGVs and cassettes remains below 10 and 24 with low traffic or 15 and 36 with high traffic density an increase in number of AGVs and cassettes has a significant increase in the time required to handle the traffic. Once beyond this point however the rate of improvement for each added AGV and cassette is significantly lower.

A similar situation can be seen during unloading: while the number of AGVs and cassettes stays below 10 and 24 with low traffic density or 15 and 36 with high traffic density there is a significantly better Return on Investment (ROR).

Figure 9.9 and 9.10 allow us to determine the optimal AGV to cassette ratio. We can see that after a certain number of cassettes, adding new cassettes does not result in a significant increase in the turnaround time of the entire process. This ratio however is different for each operation and scheduling algorithm used and also varies depending on the number of AGVs deployed.

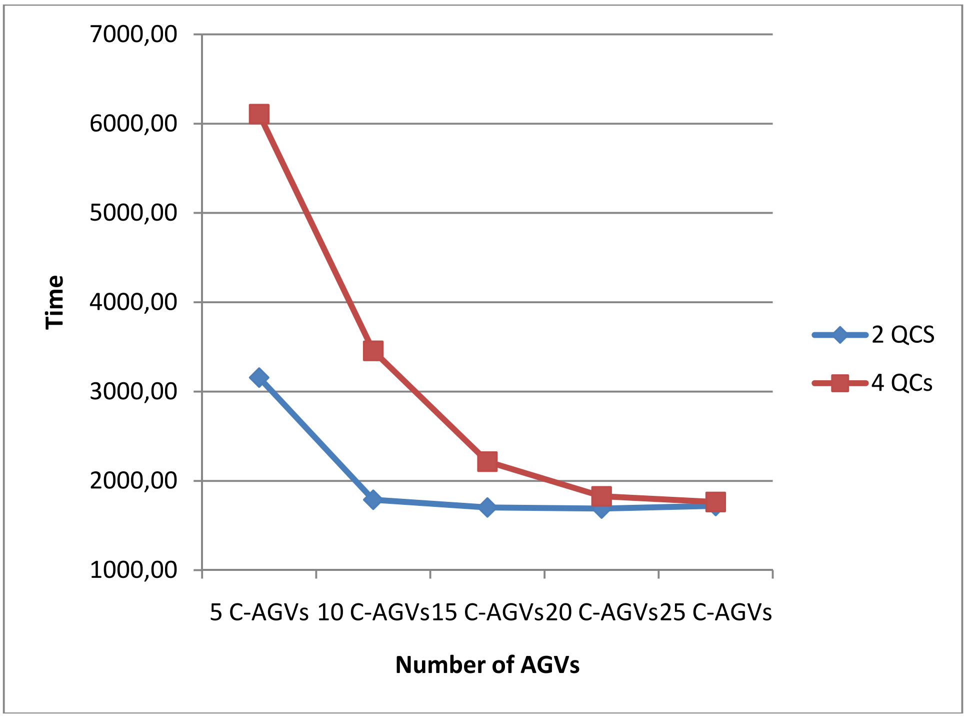


Figure 9.5: Loading process with 2QCs and 4QCs with Random Scheduling Algorithm

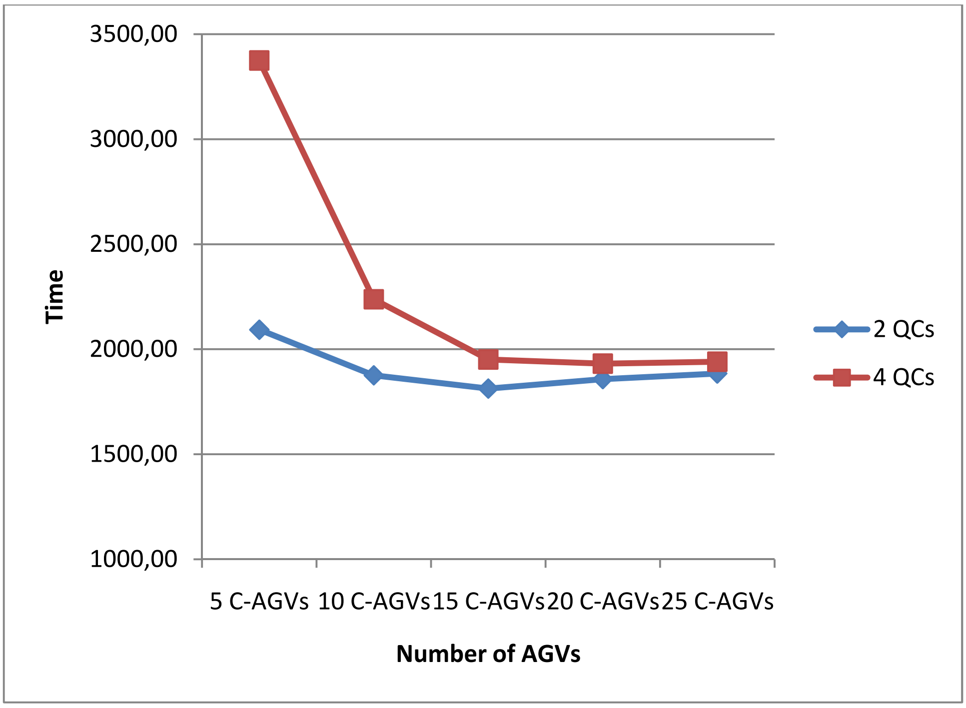


Figure 9.6: Unloading process with 2QCs and 4QCs with Random Scheduling Algorithm

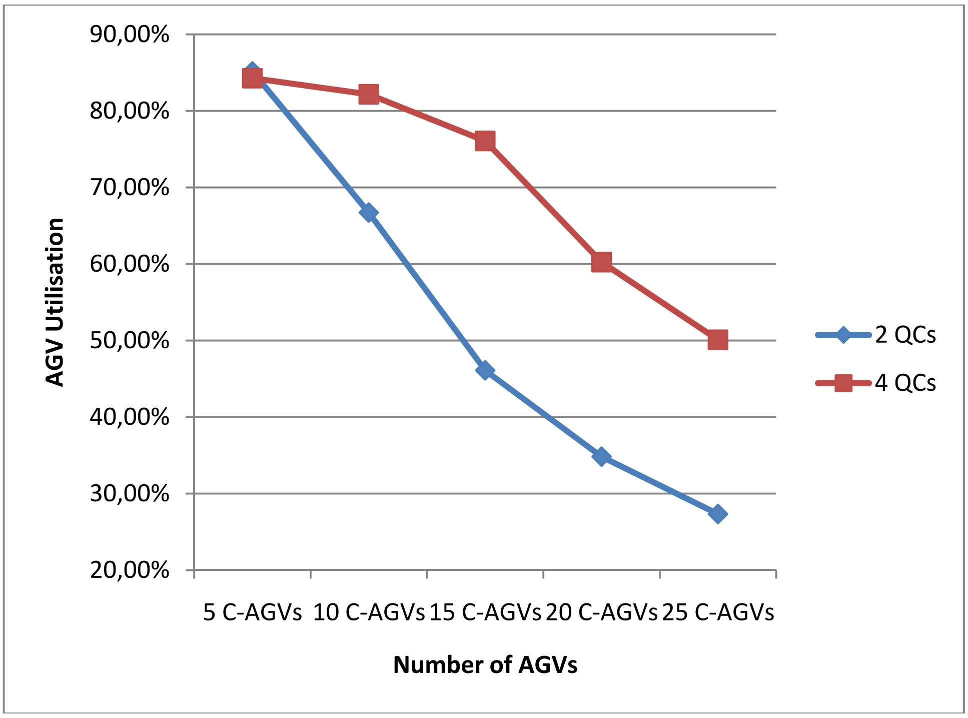


Figure 9.7: AGV utilisation during loading process with 2QCs and 4QCs with Closest Scheduling Algorithm

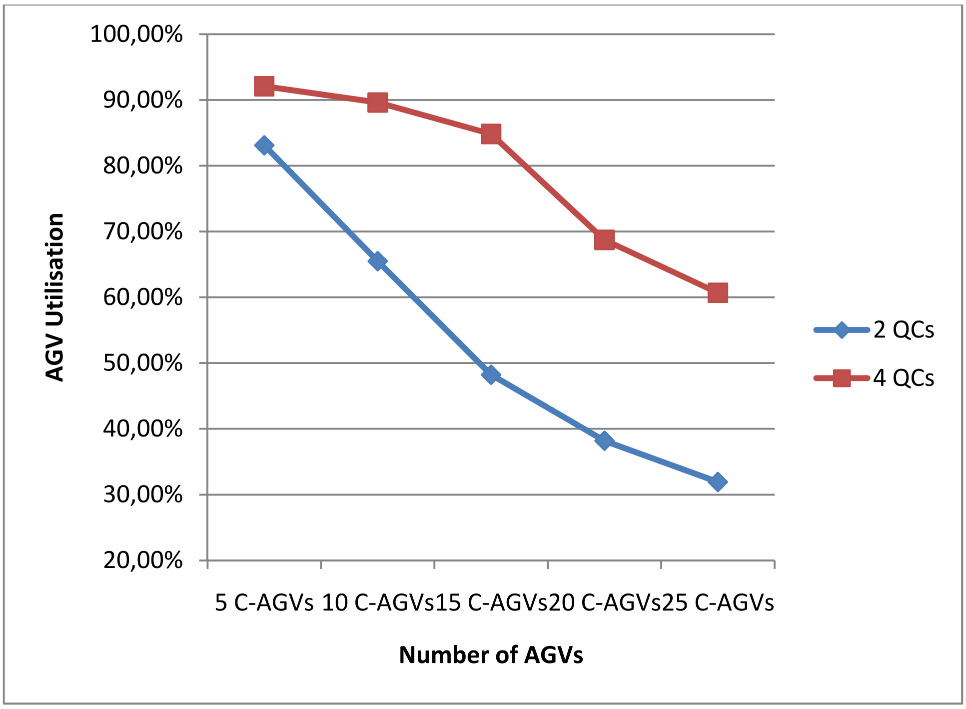


Figure 9.8: AGV utilisation during unloading process with 2QCs and 4QCs with Closest Scheduling Algorithm

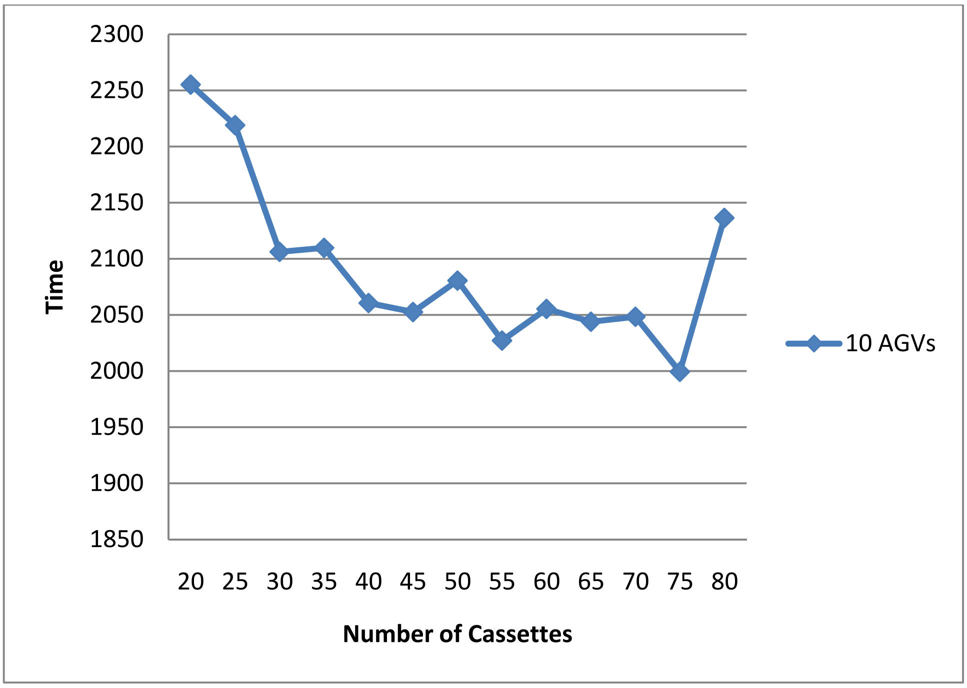


Figure 9.9: Unloading process with 2QCs, 10 AGVs, Random Scheduling Algorithm with variable cassettes[1]

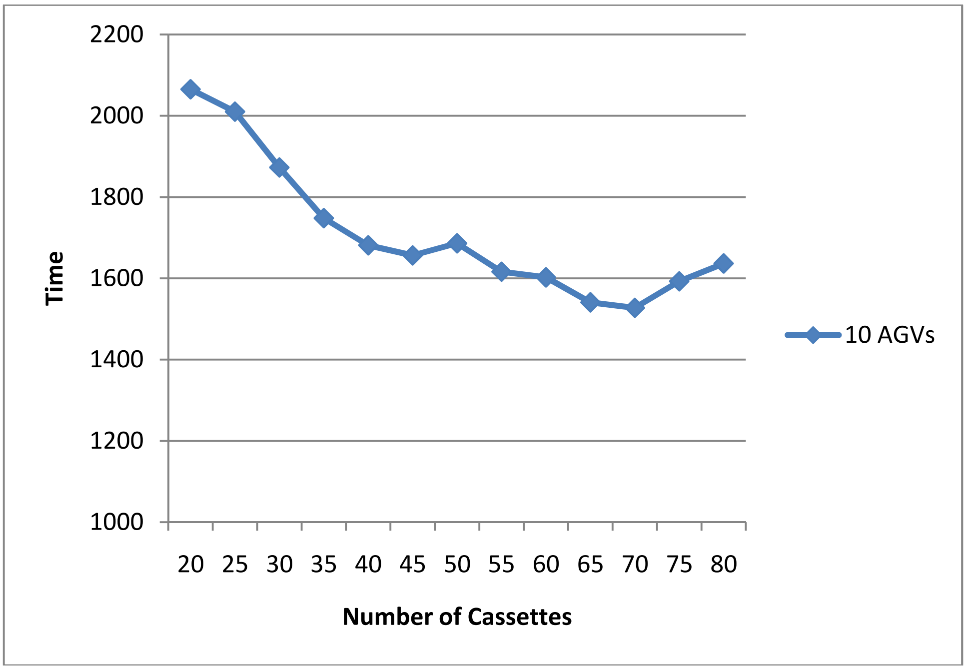


Figure 9.10: Unloading process with 4QCs, 10 AGVs, Closest Scheduling Algorithm with variable cassettes[1]

[1] Graph created with data from model version 1.2.

CHAPTER 10: DISCUSSION & ANALYSIS

10.1 Conclusion

Despite the environment related problems encountered while developing the model in NetLogo, we succeeded in developing in a working Container Terminal model. The MAS based simulation model uses agents to represent individual AGVs and thus manages to simulate a complex domain using fairly simple agents.

Overall the model performed well and we were able to locate several important trends based on the graphs of the results produced by the model. We were able to compare the different scheduling algorithms and the effect of an increase in traffic and C-AGVs and cassettes. The C-AGV utilisation was also modelled during our test runs, however indicated an identical trend as the turnaround time.

Additionally, more than 15.000 simulation runs as well as during other test runs we rarely encountered C-AGVs with a power shortage. It only occurred when using the “Furthest” scheduling algorithm, and even then it only happened in less than 0.05% of the runs. Because the AGVs are programmed to automatically divert to a recharge point when running out of power, we consider this to be an error in the simulation model, rather than a conceptual error. Overall we can conclude that the number and position of recharge points is more than sufficient. Even the special recharge modes of the C-AGVs were rarely ever used.

10.2 Points of Improvement

Due to the short time span in which the model was implemented, some things are certainly up for improvement…

The traffic management and routing system currently does not feature a collision prevention system. Instead it uses collision avoidance whenever possible. Highways are wherever possible single directional in order to prevent AGVs from having to cross each other, however on the quay and yard highways this is impossible because often a singly highway is the only way to reach a destination patch. By having AGVs use the single directional highways below the quay when possible, overlapping AGVs should be avoided as much as possible without having to fully implement a highly complex routing and collision prevention system.

The time normally required for AGVs to avoid one another is estimated to be compensated for by the slightly longer time AGVs have to travel due to the single directional highways. It should be noted however that this means the effect of traffic congestion when using a large number of AGVs cannot be monitored. One of the main technical reasons the model currently does not even attempt collision prevention is the fact that in NetLogo a turtle – in this case an AGV – can only take up a single patch, whereas in reality the AGV and cassettes are around 5 patches long and a single patch wide. This makes programming collision prevention a much more complex and time consuming task.

Another point of improvement are the scheduling algorithms. The currently implemented scheduling algorithms do not plan ahead, instead they assign AGVs to jobs as they become available. Therefore when a QC unloads a containers a AGV is only dispatched when the container is dropped into a cassette. Technically it should not be hard to add another algorithm since the routing and scheduling are completely independent.

Also up for improvement are the already implemented loading scheduling algorithms. When compiling the results graphs for the loading process with all 3 scheduling algorithms we could see a 50% greater standard deviation than during unloading. This can be explained by the increased complexity of the process: whereas during unloading the ship the only major bottleneck of the system is the quay cranes, during loading, a bottleneck exists at both the quay cranes – removing of empty cassettes – and at the yard cranes – supplying of empty cassettes.

10.3 Future work

Because of the large number of options available in the model developed here, only a small number of possible simulations has been run. The model is well suited to simulate the effect of changes in C-AGV speed, container destination distribution, capacitor capacity and crane speeds.

However to accurately validate and verify the results an actual C-AGV prototype should be used in a CT simulation to generate accurate verification values.

In addition to the points of improvement related to the model itself that are mentioned in the previous chapter there is also some work that can be done based on this module or working from this module in building a better, more accurate model. An example of this would be charting the effects of disabling container stacking or changing the AGV capacitor capacity.

It would also be interesting to look into adding a few more advanced scheduling algorithms such as a pre-emptive scheduling algorithm in which the assignment of a job to an AGV is being continuously re-evaluated.

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