Advanced Material Handling: Automated Guided Vehicles in Agile Ports

FINAL REPORT

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for the Center for Commercial Deployment of Transportation Technologies

by

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List of Abbreviations

AAS	Average Actual Speed
ACC	Average Cost per Container
AC	Automated Cart
ACT	Automated Container Terminal
AGV	Automated Guided Vehicle
AGVS	Automated Guided Vehicle System
AGV-ACT	AGV based ACT
AIT	Automatic Identification Technology
ALV	Automated Lifted Vehicle
APL	American Presidents Lines
AS/RS	Automated Storage/Retrieval System
AS/RS-ACT	AS/RS based ACT
ASC	Automated Stacking Crane
ASP	Application Specific Provider
Bps	Bit per second
Caltrans	California department of transportation
CATT	Center of Advanced Transportation Technologies
CCDoTT	Center for Commercial Deployment of Transportation Technologies
CD	Compact Disk
CSULB	California State University at Long Beach
CT-control	Central Traffic Control
DGPS	Differential Global Positioning System
DoD	U.S. Department of Defense
DRMG	Doppel Rail Mounted Gantry Crane
DS	Direct Sequence
DT-control	Distributed Traffic Control
EC	European Commission
ECT	Europe Combined Terminal
EDI	Electronic Data Interchange
EDIFACT	Electronic Data Interchange For Administration, Commerce and Transport
FC	Fixed Cost
FCC	Federal Communications Commission
FCFP	First Come First Pass
FEU	Forty-foot Equivalent Unit
FH	Frequency Hopping
FIFO	First In First Out
FNS	FROG Navigation System
FROG	Free Ranging On Grid
FT	Foot (feet)
FY	Fiscal Year
GHz	Giga Hertz
GPS	Global Positioning System
GR	Grid Rail
GRAIL	Grid RAIL
GR-ACT	GR based ACT
HHLA	Hafen-und Lagerhaus AG
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Standards Organization
IT	Information Technology
ITV	Internal Truck Vehicle
JIT	Just In Time
K	Kilo (1,000)

KIPD	Kaoshiung International Port Development Project
Km/h	Kilometer per hour
KWHR	Kilo Watt HouR
LAN	Local Area Network
LEO	Low Earth Orbit
LMCS	Linear Motor Conveyance System
LMCS-ACT	LMCS based ACT
MFCFP	Modified First Come First Pass
Hz	Hertz
MARAD	MARitime ADministration
MHz	Mega Hertz
MIV	Mobile Inventory Vehicle
MMWR	MilliMeter Wave Rader
MPH	Miles Per Hour
MV	Moving Vehicle
NIT	Norfolk International Terminal
OMC	Optical Memory Card
P/D	Pick up and Delivery point
PATH	Partners for Advanced Transit and Highways
PSA	Port of Singapore Authority
QC	Quay Crane
RF	Radio Frequency
RFDC	Radio Frequency Data Communication
RFID	Radio Frequency Identification
RO/RO	Roll on/Roll off
Sec	Second
SRM	Storage and Retrieval Machine
TC	Total Cost
TEU	Twenty-foot Equivalent Unit
TrAMS	Transportation Automation Measurement System
USC	University of Southern California
USTRANSCOM	United States TRANSportation COMmand
VC	Variable Cost
VLSI	Very Large Scale Integrated circuit

ES.0 EXECUTIVE SUMMARY

This report describes the work performed by the Center of Advanced Transportation Technologies (CATT) at the University of Southern California (USC) for the Center for Commercial Deployment of Transportation Technologies (CCDoTT) at the California State University at Long Beach (CSULB). The report presents the results developed for Task 1.2.6.1 entitled “Advanced Material Handling: Automated Guided Vehicles” for the project entitled “USTRANSCOM/MARAD/CCDoTT: *Agile Port*”.

The work is performed in collaboration with August Design, Inc. whose support of this task was in kind. The work and some of the results developed under this task were discussed with several terminal operators and their comments and suggestions are incorporated accordingly.

The main objective of Task 1.2.6.1 is to research the use of Automated Guided Vehicles (AGVs) and automation in general in improving terminal capacity and efficiency in the context of the agile port concept. In particular, several automated container terminal concepts that employ AGVs are developed and evaluated using a computer performance and cost model. The most promising concepts are compared with other competitive concepts that include the Grid RAIL (GRAIL) and Automated Storage/Retrieval System (AS/RS).

Based on future projections made by several ports, regarding container volume and the use of larger ships to be served at terminals as fast as possible, we came up with design characteristics an Automated Container Terminal (ACT) needs to have in order to meet the projected demand. A general layout of the ACT was developed where the interfaces of the storage yard with the ship, inland trucks and trains as well as the desired storage capacity of the yard are specified in order to meet the projected demand. The layout is such that different concepts regarding the storage yard and the way containers are moved between the storage yard and the ship/truck/train buffers can be considered without major changes to the configuration of the ACT.

The following four ACT concepts are considered and evaluated in this project.

1. **The AGV based ACT (AGV-ACT).** In this concept the terminal configuration is similar to that of conventional terminals but instead of using manually operated equipment we use AGVs to transfer containers within the yard and automated cranes for loading and unloading.
2. **A Linear Motor Conveyance System (LMCS) based ACT (LMCS-ACT).** This terminal is the same as the AGV-ACT one with the exception that instead of the AGVs, automated shuttles driven by linear motors are used to transfer containers within the terminal. The shuttles play the role of AGVs but unlike AGVs, their path is fixed by the guide ways of the LMCS system.
3. **An overhead Grid Rail (GR) based ACT (GR-ACT).** This system is obtained by replacing the storage yard in the general layout of the ACT with a

number of GR units in order to achieve the desired storage capacity considered to be about the same for all concepts. A GR unit or module consists of an overhead rail system with shuttles that travel over stacks of tightly packed containers in the yard, retrieve them and carry them to the GR unit buffers or carry them from the GR buffers to locations in the yard. The GR concept was researched in more detail in Task 1.2.6.2 where the operations within the GR units were optimized. AGVs are used to transfer containers between the GR buffers and the ship/truck/train interface buffer in a similar manner as in the AGV-ACT system.

4. **The AS/RS based ACT (AS/RS-ACT).** The GR units in the GR-ACT system are replaced by an AS/RS storage system that provides the same storage capacity. As in the GR-ACT system, AGVs are used to transfer containers between the AS/RS buffers and the ship/truck/train interface buffers the same way as in the GR-ACT system. The AS/RS container storage system was designed and its operations optimized under a project funded by METRANS [52].

The number of AGVs (shuttles in the case of the LMCS-ACT system) and loading unloading equipment is optimized so that the expected demand can be met with the least amount of equipment.

A microscopic simulation model that models the proposed ACT systems, (validated using data from a conventional terminal), is developed and used to simulate the ACT systems for the same operational scenario in order to evaluate, and compare their performance. A cost model is also developed to calculate the average cost per container, a measure used in the industry to assess cost effectiveness.

The following performance criteria are used to assess performance and compare different systems.

- Throughput (moves per hour per quay crane)
- Throughput per acre
- Annual Throughput per acre (no. of processed TEUs per acre per year)
- Ship turn-around time
- Truck turn-around time
- Gate utilization
- Container dwell time
- Idle rate of equipment

The proposed ACT systems are designed to handle 2,482,000 TEUs per year and serve one ship every 24 hours. The ship has to be unloaded/loaded with 3,400, 40-foot containers (6,800 TEUs) in less than 24 hours (desired about 16 hours) so that the next ship can come in. The container arrival and departure rates for trucks and trains are characterized appropriately so that a complete hypothetical operational scenario is defined that is repeated every 24 hours. This hypothetical scenario is based on future projections made by various ports regarding container volume, size of ships, etc. and is used to simulate and evaluate the proposed ACT systems. The performance results for a

24-hour simulation for each ACT system are used together with cost data to feed the cost model and calculate the average cost per container for each ACT system. The performance and cost results are summarized in Table 0.1.

Table 0.1: Performance and Cost Results for Different Concepts

	AGV-ACT	LMCS-ACT	GR-ACT	AS/RS-ACT
Ship turnaround time [hours]	16.81	16.83	16.47	16.24
Throughput, while the ship is at berth [moves/quay crane/hour]	40.45	40.40	41.68	41.7
Throughput per acre, while the ship is at berth [moves/quay crane/acre/hour]	0.579	0.575	0.652	0.767
Annual Throughput per acre [TEUs/acre/year]	35,310	35,310	39,173	45,583
Gate utilization	65.7%	66.03%	65.7%	66.4%
Truck turnaround time [seconds] (does not include processing time at the gate)	127	127	120	110.75
Throughput (train crane) [moves/hour/crane]	29.4	29.4	28.6	30.6
Throughput (buffer crane) [moves/hour/crane]	33.7	33.7	35.7	38.32
Idle rate of AGVs over 24 hours	36.3%	36.2%	31.81%	30.9%
Idle rate of gate buffer cranes over 24 hours	12.7%	12.7%	10.8%	6.8%
Idle rate of train cranes over 24 hours	23.0%	23.0%	31.9%	27.86%
Idle rate of quay cranes over 24 hours	31.7%	31.8%	31.8%	32.33%
Container dwell time [hours]	19.1	19.1	19	18.9
Average cost per container (U.S. $)	77.0	147.4	89.7	102.0

Since the amount of equipment and number of vehicles in each ACT system are optimized based on the same expected demand, it is not surprising that the performance for each ACT system is almost identical for all measures with the exception of the throughput per acre. The highest throughput per acre was obtained for the AS/RS-ACT system since it requires less land to be implemented for the same storage capacity. Next comes the GR-ACT system, which also requires less land for the same storage capacity. All the ACT systems operated close to the maximum possible capacity of the quay cranes, which was assumed to be 42 moves per hour per crane for combined loading/unloading. This is much higher than the average of about 28 moves per hour measured in many of today's conventional terminals. The simulation model when exercised for a conventional terminal of similar layout as the ACT and with characteristics of equipment and operations based on measured data, generated a throughput of about 27 moves per hour per quay crane, which is very close to the value of 28 that was measured in the terminal.

The significant difference between the various systems is the average cost per container. The LMCS-ACT was found to be the most expensive due to the high infrastructure cost associated with the LMCS. The second most expensive system is the AS/RS-ACT, due to the infrastructure cost of the AS/RS structure. The AGV-ACT system was found to be the most cost effective followed by the GR-ACT. The cost model was exercised for a hypothetical conventional terminal that has a performance similar to what is observed in most of today's terminals. The average cost per container generated was $143.7, which is within the range ($130-$200) of costs reported in the literature for similar terminals.

The cost analysis was based on several assumptions regarding cost of equipment, land, labor, etc. Most of these numbers were provided by professionals based on existing or very similar systems and are quite accurate. Others were estimates by the same professionals and their accuracy could be questioned where it involves equipment or systems that have not yet been built and no detailed design is available. A sensitivity analysis is performed in order to calculate how the Average Cost per Container (ACC) varies with variations in the cost data assumed. This sensitivity analysis with respect to the land cost led us to the following conclusions:

- The LMCS-ACT system continues to have the highest ACC value independent of the cost of land.
- The AGV-ACT system has the lowest ACC value when the cost of land is less than about $12 million per acre. Above $12 million per acre, the AS/RS-ACT system becomes the one with the lowest ACC value followed by the AGV-ACT and GR-ACT systems. For a land cost greater than $13.5 million per acre the AS/RS-ACT continues to have the lowest ACC, followed by the GR-ACT and the AGV-ACT system.

The ACT systems designed and evaluated in this project could be modified and improved further. The AGV-ACT and GR-ACT systems appear to have the strongest potential for a successful implementation depending on the land cost. The LMCS-ACT system could become equally competitive if the cost of the infrastructure is reduced. The AS/RS-ACT system is attractive when the land cost is fairly high as indicated above.

In addition to the four ACT systems discussed above, a concept that is applicable to wheeled operations especially in areas with limited infrastructure is proposed, simulated and evaluated. The concept is based on automatic guidance of manually driven vehicles coming off the ship or entering the yard from the gate using low cost automated carts to lead and guide the vehicles to assigned spots in the yard. This concept can be proven useful during military operations in under-developed ports as well as during adverse conditions where visibility is limited.

1. INTRODUCTION

The elimination of international trade barriers, lower tariffs and shifting centers of global manufacturing and consumption leads to new dynamics in intermodal shipping. Worldwide container trade is growing at a 9.5% annual rate, and the U.S. rate is around 6%. It is anticipated that the growth in containerized trade will continue as more and more cargo is transferred from break-bulk to containers [34]. By 2010, it is expected that 90 percent of all liner freight will be shipped in containers [27]. Every major port is expected to double and possibly triple its cargo by 2020. To handle this amount of freight and reduce the cost per 'Twenty-foot Equivalent Unit" (TEU) slot, shipping companies are forced to order faster, larger and deeper ships. New massive container ships on one hand, and scarcity of the yard land on the other hand, put an enormous pressure on port authorities to find and deploy effective container handling systems in order to increase the throughput of the current container terminals. At the same time, it is expected that the trend in the growth of the number of export/import containers from/to a container terminal will continue.

High-density, automated container terminals are potential candidates for improving the performance of container terminals and meeting the challenges of the future in marine transportation. Recent advances in electronics, sensors, information technologies and automation make the development of fully automated terminals technically feasible. Europe and other countries are ahead of the U.S. in using automation to improve their terminal operations. The Port of Rotterdam is operating a fully automated terminal using Automated Guided Vehicles (AGVs) and automated yard cranes to handle containers, whereas the Port of Singapore, Thamesport of England, and the Port of Hamburg [26] are experimenting with similar ideas. Sea-Land at the Port of Hong Kong implemented a grid rail system referred to as the GRAIL designed by Sea-Land/August Design, Inc., a high-density manually operated terminal. In the U.S. the labor unions strongly oppose any type of automation that is viewed as threat to current jobs, making it difficult, if at all possible, for terminals to advance in this area at the same speed as the European and other overseas counterparts. It is envisioned that competition in the global market will begin to put pressure on all sides involved to cooperate in order to improve productivity and reduce cost through the use of advanced technologies and automation.

In this report, we address the design, modeling, simulation and evaluation of several automated container terminals. These include an Automated Container Terminal (ACT) that employs Automated Guided Vehicles (AGVs) and an ACT with a Linear Motor Conveyance System (LMCS). The ACT is an extension of the design studied in FY97 work [26] to include the gate and train interfaces. The configuration of ACT is such that the storage area could be replaced with storage modules based on different concepts leaving the interfaces the same. This allows the comparison of different concepts for the same operational scenario. A concept based on an overhead Grid Rail (GR) system and one based on an Automated Storage/Retrieval System (AS/RS) are also considered and compared with the AGV based ACT (AGV-ACT) and LMCS based ACT (LMCS-ACT) systems. Each ACT system is designed to meet the same demand based on future projections made by several ports on the expected size of ships and container volumes. A model is developed that is used to simulate all the operations of the ACT down to the finest detail of the characteristics of each piece of equipment. The model is exercised for each ACT system based on the same operational scenario, i.e. based on the same incoming and outgoing traffic of containers at the interfaces. Performance criteria that include throughput in moves per hour per quay crane, throughput per acre, ship turn-around time, truck turn-around time, container dwell time and idle rate of equipment are used to evaluate each system and make comparisons. A cost model is developed and used to calculate the average cost for moving a container through the ACT. The performance and cost criteria are used to compare the pros and cons of each ACT system and make recommendations.

In addition to the ACT concepts discussed above, a concept that is applicable to wheeled operations (especially in areas with limited infrastructure) is proposed, simulated and evaluated. The concept is based on automatic guidance of manually driven vehicles coming off the ship or entering the yard from the gate using automated carts to lead and guide these vehicles to assigned parking spots in the yard. This concept can be proven useful during military operations in under-developed ports as well as during adverse conditions where visibility is limited.

The report is organized as follows: Section 2 reviews the state of art in AGVs. Emerging hardware and software technologies with emphasis on information technologies that are applicable to port operations are reviewed in section 3. Section 4 presents the general layout of the proposed Automated Container Terminal (ACT), and calculates the amount of equipment and desired characteristics necessary to meet a projected volume of container traffic. Section 5 presents the cost and performance criteria and simulation and cost models that are used to evaluate different ACT systems. Sections 6 to 9 present the design, analysis and simulation of the proposed AGV-ACT, LMCS-ACT, GR-ACT and AS/RS-ACT systems respectively. In section 10, a new concept for leading and guiding manually driven vehicles using Automated Carts (ACs) in wheeled-operated ports is introduced. In section 11, we summarize the performance and cost results and compare and evaluate the proposed ACT systems.

2. REVIEW OF THE STATE-OF-THE-ART IN AGVS

In this section, we review the state of the art in research, design and implementation of Automated Guided Vehicles (AGVs) for port applications.

2.1 Automated Guided Vehicles (AGVs)

An automated guided vehicle (AGV) is a vehicle that is driven by an automatic control system that serves the role of the driver. Sensors on the road or infrastructure and onboard the vehicle provide measurements about the location and speed of the vehicle which are used by the automatic control system to generate the appropriate commands for the throttle/brake actuators in order to follow certain position and speed trajectories. AGVs are considered to be the most flexible type of material handling system. Their size ranges from small load carriers of a few kilograms to over 125-ton transporters. The vehicles' working environment ranges from small offices with carpet floor to huge harbor dockside areas [43].

The AGV system consists of the vehicle, onboard controller, management system, communication system, and navigation system.

The ***onboard controller*** is responsible for initiating start-up and shutdown procedures. It manages the propulsion, steering, braking, and other functions of the vehicle. It also monitors and detects any error and issues the necessary commands for error correction.

The ***management system*** deals with planning, scheduling, and traffic control. It is responsible for optimizing the vehicle utilization, giving transport orders such as dispatching and routing, and tracking the material in the manufacturing environment.

The ***communication system*** is used to transmit data from the AGV to a central controller and vise versa. This information consists of the position and the status of the vehicle, the position of currently assigned job(s), and possibly the position of the next scheduled job(s).

The ***navigation system*** provides guidance and navigation to the AGV in the operating environment. The guidance and navigation could be based on a fixed path or free path approach [41].

In the ***fixed path approach***, the AGV is restricted to follow a fixed path and there is no flexibility to change the guide-path. Examples of fixed path include rail tracks, embedded wires or other type of guide-ways (see Figure 2.1).

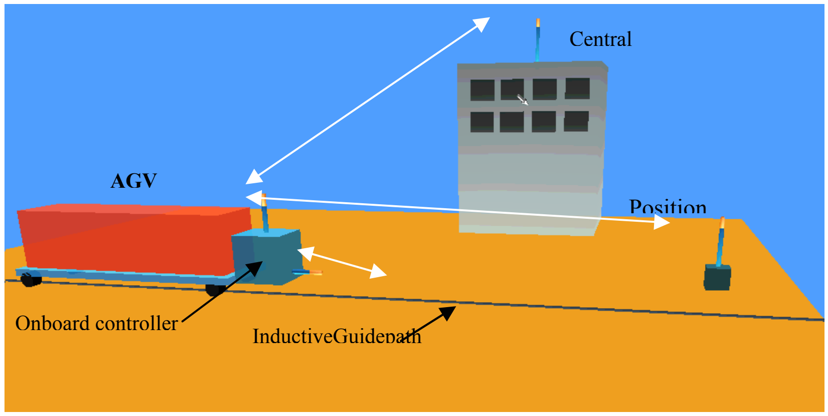

Figure 2.1: Sketch of a basic AGV system using a fixed path method

In the ***free path method***, the path of the AGV can be changed dynamically. The system is autonomous and is capable of detecting the path using online information, obstacle detection and collision avoidance systems.

AGVs have been in use since the 1950's. A U.S. company, the Cravens Company at Mercury Motor Express in Columbia, S.C., installed the first AGV in 1954. However, the use of AGVs did not take off in the U.S. By the early 80's, the entire investment by U.S. firms in AGVs was less than $70 Million. Meanwhile, several European companies grabbed hold of the idea and rapidly evolved it [2].

In 1986, the California Department of Transportation (Caltrans) initiated a large program at PATH (Partners for Advanced Transit and Highways) to support research in automated vehicles and automated highways [51]. The activities at PATH were later increased to nationwide programs on automated highway systems supported by the Federal Highway Administration. A demonstration that took place on I-15 north of San Diego in August of 1997 involved platoons of fully automated vehicles guided at speeds of 65 mph and at distances a few meters from each other [51]. Similar demonstrations took place in Europe and Japan. Currently PATH and Caltrans are planning Demo 2002 where full automation of trucks on a highway will be demonstrated. The research on vehicle and highway automation led to the development and testing of a wide range of sensor technologies. These include embedded magnetic ‘nails’ in the middle of the lane to provide a reference as to the location of the vehicle relative to the lane by sensing the magnetic field of the nails using magnetometers on board of the vehicle. Low cost radar sensors are developed for providing measurements of relative speed and distance between the vehicle and any obstacle or other vehicle ahead. Similarly, vehicle-to-vehicle communications and Differential GPS (DGPS) systems have also been tested successfully as sensors for providing the appropriate measurements for the automatic guidance of the vehicle at high speeds and with great accuracy [51], [55].

In container terminals, AGVs could be used to replace the manually driven trucks that transport containers within the terminal. In this application, AGVs are automated industrial trucks, which could be powered by electric motors and batteries or by the conventional diesel engine. Modern AGVs can be equipped with robot arms and grippers and perform robotic handling functions. AGVs could also be used as storage machines equipped with forks, handling loads in storage racks up to 10 meters in height or more.

While the automation of vehicles and trucks on highways does not have strong support of manufacturers due to liability issues and the complexity of the environment in which they have to operate, the use of automated trucks at low speeds in a restricted environment such as a terminal is a completely different story. The low speed characteristics of AGVs together with the restricted area they have to operate in makes the overall problem much simpler to solve. Therefore, the use of AGVs as container handling devices in terminals is feasible from the point of view of technology and has a strong potential to improve efficiency and reduce labor cost.

2.2 Port Applications of Automated Guided Vehicles (AGVs)

Due largely to the repetitive nature of movements within the terminals, AGVs are very well suited to be deployed for terminal operations. The promise of deploying AGVs in container terminals lies in their capability of achieving the following benefits: [54]

- High container throughput
- Continuous operation: 24 hours a day, 365 days a year
- High controllability and reliability
- High safety standards
- Automated and consistent container handling operation
- Reduced operational costs, especially labor costs
- High position and heading accuracy

AGVs are making initial inroads for port applications in many parts of the world. Current commercial applications of AGV technology include systems at the Ports of Rotterdam, Singapore, Thamesport, Kawasaki, and Kaoshiung. The next three subsections review the application of AGV technology in several terminals.

2.2.1 Delta Port at Rotterdam

The Delta Port terminal also referred to as Delta/Sea-Land terminal, at Rotterdam uses AGVs to transport containers from the stacked storage area (served by fully automated rail-mounted gantry cranes) to the apron. The terminal is a 500,000-container-lift-a-year facility. It is one of the most technologically advanced terminals in existence [39]. It operates around the clock, 363 days a year, and is located on Rotterdam's Maasvlakte peninsula close to the North Sea adjacent to the mouth of the Maas River. Europe Combined Terminals (ECT) developed it in collaboration with Siemens, Nelcon and FROG Navigation Systems (FNS). Figure 2.2 shows part of the terminal with the AGVs.

Figure 2.2: The Delta Port Container Terminal at Rotterdam

A central control system instructs the AGVs where to go for each new task. The AGVs, built by Gottwald of Germany, run on a diesel hydraulic driveline. Each AGV weighs 14 tons and is capable of carrying up to 40-ton loads (see Figure 2.3). Initially there were about 58 AGVs at the terminal; recently their number was increased to 150 [4]. They move noiselessly along at 6.8 mph, guided by transponders located beneath the pavement at about 6.46 ft intervals. An on-board computer instructs the AGV as to its movements and also monitors maintenance parameters. For servicing, the AGVs are designed so that they can be lifted by straddle carrier and taken directly to a repair shop at the terminal. The 25 Automated Stacking Cranes (ASCs) travel at 9.3 mph and can create a stack of containers 42 long, 6 abreast and 2 high.

Free Ranging On Grid (FROG) Systems of the Netherlands designed the navigation system, which utilizes fiber optic line grids and transponders located throughout the facility for position update information. Between transponders, the vehicles use their onboard inertial navigation system [39]. While the original facility had some bugs, the company is satisfied with the facilities and plans to continue building automated terminals [19].

Figure 2.3: The Delta Port AGV

The main reasons for deploying AGVs in the Delta Port were to reduce labor cost and achieve round the clock improved productivity [4]. According to Rose Wiggers, a spokeswoman for ECT, automation has cut the terminal's labor costs by about 25% [19].

2.2.2 Port of Singapore Authority (PSA)

In order to overcome the growing shortage of skilled labor and improve productivity the Port of Singapore Authority (PSA) is considering the design of the most significant automated terminal system. PSA plans to operate hundreds of AGVs under a sophisticated traffic management scheduled for container movements. A contract for 5 prototype AGVs (see Figure 2.4) was awarded to Kamag of Germany and Mitsui of Japan. Tadiran of Israel was selected to provide the sophisticated navigation system for the test units [39]. The vehicles were designed to be able to accelerate from 0 to 5 mph in under 10 seconds, with the top speed of 15.5 mph – loaded or unloaded [16]. They can accept either 20- or 40-foot containers with 50 tons maximum payload and can operate independent of the weather conditions. The pilot AGV system started in the late 1994 at Brani Terminal and was completed in 1997.

In May 1998, PSA signed another agreement for the phase II program to develop and test AGV systems for container terminal operations. The completion date for phase II is scheduled for 2002. It is expected that with the use of AGVs each berth will be able to handle 25% or more containers that the PSA currently handles.

Figure 2.4: Port of Singapore prototype AGV

2.2.3 Other Ports

Thamesport of England: Another example of a successful, AGV deployment took place in 1992 at the Thamesport intermodal port facility in England. Thamesport is a green-field container terminal in Southeast England, and is thought to be the world's first fully Automated Container Terminal (ACT). Thamesport uses fully automated yard-stacking equipment (gantry cranes), and had been testing prototype AGVs, built by Terberg Benschop of The Netherlands, for 4 years. The AGVs used MilliMeter Wave Radar (MMWR) for navigation and operated in conjunction with manned vehicles carrying containers from ship to stack. Initially, the navigation system encountered problems due to the high level of clutter within the container environment. While modifications to the control hardware and software resolved the problems, Thamesport removed the AGVs due to lack of funding. While there were no reported incidents, there was concern expressed about vehicle safety throughout the test. Terberg representatives expressed the belief that quantifying operational safety would become a requirement in the future as terminals deploy more automated systems [39].

Port of Hamburg of Germany: In October 1997, the city of Hamburg granted Hamburger Hafen-und Lagerhaus AG (HHLA) the right to operate the Altenwerder container terminal. Since 1998, the HHLA has been considering different scenarios to increase productivity, improve quality (less berthing time for ships and easier planning), and reduce operational cost through establishing automated handling technology. HHLA initially has considered using linear motor technology in the terminal, but they changed their decision and developed the so-called DRMG system in April 1999. In this system, AGVs are used to transfer containers between remotely controlled mobile cranes in the marshalling area and the berth area. Containers are directly transferred to in-land trucks by automated mobile cranes, and to railcars by in-yard trucks and chassis [3].

Port of Kawasaki of Japan: The Port of Kawasaki has bought AGV test units from Mitsui of Japan, and one test unit from a German firm, Schueulre of Germany, for its NKK terminal. The final plan is to build a totally automated terminal at Kawasaki using an AGV system [14].

Port of Kaoshiung of Taiwan: The Port of Kaoshiung also has a commitment to automate for expected future growth. In the final report from the Kaoshiung International Port Development Project (KIPD), it is recommended that the Number 5 terminal be completely automated for the purpose of container handling. It is known that the Port of Kaoshiung has various automated technologies under review, although details are currently scarce [26].

2.3 Research Developments in AGVs Applicable to Marine Ports

Although the concept of AGV systems was introduced a few decades ago, the use of AGVs for port applications has just begun. AGVs are a proven technology, but it is not mature enough to the point it can justify its widespread use in marine transportation. As the type, quality and quantity of demands in container terminals are changing, more developments at different levels of the system (communication, navigation, and control) need to be explored. In this part, we investigate recent developments in AGVs that are relevant to their use in port applications.

Management System: The key issue in an AGV operation lies in its management system, in which the traffic control is the fundamental part. There are two types of traffic control: ***central traffic control*** (CT-control) and ***distributed traffic control*** (DT-control).

CT-control refers to the system where all the movements in the port are directly controlled and guided by a central traffic controller. This method has been used in ECT's Delta Port terminal in Rotterdam.

In DT-control, AGVs, and possibly a number of (critical) areas, are endowed with a form of intelligence to make decisions about movements and conflict resolution. In this concept, the communications with the AGVs are reduced to incidental instructions and overall control is reduced to overall coordination [21].

It is worth mentioning that as the number of AGVs increases in the terminal, the amount of information to be passed and processed by the central controller in the case of CT-control also increases. If this information contains voice and image data obtained by the equipment in the yard, the transmission time of data and computation time for monitoring and controlling all equipment increases abruptly. In such case instead of the CT-control approach the CD-control approach may be more desirable. In such case, the use of intelligence on each AGV, for the purpose of control and guidance, reduces the burden on the central controller.

Container Handling: In many container terminals, the on-yard vehicles have to wait for a period of time before being served by a yard crane or straddle carrier. To reduce this amount of time, one may think of developing a type of on-yard vehicles that can load and unload the containers by themselves, without waiting for the yard cranes. This type of vehicle will be ideal for container terminals with at most two-container high stacks.

This is the main idea behind the August Design's robotic arm built for on-yard vehicles. The concept can be easily extended to AGV technology [45]. In this case, AGVs can be equipped with robotic arms and grippers to perform handling functions. Instead of using yard cranes and/or straddle carriers, AGVs will load or unload the containers by themselves. For instance during the loading operation, an AGV stops by a container in the yard, it grabs the container (which is now located just beside the AGV) with its robotic arm, and pulls and loads the container onto itself. The unloading operation will be similar.

In a similar idea, TRAIL research group from the Delft University in Netherlands proposed Automated Lifted Vehicles (ALV). ALV, as shown in Figure 2.5, is an automated guided vehicle equipped with special facilities to pick up and hold a container without using a crane [50], [58].

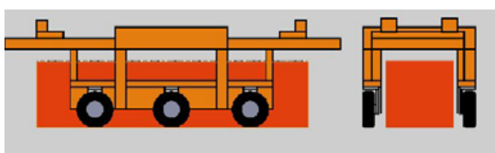

Figure 2.5: Automated Lifted Vehicle

Wheeled Operation: An automated hustler, which can carry chassis within a container terminal, is another technology that can be used in wheeled-operated terminals. An existing tractor can be modified easily for automation since most use automatic transmission and electronic controls [40]. The strongest support for the deployment of automated hustler comes from in-land terminal operators where much of the cargo is loaded on trailers. In these terminals, most containers are placed on trailers and an automated hustler will automatically move a chassis within the terminal, or park it in its slot in the yard [40].

However, there are two particular operations in this idea that would be very much challenging for automation: connecting hustler-to-chassis brake hoses and performing safe backing operations [29].

Linear Motor Conveyance Systems (LMCS): Linear Motor Technology is another technology that can be used for transferring containers in a terminal. A linear induction motor operates on the same basic principles as a conventional, rotary induction motor, except that instead of the coils being wound around a shaft, the entire assembly is "unwound" into a linear configuration. Running current through the unrolled, flattened stator moves a metal flat blank, which is placed above the stator, as though it is a rotor

[13]. By controlling an array of linear motors that are placed underneath a platform, one can accurately move the platform (given that it is on a sliding or rolling surface).

Linear motor systems have several attractive characteristics: The motors themselves consist of no moving parts, they are very reliable, and last a long time. Platforms, which are conveyed via linear motor technology, are unmanned and have very few moving parts. The wheel assembly on the platform is the only moving part. In addition, no power is required onboard the platform. These characteristics make linear technology very promising for a wide array of applications, including container conveyance at marine terminals. However, the distance between the vehicle and the motor needs to be carefully controlled to maintain reasonable power efficiencies.

In practice, linear motors are currently used widely for smaller scale, manufacturing applications, such as conveyance systems for sorting systems or assembly plants. However, the technology is scalable to larger tasks, including container transfer within marine terminals. Currently operational larger scale applications include the Sky train in Vancouver, Canada, and Disneyworld in Orlando, U.S. A fully automated container terminal based on the LMCS technology was developed by Noell [1]. Noell had operated a pilot plant, constructed in a scale of 1:1 at Hamburg Docks on behalf of the Eurokai Container Terminal in Hamburg, Germany, in order to demonstrate the feasibility of the concept.

Navigation Systems: Until recently, technologies such as laser and Global Positioning Systems (GPS) did not provide the accuracy required to meet the needs of the AGV system. In the Delta Port of Rotterdam, the FROG navigation system is used and fiber optic cables are buried in a grid 20 centimeters below the ground. The primary drawback to the grid system is the transponder installation. At Rotterdam, this was not a serious problem since the system was installed during facility construction and the pavement surface is brick, which provides a dimensionally stable surface for embedding the transponders [40]. GPS on its own does not offer a sufficient navigation resolution to allow it to be used for AGV navigation. The accuracy for GPS is only 100 meters, which is unacceptable for AGV navigation in the terminal [18].

It has been suggested that Differential GPS (DGPS) systems could serve as navigation systems for AGVs, although there are some critical issues regarding the satellite coverage, and reliability of the signal for commercial AGV operations in ports. This system is robust and accurate up to $\pm 5\,\text{cm}$, has a relatively low cost installation, and requires few modifications to an area [40]. DGPS could provide a free path navigation system for the AGVs deployed at container terminals.

3. EMERGING HARDWARE AND SOFTWARE TECHNOLOGIES

Even in the most modern terminals, work is still very much paper based. Data are stored and updated on papers, transferred by faxes and phones, and processed manually and/or by small computers. Terminal management often does not regard the paper techniques as a problem since ships, trucks, and trains have been processed successfully for years. However, this "business as usual" scenario is unlikely to help the terminal cope with the complexity of tomorrow's mobility requirements in a sustainable manner [47]. The transition must be made from paper-based documents to electronic messages to create a fast, safe, reliable, efficient, and uniform system for electronic transport documents and procedures.

In an automated container terminal environment, AGVs or any other type of automated equipment are parts of an overall system which in order to function requires a continuous flow of information between different parts within and outside the system. The use of information technologies is therefore as important as any piece of automated equipment. For instance, not having information about misplaced containers and stacking errors could degrade terminal productivity as much if not more than slow mechanical systems [4].

In this section, we review the current and emerging information technologies with primary focus on communication and software technologies, and their potential application to terminal operations.

3.1 Information Technologies

The term ***information system*** refers to an organized set of components for collecting, transmitting, storing and processing data to deliver information for action. ***Information Technologies*** (ITs) are means for creating this information system. Most information systems in today's organizations are built on two main technologies: computers and telecommunications [60].

Information technologies have become the key factors and instruments for managing complex businesses requiring multi-party cooperation; container terminals are such a business. Information systems can improve many internal and external operations at a terminal. Internally, interactions between the terminal parties can be improved by using ITs. Externally, customers can have a real-time, accurate and reliable communication with port authorities and terminal operators in order to book, monitor and transfer their cargo and therefore improve on Just-In-Time (JIT) delivery of containers. The quality of the information system within a terminal is a key determinant in the safety, security, environmental soundness, and mobility of the terminal system [56].

In a research study, funded by the European Commission (EC) as part of its "Innovation" program - EUROBORDER, the effects of information technologies on small to medium size terminals were investigated and suggestions were made for improvements [47]. These suggestions include:

- Networking of terminal departments,
- Electronic Data Interchange (EDI) for communications on a large scale,
- On-line monitoring of movements throughout the terminal,
- Automatic data capture and data handling within the terminal,
- Other organizational changes, e.g. longer opening hours,
- Changes in port terminal layout,
- Changes for the interaction with customs, and
- Acquisition of new terminal equipment.

The suggested improvements largely change the administrative routines of port terminals (and to some extent the routines of their customers) and their organizational structure. The study concluded that if all tools suggested by the EUROBORDER were combined, this would lead to a fully automated terminal. Such a terminal would provide extensive control over the cargo and provide timely and accurate knowledge of cargo status to authorized parties internal and external to the terminal.

The EUROBORDER research shows that substantial improvement can be achieved by improving information exchange, organizational structure and administration routines. Table 3.1 summarizes the results of the study performed by EC [47].

Table 3.1: Main quantitative evaluation results from EUROBORDER

Throughput time of truck - reduced	- 30% to -45%
Yard control routines - reduced	- 30% to -85%
Internal equipment handles more cargo	+ 30%
Different processes in the administrative follow-up of the transports	-66% to -100% [1]

It is worth mentioning that the needs of each terminal have to be analyzed carefully, while taking its interaction with other organizations into account. Investments into personnel, technology, infrastructure and handling equipment have to be made in accordance with the terminals' requirements and capabilities.

As mentioned earlier, information technologies within a terminal provide the basis for a structure to optimally integrate terminal entities. This structure includes components and methods for collecting, transmitting, storing and processing data in order to deliver information for the best action. In the following sub-sections, the main components and methods applicable to container terminals are investigated.

[1] Some processes are automated by Electronic Data Interchange (EDI) which means that time is reduced to 0.

3.2 Data Collecting Technologies

Automatic Identification Technologies (AIT)

A container, to be properly handled, has to be identified several times during its passage through a terminal: at the entry and exit gates, when it is moved within the terminal, and when it enters or exits the terminal from a ship or train. In most existing terminal facilities the identification information must be manually entered into the information systems several times.

To increase the performance and mobility in a container yard, cost-effective equipment location and identification systems and devices should be deployed. Terminal operators should have real-time information regarding the current and planned locations, and the current status of cargo and material handling equipment in the terminal. Recent advances in positioning sensors have made precise and lower cost positioning available to an unprecedented degree. These technologies can quickly locate and communicate with containers and material handling equipment at various locations throughout the terminal including the gate, the quay, storage areas, maintenance areas, customs, etc.

Automatic Identification Technology (AIT) is a generic name given to devices used to automate data capture in a variety of applications. The goal of AIT is to provide cost savings by facilitating the collection of accurate data [44]. Growing rapidly within the past five years, the technology focuses on the most common sources of loss of efficiency and unnecessary costs in container operations: human interface and the inevitable human errors. The most popular AIT technologies are listed and described briefly below:

Linear Bar Codes: In this technology, the information is encoded in a printed image that is composed of varying width (and, in some cases, varying length) lines and spaces. As the bar code reader is passed over the image, it detects the transitions from light to dark and dark to light and also the length of time it sees a light or dark image. These digitized representations are then translated based on a pre-determined coding structure.

Two Dimensional Bar Codes: Sometimes called a stacked bar code, it offers high density data encoding with lines of bar codes stacked on top of one another. Beyond the greater capacity, this method features edge-to-edge decoding, stitch-able partial scans and an extensive error correction capability. Capable of enduring considerable damage and still being readable, the technology is appropriate when more data needs to accompany an item.

Optical Memory Cards (OMC): Being a relatively new AIT device, the technology employs the optical technology used in audio Compact Disks (CDs) and audiovisual CDROM (read only) products. In this technology, the information is written to a card in increments rather than at one time. That is, data can be written in a sequential order on many occasions on a card until all available memory has been used. Since an OMC is similar in size to a credit card, a person can carry it easily in a pocket or wallet. OMCs are used best when a data audit trail is required or an extensive amount of data has to be stored.

Radio Frequency Identification (RFID): This is a relatively mature approach to identify, categorize, and locate material automatically within relatively short distances. RFID capabilities are beneficial when a user wants to locate and redirect individual containers or to identify the container contents. RFID may also be used to support a customer in a forward area with inadequate systems or communications infrastructure. There are two types of RFID technologies: passive and active.

Passive: When compared to active RFID, it has shorter range, no write capability, and its data capacity is significantly limited. However, they do not require batteries, as do active devices.

Active: RFID labels are known as tags or transponders. They contain information that can range from a permanent ID number programmed into the tag by the manufacturer to a variable 128-kilobyte memory that can be programmed by a controller using RF energy. The controller is referred to as the reader or the interrogator.

An interrogator and a tag use RF energy to communicate with each other. The interrogator sends an RF signal that "wakes up" the tag, and the tag transmits information to the interrogator. In addition to reading the tag, the interrogator can write new information on the tag, thus permitting a user to alter the tag's information within the effective range. Interrogators can also be networked to provide almost unlimited coverage for a system [44].

Satellite Tracking Systems: A satellite tracking system provides the ability to track the exact location of vehicles and convoys in the terminal. Two methods can be used for vehicle positioning: using satellite for all communications and using satellite for position detection. In the first method, the latitude and longitude locations of equipment and other transportation assets equipped with a transceiver are transmitted periodically via a satellite to a ground station. Satellite tracking uses a cellular or satellite based transmitter or transceiver unit to communicate positional information, encoded and text messages, and emergency messages from in transit conveyances to the ground station. Transceiver based technologies also permit communications from a ground station to the in-transit conveyance. A user can compose, transmit and receive messages with very small hand-held devices or units integrated with computers anywhere in the world. The emerging low earth orbit (LEO) satellite constellations will facilitate tracking international multi-modal shipments [44].

In the second method, the system provides two-way communications between a vehicle and a ground station. Differential Global Positioning System (DGPS) receivers are used to determine the location of vehicles, ships, trains, and equipment. Location information from DGPS devices is transmitted back to control centers over the in-yard communication networks (such as wireless LAN), to be discussed in the next subsection. Container terminals may employ mobile inventory vehicles (MIVs), which deploy RFID devices in conjunction with DGPS receivers for position identification, as part of a system for automated equipment inventory control leading to an integrated equipment inventory and location identification system.

Table 3.2 summarizes some of the features, strengths and weaknesses of selected AIT devices [44].

Table 3.2: AIT Capabilities

Technology	Typical Data Capacity	Range	Strengths	Weaknesses
Linear bar code	20 characters	Close, line-of-sight	Inexpensive; disposable; part of DoD and commercial business practices; established standards	No updates; low tolerance to damage; pre-positioned data required for effectiveness; human involvement required
2D Bar Code	1850 Characters	Close, line-of-sight	Inexpensive; several layers of redundancy; durable; pre-positioned data not required; 2D scanners also able to read linear bar codes	No updates; human involvement required
Optical Memory Card	2.4 megabytes	Contact	Able to withstand harsh environments; inexpensive; established standards	Reader-writer not portable (cabled to PC); slow data transfer rates, human involvement required
RFID Passive	Up to 20 bytes	Inches to 240 feet line-of-sight	Quick data transfer rates; no battery required for interrogation; some read/write capability; inexpensive; durable; reusable; established standards for commercial transportation applications	Line of Sight interrogation; moderately expensive
RFID Active	Up to 128 kilobytes	Inches to 300 feet omni-directional	Omni-directional interrogation; reusable; read/write capability; durable; no human involvement required	Battery required for interrogation; moderately expensive
Satellite Tracking System	Extensive	Long range, line of-sight	Precise location of conveyance; two way communication; able to redirect vehicle in minutes; no human involvement required	Expensive; equipment needed in each vehicle to allow communication between the dispatcher and host system

3.3 Communication Technologies

Traditional communication technologies at container terminals are based on a combination of paper or data-inputting based systems and a telephone or other type of 'wire/cable' technologies. Such traditional systems cannot support the desired mobility needed for monitoring and controlling the large number of containers at a modern terminal. To achieve effective control in a terminal, it is essential to have a real-time continuous communication link between the various components within the system. This leads to a highly efficient monitoring of equipment and container positions within the terminal.

The key factor in achieving continuous communication lies in wireless communications technology capable of transmitting and receiving signals in real-time. In this subsection, we review two such technologies: Radio Frequency Data Communication (RFDC) and Electronic Data Interchange (EDI). The former is addressing the communications within a terminal and currently is the standard for real-time communications between central control and terminal equipment, while EDI is a system of choice for real-time communication between the terminal and external parties [4].

3.3.1 Radio Frequency Data Communication

RFDC provides direct real-time communication between central computers and on-yard equipment. When any equipment in the yard is moved or its status is changed, it transmits the new data via the nearest base station to the host computer. Using RFDC, on-yard equipment either provides feedback to central computers, such as delays and job status, or requests for a new task. In return, the central computer verifies the accuracy of this information and updates the database, and thus provides a real-time inventory of yard activities.

There are two systems currently used for RFDC applications: narrow band and spread spectrum.

Narrow Band System: This system operates in the range of 400 to 512 MHz. It transmits data at up to 10,000 bits per second (bps). This system has the longest range, when compared with other systems, of transmitting data over 1,000 to 5,000 ft, minimizing the number of antennas required. Generally, the overall system cost is lower than other types of RFDC due to less costly components and fewer required base stations. A Federal Communications Commission (FCC) site license is required to ensure that no other system within range operates on the assigned frequency. The system needs the highest power (2 watts) among RFDC technologies.

Spread Spectrum System: In this system signals are transmitted over a wideband frequency: 900MHz or 2.4GHz.

Spread Spectrum (902-928 MHz): This system has intermediate range (approx. 135-300 m), moderate power (0.25-1 Watt), and high data transfer rates (60-600 Kbps). No site license is required. This range of frequency is available only in North America and Australia.

Spread Spectrum (2.4-2.5 GHz): This RFDC system is designed to offer transportability not only between facilities within North America but globally. They have the shortest range of all RFDC systems (approx. 75-210 m), least power (0.1 Watt), and highest data transfer rates (approx. 500 Kbps-2 Mbps). They do not require site licenses and this band is, or will be, available in most countries.

It is worth noticing that the 2.5 GHz spread spectrum range is the area that is being standardized by the Institute of Electrical and Electronics Engineers (IEEE). All wireless LAN components sold today comply with the IEEE 802.11 standard, resulting in interoperability among varying compliant product vendors. The maximum data rate of 802.11-compliant products is 2 Mbps, but IEEE will soon release an 11 Mbps data rate version of the standard [23].

The spread spectrum systems' bands are shared by a number of other types of RF devices so some interference is to be expected. These systems are using either ***Direct Sequence (DS)*** or ***Frequency Hopping (FH)*** to mitigate the effect of interference. With DS a continuous signal is transmitted over a very wide part of the overall available bandwidth. This allows for greater data throughput but power and range are compromised. Continuity is achieved via redundancy. This term is applied to the alternative transmission of binary-based digital data, where the '0' is converted into one long bit-stream and the '1' is inverted. This means that there could be up to 1,000 bits representing each individual bit. Using appropriate encoding techniques, single bits are converted into a long bit-stream that can be probably 1,000 bits long. Even if the signal breaks up during a DS type transmission the data can be statistically recovered using redundancy.

The approach using FH involves the transmission of information by 'hopping' from one frequency to another, with terminals and transmitters in synchronization. Normally, the number of frequencies 'hopped' is about fifty, with the overall band remaining on each for less than one second. The advantage of FH is that usable power is more tightly concentrated, thus greater ranges can be obtained at only marginally lower data rates. On the negative side, because redundancy is not available broken signals have to be sent again.

In June 1999 LXE introduced a new spread spectrum system claimed to be a major step in reducing the number of access points required for a spread spectrum system. Using the Spire antenna, developed by LXE's parent company EMS, LXE claims it is now possible to reduce the number of access points required for online and real-time data communications down to almost the same number as needed with a narrow band system. The Spire antenna can be placed between container stacks without suffering from significant interference in transmission [4].

The greater information carrying capacity of spread spectrum means that it is possible to put more devices on the system backbone when compared to narrow band systems. Spread spectrum, while more expensive, enables a terminal to put both voice and data on the same band. This makes the spread spectrum and narrow band systems more comparable in terms of cost. Spread spectrum coverage is also beneficial to a terminal that is operating a RFDC system in client/server mode and/or using a graphical user interface.

A further option is to combine the two systems. Teklogix offers base stations that support both spread spectrum and narrow band radio bands. One such system was recently installed at Shanghai Container Terminals Limited. Narrow band was used for the main terminal management system, with spread spectrum being employed for the gate operations where the small area and high data throughput made it more effective.

3.3.2 Electronic Data Interchange (EDI)

Electronic Data Interchange (EDI) is the transmission of data structured according to agreed message standards, between information systems, by electronic means [53]. In other words, EDI is the communication of data from one computer to another in a standard format with no human intervention in the reading or recording [4], [48]. EDI is a process and not a system.

Perhaps the main advantage of EDI is that it allows for the access to the same information in real-time by all interested parties via an electronic medium (such as the internet). Shipping lines, haulage companies, carriers, terminal operators and so on can communicate efficiently, creating the operation of a seamless transportation system. Sharing information in real-time between different parties creates opportunities for increasing efficiency and accuracy in container terminals.

The major benefits of using EDI in container terminals can be summarized as follows:

- Increasing transactions speed.
- Increasing accuracy.
- Minimizing manual data entry.
- Lowering communications costs.
- Enabling information to be shared between a wide range of parties in real-time.

With trading conditions subject to constant change, owing to factors such as late arrivals of ships, all interested parties can be duly notified. Using audit trails or electronic logs of document handling activity information can be tracked as it passes through the system, thereby offering secure transfer of data and accountability, which otherwise can be subject to loss or tampering in a paper-based system.

Successful implementation of EDI in the shipping industry is dependent on all communication partners subscribing to EDI as the only way for information exchange, the ability to interconnect all in-house IT systems, and the capability to make arrangements relating to message content. While the computer systems operating within the terminal might be different, the external interfaces are in accordance with international standards, which harmonize the differing and often incompatible computer systems available. The United Nations developed its "rules for Electronic Data Interchange for Administration, Commerce and Transport" (EDIFACT), now the most widely used language for standardizing EDI messages relating to commerce and transport. Electronic document exchange can of course take place using either EDIFACT or any other language the parties may agree upon, but as mentioned above EDIFACT is the most widely accepted standard in commerce and transport.

Although EDI has the potential to completely replace paper-based information exchanges, few container terminals have yet completely done away with paper systems. Perhaps the biggest barrier in implementing EDI is the gate, where most truck drivers still submit customs documents in person. Many haulers are small companies, or owner operators that are unwilling to invest in EDI technology. A number of ports are using self-service or 'fast' gates for drivers whose container has been pre-booked or released. This reduces queuing and saves haulers time. Using the EDI link, customs procedures can be started before the truck driver arrives (Australian customs have started to charge for documents not submitted by EDI). The pre-information sent by the hauler also allows for the correct allocation in the yard of the import container so that the incoming driver, on passing through the gate, notifies the central control of his arrival and is in turn directed to the appropriate location.

3.4 Computer Hardware and Software Technologies

Not until recently management of complex systems such as container terminals had to invest a great amount of capital on huge computer mainframes. These computers were mainly used to store and run some routine functions. Recent advancements in VLSI technologies made it possible for port authorities to deploy very fast, reliable, yet not expensive computers for storing and processing the data collected on the container yard or received from outside parties. In fact hardware is not the problem anymore, but it is software that needs to be advanced.

The software industry for container terminals’ applications is still very young. Until the late 1980’s, just a few big container terminals had deployed their self-developed software packages. As the software industry has advanced in recent years, the trends have been shifted toward using general-purpose terminal software packages, which are tailored for a particular container terminal usage. Companies such as Navis and August Design, Inc. from the U.S., CMC from India, and Cosmos from Belgium have emerged among the pioneers in this industry. It is generally believed that a software package has a maximum life of five years, unless the terminal does not change. Therefore, it is more economical to use such a general-purpose package.

August Design, Inc. (Trimodal ™) and America Systems, Inc. (E-term) have introduced terminal management systems able to run over the Internet. This is in response to the desire of many terminals to have an ASP (Application Specific Provider). The ASP method greatly reduces both the terminal’s hardware and software applications costs, and minimizes the problems involved with software updates. In the ASP model the terminals do not need an IT (information technology) staff as the application software runs remotely, and the only local hardware and software is a simple computer running a browser. (Note: Trimodal is a trademark of CSX Technology, Inc.).

Whatever the computer software technology is, it should store and process the collected and transmitted data from the container terminal internally as well as the received information from outside parties. It should contain modules for yard planning and control, ship planning and control, real-time on-yard equipment control, gate and rail operation, EDI management, booking and billing system, etc. [46].

The yard planning and control module determines the optimal position for import and export containers in the yard in order to reduce cost and container dwell time in the yard, and to increase the efficiency in the yard. A graphical view would provide a better interface with the user.

For export containers, the ship planning and control module determines the optimized stowage plan based on ship's capacity, stability, destinations, safety restrictions, available equipment, number and type of export containers, etc. For import containers, the module comes up with an optimized plan for ship unloading before it has even docked.

The equipment control module determines the position and status of each piece of equipment, resolves congestions on the yard, dynamically re-routes the vehicles, assigns a new job and sends the appropriate commands to each piece of equipment.

The gate and rail operation module controls the operation at the gates. Every container entering the terminal is checked administratively and physically, after which the order is confirmed. After the container is checked, all other software programs linked to the central database are able to use the available container information. For outbound trains, the list of containers to be loaded on the train is extracted from the central operations database. The module determines the optimum plan for assigning containers to rail cars based on rail-carts' characteristics and sequence, containers' size and content, destinations, safety restrictions, available equipment, etc.

4. AUTOMATED TERMINALS: CONCEPTS AND DESIGN CONSIDERATIONS

The recent advances in information technologies, electronics, computers, sensors, robotics, etc., coupled with the increasing volume of containers to be processed at terminals, motivate the use of automation as the only way to meet increasing demands and compete in global markets especially in places where further expansion of the terminal facilities is not possible due to the scarcity of land. While labor issues are considered to be a major obstacle for the speedy introduction of automation, global competitiveness will put enormous pressure on all sides involved to cooperate in order to technologically advance the current port facilities and improve capacity and efficiency.

The review of AGV and hardware and software technologies in sections 2 and 3 indicate that the development of fully automated container terminals is technically feasible. In this report we consider several automated container terminal concepts that have a strong potential for implementation. These concepts have been considered in a FY97 task under CCDoTT [26] but their evaluation was limited to operations within the terminal, namely the loading/unloading of the ship with containers from the storage yard. In this report we extend these concepts to automated container terminals (ACT) that include the gate, train and ship interfaces. The ACT systems to be designed and evaluated under this project employ AGVs and Linear Motor Conveyance System (LMCS) for the transport of containers. For comparison purposes we add another two designs that are also treated in other CCDoTT tasks and work outside CCDoTT. These include a Grid Rail (GR) system [27] and an Automated Storage/Retrieval System (AS/RS) [12]. The general layout of the automated container terminals considered in this report is shown in Figure 4.1.

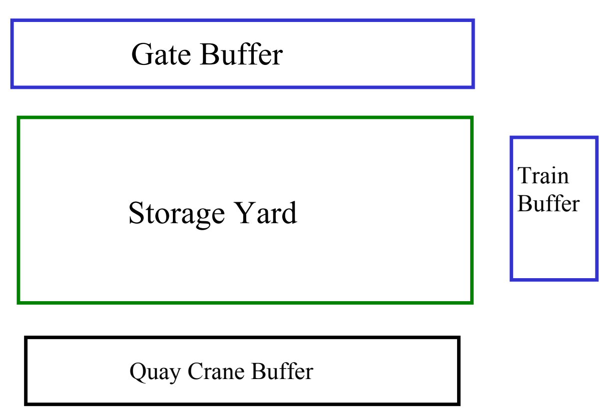

Figure 4.1: General Layout of Automated Container Terminal

Figure 4.1 shows the interfaces of the gate, the train and quay crane buffers with the storage yard. In the case of the AGV based ACT (AGV-ACT) the storage yard is a collection of stacks separated by roads where the containers are stacked and served by yard cranes. AGVs are used to transfer containers within the terminal and the storage yard. In the case of the LMCS based ACT (LMCS-ACT) the storage yard is the same as in the case of the AGV-ACT system. The only difference is that shuttles driven on a linear motor conveyance system are used for the transport of containers. For the Grid Rail (GR) based ACT (GR-ACT) the storage yard in Figure 4.1 is replaced with a number of GR units that provide the same storage capacity as in the other concepts under consideration. A GR unit consists of an overhead rail system with shuttles that can move above the storage yard and transfer containers between the GR buffers and the storage yard. AGVs in this case are used to transfer the containers between the GR buffers and the gate, train and quay crane buffers. The AS/RS based ACT (AS/RS-ACT) is similar to the GR-ACT system in the sense that the GR units forming the storage yard are replaced with AS/RS modules that form a high-rise structure for container storage. As in the case of the GR-ACT system AGVs are used to transfer containers between the AS/RS buffers and the gate/train/quay crane buffers.

The gate buffer is designed to interface between the manual operations (inland side) and the automated ones (internal terminal side). It provides a physical separation between the manual and automated operations for safety reasons and also for efficiency. It helps reduce the turnaround time for trucks by providing a temporary storage area for the export containers, until AGVs are assigned to process them as well as a temporary storage area for the import containers waiting to be picked by trucks. The train buffer is the area next to the train where loading and unloading between the AGVs and the train takes place.

The size of the ACT and its characteristics such as storage capacity, number of gate lanes, number of berths, number of quay cranes, etc. depend on the expected volume of containers the ACT has to process per day, the ship/truck/train arrival rates, and the volume of containers they carry, etc. These considerations together with the type of equipment that is available could be used to specify and design the components of the ACT system in general and specifically for each concept.

4.1 Design Considerations

The first generation container ships built in the late 1960's had a capacity of about 400 TEUs. In the late 1970's, container ships carried about 2,000 TEUs. The post Panamax ships have capacities of 6,000 TEUs, while the largest ships today are 17 containers wide and capable of over 8,000 TEUs. It is important to note that ships that are 20 containers wide could be accommodated by enough major ports to make them viable in the near future [32]. A current service-window expectation for mega-ships (over 6,000 TEUs) is 48 hours [34]. According to the plan for the Port of Rotterdam, the North West terminal will be able to accommodate container ships of 8,000 TEUs. It is expected that ten ships will arrive every week (85% loaded) to this terminal. If the maximum in port time is restricted to 24 hours, two berths for these ships with a capacity of 250 moves per hour will be required. This can be accomplished using five cranes per berth, each with a capacity of 50 moves per hour [20]. Using similar projections as for the Port of Rotterdam we come up with the following design consideration for the proposed ACT systems.

Design Consideration 1. The ACT will serve ships capable of carrying 8,000 TEUs. The ships will arrive every 24 hours 85% loaded and should be served in less than 24 hours. In our design we assume a desired ship turnaround time of about 16 hours.

The Ports of Long Beach and Los Angeles currently handle around 20,000 truck and 30 train movements per day and it is projected that these numbers will grow to 50,000 trucks and 100 trains per day by 2020. From the Port of Long Beach, approximately 15% of the container traffic is carried directly via rail with no truck movement involved. From the Port of Los Angeles, 55% of containers are intermodal, and are destined for inland regions via rail. However, the port has estimated that approximately one half of that number is first moved by truck to the rail yards. The Port of Los Angeles estimates that by 2020, up to 40% of intermodal containers will be moved via on-dock rail, while 60% will continue to be moved via trucks [30]. We use the projection of the Port of Los Angeles to come up with the following design consideration for the proposed ACT systems.

Design Consideration 2. About 60% of the containers will arrive at the ACT by trucks and about 40% will arrive by rail.

The expected export container arrival patterns at the terminal can be assumed from prior experience with land transport (road and rail) carriers. These patterns however are found to vary considerably from one port to another.

Taleb-Ibrahimi et al. [36] present various container arrival patterns and indicate the proportion of containers that arrive x (x = 1 to 6) days before the cutoff time. Some ports advertise cutoff times for each ship, after which cargo for that ship is no longer received, in an effort to meet ship departure schedules and operate efficiently. For example, for some ships, containers start trickling in 6 days before the cutoff time with a maximum arrival rate the second day before the cutoff time. Starting from the sixth day before the cutoff, the arrival rates are 0.05, 0.05, 0.1, 0.2, 0.4, and 0.2 in this case [36] meaning that 5%, 5%, 10%, 20%, 40%, 20% arrive during the 6, 5, 4, 3, 2, 1 day respectively before the cutoff time.

Castilho [17] presents the arrival and retrieval pattern of containers at the Virginia International Terminal for two ships, the Ever General and Marie Maersk. The arrival and retrieval rates vary with time for both ships. Exports begin to trickle in more than a month before ship arrival. Large batches of exports only arrive during the last week. The arrival rates of export containers for the Ever General were 0.002 for the first twenty-four days, 0.016 for the next five days, 0.056 for the next seven days, and 0.12 for the last four days before the ship arrival.

According to data from the Port of Rotterdam, at the North West terminal the ‘time in stack’ (stay time) for import containers is limited to 3 days, and for the export containers is limited to 2 days [20].

In our design we decided to adopt the data from the Port of Rotterdam and use reference [20] to come with a design consideration for the arrival pattern of containers relative to the arrival time of the ship.

Design Consideration 3. The export container arrival pattern relative to the ship they are bound to is .2, .5 and .3, meaning that 20% of containers arrive during the second day before the ship arrives, 50% arrive during the first day before the ship arrives and 30% arrive the same day and early enough to be loaded while the ship is at the berth.

Given the advances in information technologies (IT), improvements in dispatching and scheduling algorithms the design consideration 3 is technically feasible provided the terminal is capable of handling the container traffic. In fact the example of the Port of Rotterdam of limited stay time for containers is expected to be followed by other ports as a consequence of the use of IT and efforts to reduce cost and improve productivity.

There is a tendency to keep the import containers in the storage yard longer than the export ones. In general imports are retrieved quickly during the first week after the ship arrival, and then at a much slower rate, so that the last containers are only retrieved after spending three or four weeks in the terminal. Castilho [17] claims that each ship carries different categories of containers that are retrieved at different rates. For the cargo carried by the Ever General at the Virginia International terminal, retrieval rates were 0.1 for the first seven days and 0.02 for the next fifteen days. Refrigerated cargo is often picked up immediately after it is discharged from the ship. Also, it may be important to retrieve intermodal containers from the terminal quickly in order to keep a train schedule, while some domestic containers bound for inland warehouses may be left at the terminal for a longer time to take advantage of the storage space available at the terminal, while relieving space concerns at the destination warehouse. Having these constraints and current practices in mind and the trend of using IT and improved scheduling and dispatching techniques in the future we adopted the Port of Rotterdam numbers [20] and came up with the following design consideration.

Design Consideration 4 The import containers are retrieved during three days, with retrieval rates 0.5, 0.3 and 0.2, meaning 50% of the containers are taken away by trucks and trains during the day the ship was served, 30% the second day and 20% during the third day. Out of the 50% of the containers that are taken away the same day, 30% are taken away directly without any intermediate storage and 20% are temporarily stored in the yard before taken away.

In many of today’s ports trucks operate in cycles of less than 24 hours. There is a trend however to increase the time to close to 24 hours in order to meet the demand and avoid traffic delays in the inland transportation system. This could be proven crucial in areas such as the Los Angeles Metropolitan area where highways and surface streets during peak areas are highly congested. In our design we assume the following.

Design Consideration 5. The trucks/trains of the ACT will operate in cycles of 24 hours.

The design considerations 1 to 5 are used in the following sub-sections for designing the characteristics of the ACT system.

4.2 Storage Capacity

Given the design considerations 1 to 5, the storage capacity of the terminal should be large enough to accommodate all the containers that are required to be stored before being taken away by the trucks/trains/ships. From consideration 3 the average number of export containers that have to be stored in the terminal is about 6,120 TEUs per day (1,360 from previous day plus 3,400 from same day plus 1,360 from previous two days). From consideration 4 the average number of import containers to be stored is about 9,520 TEUs per day (1,360 stored but taken away the same day after the ship departed plus 2,040 from two days ago plus 1,360x2 from two and three days ago plus 2,040 to be stored for two days plus 1,360 to be stored for three days). This gives a total of 15,640 TEUs required storage capacity per day. Therefore a storage capacity greater than 15,640 TEUs will meet the demand and operational requirements of the ACT as characterized by the design considerations 1 to 5. It is desirable however to have a storage capacity higher than the 15,640 TEUs in order to meet emergencies such as military deployment situations and others, have the flexibility of putting an additional berth or even serving larger ships in the future. Given these considerations the desired storage capacity is taken to be about 45% higher than the one dictated by the design considerations 1 to 5, i.e. about 22,000 TEUs.

4.3 Number of Berths and Quay Cranes

The number of berths and quay cranes to meet the design considerations 1 to 5 depends on the speed of the quay cranes. The maximum physical capacity of a quay crane is assumed to be equal to 50 moves per hour [20]. We assume that quay cranes can reach their maximum capacity when they are operating in a single mode (i.e. either loading or unloading), while the average of 42 moves per hour is assumed for double mode (i.e. combined loading and unloading). A 15% variance to the maximum capacity of the quay cranes is considered in our study due to the uncertainties involved in the quay crane operations (i.e. variance in speed due to reaching different bays in the ship.). The number of quay cranes required to serve the ship with 3,400 40-foot containers (6,800 TEUs) is given by the relationship

$$ST = \frac{3{,}400}{42} \cdot \frac{1}{NC}$$

where *ST* denotes the ship turnaround time and *NC* denotes the number of quay cranes. This relationship is plotted in Figure 4.2 below:

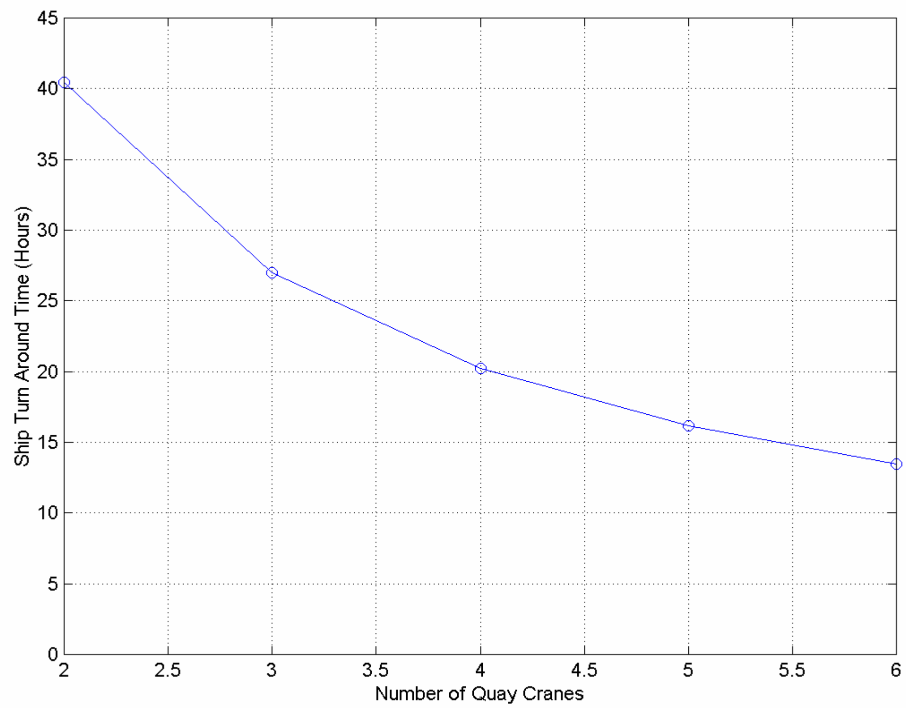

Figure 4.2: Ship turnaround time versus number of quay cranes for combined loading/unloading of 3,400, 40-foot containers with an average speed of 42 moves per hour per crane

In design consideration 1 we assumed a desired ship turnaround time of about 16 hours, which from Figure 4.2 corresponds to 5 quay cranes to meet the expected loading/unloading demand. Since 5 quay cranes in a single berth can meet the demand, the number of berths can be kept as one.

4.4 Number of Lanes at the Gate

The most important facility on the inland side of a container terminal is the gate entrance. The gate must be designed in such a manner as to provide the required number of lanes needed at peak, or close to peak hours of traffic volume for both directions (import and export operations). Some lanes are dedicated to inbound traffic, some to outbound traffic and some may be reversible in direction.

Since both truck arrival and service time at the gate are random processes, we model the gate operations as an $M(\lambda)/M(\mu)/n/\infty$ queuing system, where λ, μ, and n denote the mean arrival rate and mean service rate of the trucks and the number of lanes at the gate, respectively. The M indicates a Poisson process [8] with the argument denoting the average rate. The trucks are served according to a FIFO (First In First Out) service discipline, i.e., the first arriving truck is served first, followed by the second arriving truck, etc. The arrivals of trucks are modeled as a Poisson process, with a constant arrival rate λ. The inter arrival times are exponentially distributed. The mean service time of a truck at the inbound gates is assumed to be 3 min and at the outbound gates 2 min [11]. Service times are assumed continuous random variables exponentially distributed with service rate μ equal to 1/(mean service time).

The gate must be designed to provide the required number of lanes during peak hours of traffic volume in both directions. The minimum number of lanes n can be determined from the following inequality [8]:

$$\lambda/\mu < n$$

We have assumed that 4,080 TEUs (export containers) per day arrive by trucks and these containers are all 40-foot ones i.e. a total of 2,040 containers per day arrive by trucks. This volume corresponds to 2,040 loaded incoming trucks per day. Some of these trucks pick up import containers, and the rest leave the terminal without any load. In addition, empty trucks arrive at the gate to pick up import containers. We have assumed that the number of empty trucks that arrive at the gate to pick up containers is equal to the number of trucks that arrive loaded and leave empty. We have assumed that 40% of the incoming loaded trucks leave empty which corresponds to 816 trucks. Therefore, the total number of trucks that are expected to arrive at the gate for loading and/or unloading per day is 2,040+816=2,856 trucks/day.

By assuming a 24-hour operation we find that the truck (inbound) arrival rate is equal to λ=2,856/24h=119/h=1.98/min. Then for μ=1/3 (assuming a 3 min service rate) we have

$$(\lambda/\mu)=1.98/0.33 < 6$$

which implies that a minimum of 6 lanes is required in the inbound-gate in order to meet the demand.

The mean service time at the outbound-gates is assumed to be 2 minutes which gives μ=1/2 per min. The arrival rate at the outbound gate is equal to λ=2,856/24h=119/h=1.98/min which is the same as the arrival rate at the inbound gates. Since,

$$(\lambda/\mu)=1.98/0.5 < 4$$

the minimum number of lanes in the outbound-gate required to meet the demand is equal to 4. The number of 6, 4 of lanes for the inbound and outbound gate respectively, are the minimum possible as the above inequalities are tight. The use of 6, 4 lanes at the gate will lead to a high utilization of the gate during the assumed scenario. Small deviations from the assumed arrival and departure rates may cause saturation at the gates that may lead to congestion on both sides of the gates. In order to avoid such situations we increase the number lanes for the inbound-gate to 9 and for the outbound-gate to 6.

4.5 Number of Yard Cranes at the Buffers

We assume that the yard cranes used at the gate buffer have the following characteristics:

The yard crane's speed is 5 mph. It takes 15 sec. to line up with the stack, and an average time of 65 seconds to unload and load an AGV. These characteristics give an average speed of about 36 moves per hour per crane calculated by assuming 15+65+20=100 sec per move where an average of 20 seconds are used for the lateral motion of the crane along the stack. It is also assumed that these cranes are gantry cranes of the same type used in the yard. They are able to go over stacks of containers (up to 4 containers high) and load and unload vehicles from both sides of the stack.

The number of containers handled by the yard cranes at the buffer per day is calculated as follows:

Number of containers (40-foot) that arrive by truck=2,040

Number of containers (40-foot) that arrive to the buffer from the yard=2,040

Number of containers (40-foot) to be loaded on trucks that arrive empty=816

Therefore the maximum total number of containers to be processed by the yard cranes at the buffer per day is 2,040x2+816=4,896 or 4,896/24=204 containers per hour. This implies that the number of yard cranes needed to meet this demand is equal to 204/36=5.7 i.e. 6 yard cranes will meet the demand at the gate buffer. The use of 6 yard cranes gives a maximum average throughput at the buffer of 204/6=34 moves per hour per yard crane.

The number of yard cranes to serve the train buffer is calculated similarly. The number of containers (40-foot) to be processed at the train buffer is 1360 per day or 1,360/24=56.67 containers per hour. For an assumed crane speed of 36 moves per hour we have that 56.67/36=1.57 cranes are needed. Choosing 2 cranes for the train buffer, we guarantee that we will meet the expected maximum demand. In such case, the maximum average throughput at the buffer is 56.67/2=28.3 moves per hour per crane.

For the yard cranes we assume a variance of 10% of the average speed in order to account for the randomness in the operation due to the different location of the containers in the stack etc.

4.6 Summary of Equipment for the ACT system

The equipment and characteristics of the ACT system developed in the previous subsections apply to all the concepts considered in this report and are summarized below:

Storage Capacity of ACT: about 22,000 TEUs

Berth and Quay Cranes: 1 berth with 5 cranes. The average speed of each crane for combined loading/unloading is 42 moves per hour with 15% variance.

Number of Lanes for Inbound-Gate: 9 (24-hour operation, processing time 3 min per truck).

Number of Lanes for Outbound-Gate: 6 (24-hour operation, processing time 2 min per truck).

Number of Yard Cranes at Gate Buffer: 6 with an average speed of 34 moves per hour per crane with variance of 10% of the average value.

Number of Yard Cranes at Train Buffer: 2 with an average speed of 28.3 moves per hour per crane with variance of 10% of the average value.

The characteristics of the equipment that is specific to each ACT concept will be developed when the particular ACT concept is addressed in subsequent sections.

4.7 Operational Scenario

In the above subsections we assume a certain pattern of incoming and outgoing flow of containers in order to come up with the number of equipment that is needed to meet the demand. This operational scenario will be used to evaluate different ACT systems and is summarized in Tables 4.1 to 4.5.

Table 4.1: Arrival Rates of Containers

Ship Arrival Rate	One ship every 24 hours to be unloaded and loaded with 6,800TEUs in less than 24 hours (desired ship turnaround time 16 hours). All containers assumed to be 40-foot containers
Container Arrival/Departure Rate by Trucks	Poisson distribution with a mean of 85, 40-foot containers per hour (170 TEUs per hour)
Container Arrival/Departure Rate by Trains	56.67, 40-foot containers per hour

Table 4.2: Number of export containers, bound for one ship, arrived by trucks and trains

Container Arrival Times	2nd day before ship arrival	1st day before ship arrival	Right time to be loaded on the ship directly
The number of containers that arrive by trucks	816 TEUs	2,040 TEUs	1,224 TEUs
The number of containers that arrive by trains	544 TEUs	1,360 TEUs	816 TEUs

Table 4.3: The cumulative numbers of export containers, arriving by trucks and trains

	Every day
The number of containers that arrive by trucks	4,080 TEUs: 30% delivered to the ship directly without intermediate storage in the yard; 50% arrive one day in advance of the bound ship; 20% arrive two days in advance of the bound ship
The number of containers that arrive by trains	2,720 TEUs: 30% delivered to the ship directly without intermediate storage in the yard; 50% arrive one day in advance of the bound ship; 20% arrive two days in advance of the bound ship

Table 4.4: Number of import containers, unloaded from one ship and retrieved by trucks and trains

	Same day while the ship is at berth (direct transfer)	Same day after ship left the berth	1st day after ship departed	2nd day after ship departed
The number of containers that are retrieved by trucks	1,224 TEUs	816 TEUs	1,224 TEUs	816 TEUs
The number of containers that are retrieved by trains	816 TEUs	544 TEUs	816 TEUs	544 TEUs

Table 4.5: The cumulative numbers of import containers that are retrieved by trucks and trains

	Every day
The number of containers that are retrieved by trucks	4,080 TEUs: 30% retrieved directly from the ship without intermediate storage; 20% retrieved same day but after the ship departed; 30% retrieved from the storage yard (came one day ago); 20% retrieved from the storage yard (came two days ago)
The number of containers that are retrieved by trains	2,720 TEUs: 30% retrieved directly from the ship without intermediate storage; 20% retrieved same day but after the ship departed; 30% retrieved from the storage yard (came one day ago); 20% retrieved from the storage yard (came two days ago)

5. PERFORMANCE/COST CRITERIA AND MODELS

A container terminal is a complex system that serves the purpose of storage, processing and movement of containers between different modes of transportation. The goal of every terminal is to perform efficiently and at low cost and at the same time maintain competitiveness by providing low cost and high quality services to customers. Therefore, in order to evaluate the ACT systems, currently in the preliminary design stage, we need to come with models that mimic their behavior in a real situation and performance and cost criteria based on which the evaluation will be carried out.

In this section we present the performance and cost criteria that are used to evaluate the ACT systems considered under this project. In addition we describe a simulation model that we validate using real data. The simulation model is used to model each ACT system and simulate its performance for the same operational scenario whose characteristics are defined in section 4. The average cost for a container to go through the terminal is used as the criterion for cost comparisons and analysis. A cost model presented in this section is used to generate the average cost per container. A very similar model is used in several other marine terminal cost studies that include studies for the port of Houston, Barbours Cut terminal [28] and the port of Rio De La Plata, Buenos Aires [37].

5.1 Performance Criteria

Measures of physical capacity and productivity in container terminals include gate throughput, truck turnaround time, ship turnaround time, labor productivity, crane productivity, and utilization of berths, cargo handling equipment and yard vehicles, labor, gates, and storage yard (land). However, container ports frequently focus on internal and narrowly construed measures of productivity and efficiency [59]. For example, while the number of containers moved across the quay each hour is often a major focus of marine terminal operators, it is not a measure that is ordinarily of great concern to users of the terminal.

The most often used measure of performance of loading/unloading equipment is the average cycle time expressed in moves/hour. Moves per hour can be used either to evaluate the performance of single loading/unloading equipment or to evaluate the productivity of the terminal. Since the throughput of a terminal cannot exceed the best quay crane performance, a good measure of the terminal throughput is the number of moves per hour per quay crane. By computing the average number of moves per hour per quay crane we get a measure of the number of containers that got loaded or unloaded or both on/from the ship per hour.

A terminal can maintain a high throughput but it could be utilizing a lot of land to avoid stacking. If the cost of land is high that will raise the cost of moving containers through the terminal. Since in our study we consider concepts that require different land coverage for the same container storage and processing capacity, a reasonable measure to use to compare these concepts is the throughput per acre or throughput measured in moves per hour per quay crane per acre. In many ports such as Port of Long Beach, a similar measure defined as the number of processed TEUs per acre per year is often used.

The time a ship spends at the berth for the purpose of loading and/or unloading is referred to as the ship turnaround time. The ship turnaround time is well recognized as an important factor in the overall transportation cost of containers, and its reduction to a minimum possible is one of the main priorities for shippers and terminal operators. This is easy to understand given that modern container ships may cost around $30,000 to $40,000 to operate per day [37]. In our design considerations for the ACT systems we chose a desired ship turnaround time of 16 hours. Since in practice the actual ship turnaround time may vary due to randomness in the properties of equipment etc the ship turnaround time may be different from the desired. Therefore the ship turnaround time is another good measure for evaluating the performance of the proposed ACT systems.

The typical external truck variable cost used by the trucking industry is $75 for each hour the truck is in use. This cost includes maintenance and labor costs [28], [22]. The time a truck spends at the terminal for loading and/or unloading cargo is a real cost to the trucking company and affects the overall transportation cost of containers. The ability of the terminal to serve the trucks in short time will translate to cost reduction for the truckers and will make the terminal more attractive to do business with. Therefore, another useful measure of performance is the average time a truck spends in the terminal in order to complete the loading/unloading process and to wait in queues to be processed by the gate. This time is referred to as the truck turnaround time and does not include the actual processing time at the gates. A secondary measure that affects the truck turnaround time is the gate utilization expressed in percentage of time the gate spends serving the incoming and outgoing container traffic. A low gate utilization for a certain arrival and departure container rates shows that the gate is underutilized and it could meet the demand with less number of lanes and people. On the other hand, if the gate utilization is high (close to 100%) that would mean that small changes in the container rates might cause congestion at the gate that may propagate into the terminal.

The time that a container stays in the terminal before being taken away is referred to as the container dwell time. A high container dwell time could affect the transportation cost and the time to reach its destination in an adverse way. In addition, a high dwell time raises the required storage capacity of the yard since containers stay longer in the yard before taken away. An efficient terminal would keep the dwell time as low as possible. We have to add here that in some of today's practices containers are kept in the terminal on purpose in order to reduce cost, because the alternative of storing these containers in warehouses outside the terminal is higher.

The cost of a terminal depends on many parameters that include the land cost, the equipment cost, infrastructure, etc. The equipment cost that includes the cost for cranes and vehicles could be significant. Therefore a cost effective terminal is the one that keeps the amount of equipment to the minimum possible that is necessary to meet the expected demand. Since demand may vary with time, a good measure as to how effectively the equipment is utilized is the idle rate of the equipment measured as the percentage of time the equipment is idle. Low idle rates indicate an efficient utilization of the equipment where as higher idle rates indicate that the equipment is underutilized. Underutilization may suggest design changes, reduction of the number of machines used, and/or improvement of the management of operations, etc. in order to save costs and improve productivity.

Based on the above arguments the following table summarizes the performance criteria that are used in this study to evaluate and compare different ACT systems.

Table 5.1: Performance Criteria

Throughput	The number of moves per hour per quay crane
Throughput per acre	The throughput per acre
Annual Throughput per acre	Number of TEUs processed/per acre/per year
Ship turnaround time	The time it takes for the ship to get loaded/unloaded in hours
Truck turnaround time	The average time it takes for the truck to enter the gate, get served, and exit the gate minus the actual processing time at the gate
Gate utilization	Percent of time the gate is serving the incoming and outgoing container traffic
Container dwell time	Average time a container spends in the container terminal before taken away from the terminal
Idle rate of equipment	Percent of time the equipment is idle

5.2 Simulation Model

The proposed ACT systems are not built and therefore no real data exist that could be used to evaluate them. The complexity of the dynamics of the processes within the terminal does not allow us to perform a mathematical analysis beyond certain steady state calculations. In this case a simulation model needs to be developed and used to evaluate the performance of the terminal.

In this project the software packages Matlab, Simulink, and Stateflow developed by MathWorks, Inc., are used to generate a microscopic simulation model. The model simulates the characteristics and movements of every piece of equipment and vehicle in the terminal in detail as well as their interactions with each other and with the incoming/outgoing traffic. The model is time based and can be used to simulate different yard configurations and characteristics, different operating scenarios, different strategies and optimization techniques for cargo handling, etc. The simulation model is validated using real data from a particular terminal as discussed in the following subsection.

5.2.1 Model Validation

Real data from yard operations at Norfolk International Terminal (NIT) presented in [29] [38] are used to validate the proposed simulation model before using it to model and simulate an ACT system. We use the characteristics of NIT and its equipment presented in [29], [38] as inputs to the simulation model. We then exercise the model for the same operational scenario and compare the throughput generated by the model with that obtained from real data. The results are shown in Figure 5.1. The throughput generated by the simulation model is 26.8 moves per hour per quay crane versus the measured one of 28 moves per hour per quay crane, a difference of -4.3%.

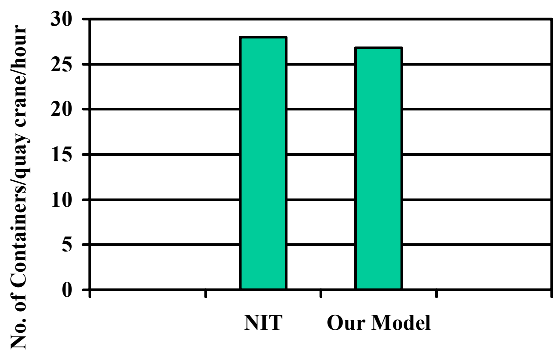

Figure 5.1: A comparison of simulated throughput and actual one measured at NIT terminal

The comparison shown in Figure 5.1 demonstrates that the simulation model is of high fidelity and the results generated could be trusted.

5.3 Cost Model

The Average Cost per Container (ACC) being processed through a terminal is among the most important cost measures considered by port authorities [37]. Though average-cost-per-container does not express pricing, revenues, or terminal profits, it provides a basis for economic evaluation of container terminal operations. In this study, we adopted this measure in order to evaluate and compare the cost associated with each proposed ACT system.

Costs associated with container handling and storage operations within a terminal can be classified into the following three categories:

- *Cost of activities*: that is the cost of locations where activities (operations) take place i.e. buildings and facilities such as gates, customs, etc.
- *Cost of land:* the capital investment for land in different areas, e.g. berth area, storage area, etc.
- *Cost of equipment*, the cost of yard equipment e.g. yard cranes, quay cranes, AGVs, etc.
- *Labor costs*.

The ACC is equal to the sum of the total annual cost for activities, land, equipment and labor divided by the total annual number of containers that are processed by the terminal.

The total annual cost for activities and equipment can be further classified into *fixed* and *variable* cost. Fixed costs do not vary with the level of activities (operations). For instance, the capital invested on purchasing the equipment is not affected by the working hours. The level of activities affects the variable costs. For example, the energy consumption, such as fuel and electricity, increases with the working hours.

The cost model that generates the ACC is a set of Microsoft Excel Spreadsheets. The first sheet calculates the total Variable Cost (VC), total Fixed Cost (FC) and Total Cost (TC) associated with location activities. The second sheet calculates the land cost, and the third one computes the VC, FC and TC for the equipment. In the fourth sheet the total labor cost is calculated based on the number of people employed, working hours, overtime, salaries etc. The fifth sheet summarizes the total cost for activities, land, equipment, and labor and calculates the ACC value. Appendix I shows the cost model for the AGV-ACT system as an example. In the following subsections, we present some of the main features of the model and the various assumptions made by using the cost model for the AGV-ACT system presented in Appendix I as an example.

5.3.1 Cost of Activities

In the cost model, location activities include various entities that are listed below together with their design and operating characteristics assumed for each ACT system:

Gates: For all the ACT systems, we designed the number of lanes to be 9 for the inbound gates and 6 for the outbound gates. The operation of the gates is assumed to be 24 hours per day (8,760 hours per year).

Customs: A truck picking up an import container at the maritime container terminal has to pass through the customs before leaving the terminal. At customs both physical and also document-based verification may be performed. Customs is scheduled to work two shifts per day (16hr/day – seven days per week – 5,840 hours/year).

Berth: It is assumed that the berth operates about 16 hours per day (the ship turnaround time assumed), seven days per week (5,840 hours per year).

Storage yard: The storage yard may be divided into the import and export storage area depending on the ACT system that is analyzed. The operation of the storage yard is assumed to be a continuous 24-hour/day operation (8,760 hours per year).

Maintenance area: It is assumed that it operates 80 hours per week (4,160 hours per year).

Central Controller: The central controller governs and monitors all the activities in the terminal around the clock (24 hours per day, 8,760 hours per year).

The variable cost for locations is mainly due to consumption cost of electricity. It is calculated by multiplying 'working hours' by 'electricity consumption per hour' by 'electricity cost'. That is the multiplication of the columns 2, 3 and 4 in sheet I.1 generates the variable cost per year for locations (column 5 in sheet I.1). The electricity cost is assumed to be $0.141 per KWHR, the wholesale price in California in August of 2000.

The life of capital investment (column 6) is assumed to be 25 years (column 7) except for the central controller whose life is assumed to be 10 years. The total investment for a location is depreciated within this period and is calculated based on a straight-line depreciation method [35]. Other fixed costs are assumed to be 3% for repair, 1% for insurance and 10% for interest per year [37]. The fixed cost per year for locations (column 12) is calculated by adding the annual cost of depreciation, insurance, maintenance, and interest i.e.

Location Fixed Cost='investment'/ ('accounting life') + 'investment'('repair'+'insurance'+'interest')*

The total location cost (TC in sheet I.1) is calculated by adding up all fixed costs (FC in sheet I.1) and variable costs (VC in sheet I.1) of all locations.

5.3.2 Cost of Land

The land cost is calculated for different parts of the container terminal: berth, storage, train, and gate area. This amount is considered to be investment only. It is calculated based on the area of each part (in acre) multiplied by the land cost per acre. In Sheet I.2, we assume that the land cost per acre for the area that does not include the berth is $500K (row 10). This is very close to the price paid by the Port of Long Beach for the purchase of land in the Long Beach Port area. For the berth area, we assume a cost of $2.5 million per acre due to the higher cost for land very close to the water. The inflation rate is assumed to be 5% per year (row 12), and the interest rate 10% annually (column 6).

Based on the above assumptions, the annual land cost (column 5) can be calculated as follows [61]:

$$A = P \times R \times \left(\frac{(1+R)^n}{(1+R)^n - 1} \right)$$

where A is the annual land cost, P is the initial land investment, R is the inflation rate, and n is the accounting life, which in sheet I.2 is assumed to be 25 years.

The total annual land cost is then computed as follows:

*Total annual land cost= P*IR+A*

where *IR* is the average (over 25 years) annual interest rate that represents lost investment opportunity. In the cost model, IR is taken to be equal to 10%.

5.3.3 Cost of Equipment

The cost of equipment is calculated in the second spreadsheet of the cost model. The equipment considered depends on the type of the ACT system under consideration. In general, it includes the number of vehicles, yard cranes, quay cranes, management infrastructure (software/hardware system), etc.

The cost associated with energy consumption by each piece of equipment is considered to be the variable cost (column 7 on sheet I.3). 'Working hours per equipment' in a year (column 2) multiplied by 'the price of energy per hour per equipment' (column 5) gives us the price of energy per year per equipment (column 6). The equipment in the yard may not be utilized all the time. The utilization factor (column 4) shows the percentage of time that a specific piece of equipment has been utilized. The performance simulation model generates this factor. Multiplying the number of equipment by its utilization factor by the price of energy per year per equipment generates the equipment variable cost, i.e..

Equipment Variable Cost =
'working hours''price of energy per hour'*'number of equipment'*'utilization factor'*

The way the fixed cost of equipment is calculated is the same as that of locations. The life of capital investment (column 8) is assumed to be 15 years (column 9). The total investment for the equipment is depreciated over the above period and is calculated based on the straight-line depreciation method. Other fixed costs are 10% for repair, 1% for insurance and 10% for interest per equipment per year [37]. The fixed cost per year for equipment (column 15) is calculated by adding up all the annual cost of depreciation, insurance, maintenance, and interests, i.e.

Equipment Fixed Cost='investment'/ ('accounting life') + 'investment'('repair'+'insurance'+'interest')*

The TC value for equipment is calculated by adding the total FC value with the total VC value of all equipment.

5.3.4 Cost of Labor

The total cost of labor is calculated in the third spreadsheet of the model. It is assumed that all employees at the facility are paid for all the hours they are physically present (scheduled to work) at the terminal no matter what percentage of time they are working (Sheet I.4 column 5). The employee's regular working week is assumed to be 40 hr/week (2,080 hr/year). The employees get paid overtime, if they are scheduled to work more than a shift a day. The overtime pay is 1.5 times the base pay (columns 6 and 7).

Three shifts per day are scheduled for labor at the gate and storage. It is assumed that two checkers and one clerical person can serve two gate lanes. For 9 inbound gate lanes, we need 9 checkers and 5 clerical persons in each shift. Thus, one shift at the inbound gate consists of 14 people; while one shift at the outbound gate (6 lanes) consists of 6 checkers and 3 clerical persons. At customs, two shifts consisting of 2 port employees are scheduled to work per shift (16hr/day – seven days per week – 5,840 hours/year). The gates in the example of Appendix I are assumed to be opened 24 hours a day for 365 days a year i.e. a total of 8,760 hours.

In order to find out how many overtime working hours are needed (column 8), the total scheduled working hours (column 5) must be subtracted from the number of shifts multiplied by 2,080 (regular working hours).

Overtime working hours = 'scheduled working hours' – 2080(number of shifts)*

The total labor cost is calculated as the sum of all the salaries of the people operating the terminal.

5.3.5 Average Cost per Container

The fifth sheet of the model includes the calculation of the ACC value. The total annual cost for the yard is calculated by adding the total cost of location, land, equipment, and labor obtained from the previous sheets of the model. Dividing this number by the total annual container volume, we obtain the ACC value.

5.3.6 Exercise Cost Model for Manual Operations

In this subsection, we use the cost model to calculate the ACC value for terminal operations where vehicles and equipment are manually operated and use it as a reference point for comparing with the ACC value of the ACT systems. Since performance and cost varies from one terminal to another, we do not expect to calculate an ACC value that is representative of every terminal with similar characteristics.

The way we collected data and calculated the inputs to the cost model is as follows: Using the data from the NIT [29], [38] facility (vehicle, crane characteristics etc) we develop a container terminal that has the same throughput as the NIT and a similar layout as the AGV-ACT system.

We use the simulation model to calculate the number of vehicles and cranes with the same characteristics as those in NIT that generate the same throughput as the NIT terminal. Given the throughput of each quay crane and assuming that 5 quay cranes are working in parallel, 16 hours a day (2 working shifts), 365 days a year, the total projected annual volume of the yard is equal to, 817,600 FEUs or 1,635,000 TEUs. These values together with all the other data generated by the simulation model are fed into the cost model presented in Appendix V. The results of the cost model are summarized in Table 5.2

Table 5.2: Cost data for manual operations

Annual projected volume	1,635,200 TEUs
Annual Variable cost	$25,371,000
Annual Fixed cost	$22,571,000
Annual Land cost	$7,930,000
Annual Labor cost	$61,602,000
Total annual cost	$117,475,000
Cost per container	$143.7

The calculated ACC value for the hypothetical terminal that has a similar throughput as many current conventional terminals is found to be $143.7. This cost value is found to be within the range of values reported in the literature for current terminal operations [28]. Unfortunately, terminal operators are very reluctant to discuss or reveal cost data associated with their operations. As a result, we have very little information as how the ACC value varies among different terminals across the U.S. and abroad. During discussions we had with several terminal operators [7], [10]-[6] regarding the cost model, suggestions were made regarding salaries, number of people and working hours that were incorporated in the model.

Figure 5.2 shows how the Average Cost per Container (ACC) value in U.S. dollars varies with the initial land cost per acre. The arrow indicates the value used in the calculations of Table 5.2. In Appendix V, the initial cost of land per acre depreciated over 25 years is considered $0.5 million, which leads to the ACC value of $143.7.

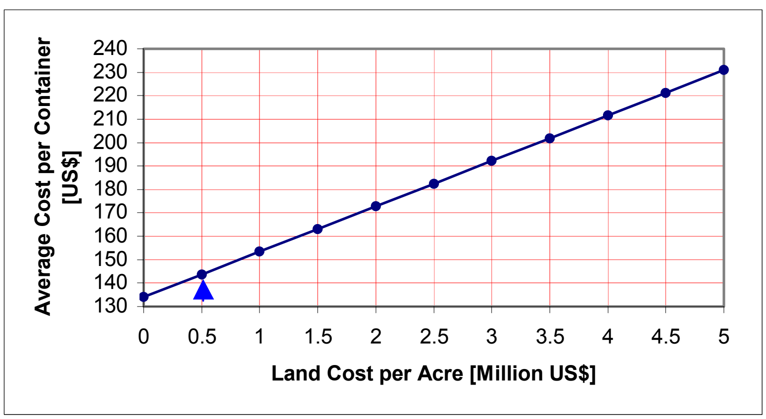

Figure 5.2: Manual operation: Average Cost per Container (ACC) vs. land cost per acre (arrow indicates the value used in cost analysis)

Figure 5.3 illustrates the sensitivity of the ACC with respect to the cost of labor. In Appendix V, the total labor cost per year is assumed $60.6 million, which leads to an ACC equal to $143.7 and is shown by an arrow in Figure 5.3. The Figure shows that changes in the labor cost have a great impact on the ACC value. For instance, increasing the annual labor cost by 50% (a $29.4 million increase) causes more than 26% increase in the ACC value.

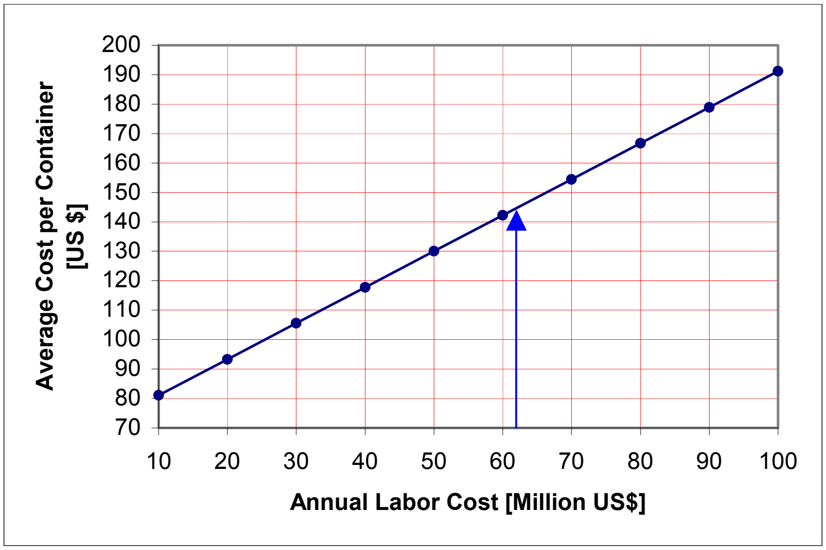

Figure 5.3: Manual operation: Average Cost per Container (ACC) vs. annual labor cost (arrow indicates the value assumed in cost analysis)

6. AUTOMATED CONTAINER TERMINAL USING AGVS

In this section, we focus on the design of an ACT that uses AGVs to transfer vehicles between the gate, train and quay crane buffers and the storage yard. Figure 6.1, shows the basic configuration of the proposed AGV based ACT (AGV-ACT) system.

In order to meet the desired storage capacity of about 22,000 TEUs calculated in section 6.2 the size and layout of the storage is chosen according as follows: The storage yard consists of 36 stacks of containers and is divided into two sections. The import storage area where the import containers are stored and is closer to the gate and the export storage area that is closer to the quay cranes. Each stack has 216 containers when containers are stacked 3-high and 288 if stacked 4-high. Assuming stacks of 4-high, the maximum capacity of the storage yard is 10,368 containers. We assume that the containers are 40-foot which gives a total capacity for the storage yard of 20,736 TEUs. In addition to the storage yard, containers can also be stored at the gate buffer whose maximum storage capacity is 1,728 TEUs giving a total storage capacity for the terminal of 22, 464 TEUs which is close to the desired capacity.

The roads as well as location of the stacks are designed using considerations such as mobility, turning radius of vehicles and efficiency. The details of these calculations are not included in this report.

Given the layout and size of the stacks and the road configurations shown in Figure 6.1, the terminal dimensions are calculated to be 1,633*1,875 ft^2 (70.29 acres). The terminal has strong similarities with existing terminals in the U.S. and abroad. In particular, it has similarities with the Sea-Land terminal at the Port of Long Beach.

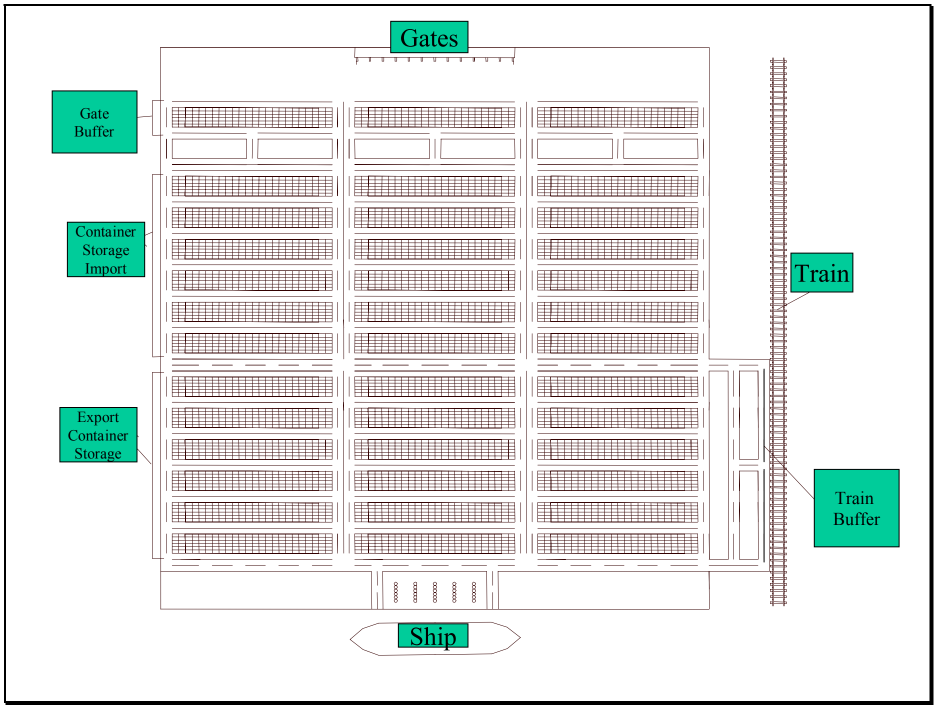

Figure 6.1: AGV based Automated Container Terminal (AGV-ACT) layout

Two types of roads are used in the proposed container terminal: transit roads, and working roads. The transit roads are denoted by dashed lines and the working roads by solid lines. No loading or unloading takes place along the transit roads as these roads are used by AGVs to get to different points in the terminal. Loading and unloading takes place along the working roads. A horizontal four-lane road separates the export and import container storage areas from each other. Each area as well as the gate buffer area is divided into three blocks by two vertical four-lane transit roads. The vertical four-lane transit roads allow direct access between the gate buffer and the berth in order to deliver containers between the berth and the gate without intermediate storage in the yard. A similar access is provided in the rail side.

The terminal operates as follows: A truck arrives at the gate, it checks in and moves along the gate buffer where it gets unloaded by a yard crane. The truck either exits the gate or it gets loaded again at the buffer before exiting. The yard crane at the gate buffer loads the container directly to an AGV or if an AGV is not available, it stores it at the buffer temporarily. An export container loaded to an AGV at the gate buffer is either transferred directly to a quay crane to be loaded on the ship, or it is transferred to a particular stack to be unloaded by a yard crane and stored in the yard. Similarly, an AGV loaded with an import container by a quay crane transfers the container to the yard for storage or to the gate or the train buffer. At the train buffer, yard cranes load and unload containers between the AGVs and the train.

A central controller with a management system synchronizes all the operations. Information technologies and sensors are used for communication, guidance and navigation. The use of these technologies will enable a central computer system to know the location of each container, the location and operating characteristics of each piece of equipment at any point in time and communicate that information to all parts of the terminal. In addition, it will register and track incoming containers by communicating with the gate, train and ship. Such a system can be developed using different types of information and sensor technologies of the kind discussed in section 3 of this report. The development of such a system goes beyond the purpose of this project. In this report, we assume however that the development of such a system is possible and use it to proceed with the development of the other components of the yard and evaluation of the system.

The main characteristics of the AGV-ACT system are the same as those of the general ACT described in section 4 and summarized in subsection 4.2. What is specific to the AGV-ACT system are the number of yard cranes needed in the storage yard and the number of AGVs to perform the various tasks in order to meet the expected container volume as described in section 4. Before we choose the amount of equipment for the various tasks another design aspect of the yard is the set of rules and logic that controls the motion of the AGVs in the yard. The AGVs have to follow certain traffic rules and protocols in order to avoid collision, possible deadlocks and congestion in the yard and complete tasks in an efficient way.

6.1 AGV Control Logic and Traffic Rules

The transfer of containers between different transportation modes and storage area to be carried out by the AGVs in the AGV-ACT system can be divided into three tasks as shown in Figure 6.2.

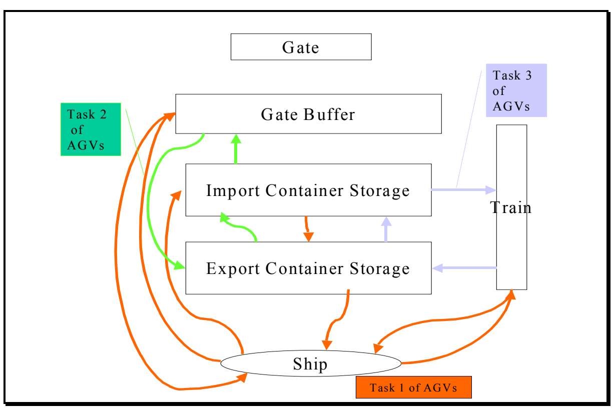

Figure 6.2: Different Tasks assigned to AGVs

Task 1: Under this task the following sub tasks are to be preformed:

1. Transfer of containers between the quay crane and gate buffers
2. Transfer of containers between the quay crane buffers and the storage area
3. Transfer of containers between the quay crane and train buffers

Task 2: Under this task containers are transferred between the gate buffer and the storage area.

Task 3: Under this task the containers are transferred between the train buffer and the storage area.

The AGVs are to perform the above tasks efficiently without the possibility of collision, conflicts or deadlocks. The terminal could be viewed as a network of intersections with *nodes* where loading and unloading takes place. The control logic and protocols that dictate the motion of the AGVs have to guarantee smooth traffic flow, and provide the required mobility as well as avoid or resolve any conflict or deadlock. In our design, the AGVs are allowed to travel on the right lane of a two-lane road in their moving direction. Therefore, once the pick-up and drop-off points are assigned to a particular AGV, the *path* is uniquely determined by using the intermediate nodes. The control logic algorithm must be able to resolve any possible conflict between AGVs. A *conflict* between two or more AGVs may occur during the following situations:

1) Arriving at an intersection from different path segments at the same time. A *segment* is defined as a part of a road located between two adjacent nodes. To resolve this type of conflict**,** we use the *'Modified First Come First Pass'* (MFCFP) protocol [26]. Although the protocol is complicated, it can resolve the conflict in an efficient way by allowing many vehicles to pass through the intersection without collision.

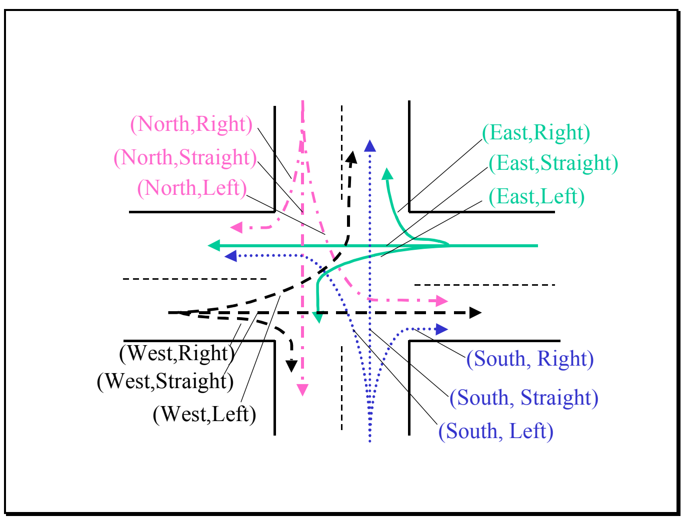

Figure 6.3: All possible directions of AGVs reached at, and passing through an intersection

Figure 6.3 shows all possible moves an AGV can make when approaching and leaving an intersection. The incoming directions toward the intersection are labeled east, west, south and north based on the direction of arriving at the intersection. The outgoing directions are labeled right, left and straight, based on the direction of the turn the AGV would make when leaving the intersection. For instance, (East, Right) means that an AGV is approaching the intersection from the east and will make a right turn. If two or more AGVs are approaching an intersection during a certain time interval, and there is no possibility for a collision between them, they will proceed with their maneuvers simultaneously. If there is a possibility of a collision, the AGV that arrives at the intersection first has the right of way according to the First Come First Pass (FCFP) rule. The other vehicles that reached the intersection have to wait until the intersection is clear by the first AGV before proceeding. If two or more AGVs arrive at the intersection at exactly the same time (very rare situation, in simulations no such case was ever encountered) then the choice as to which of the AGVs will proceed and which will wait until the intersection is clear is done randomly. Table 6.1 shows the directions of the possible conflicts based on the timing of arrival of AGVs at an intersection. For instance, if an (East, Straight) AGV arrives first, then the (West, Left) and (South, Straight) AGVs have to stop until the first AGV finishes its maneuver i.e. clears the intersection.

Table 6.1: The first arriving AGV and the approaching AGVs that need to stop to avoid collision at intersection

First Arriving AGV	**(East, Straight)**	**(West, Straight)**	**(South, Straight)**	**(North, Straight)**
Approaching AGVs that need to stop	(West, Left) (North, Straight) (North, Left) (North, Right) (South, Straight) (South, Left)	(East, Left) (North, Straight) (North, Left) (South, Straight) (South, Left) (South, Right)	(East, Straight) (East, Left) (East, Right) (West, Straight) (West, Left) (North, Left)	(East, Straight) (East, Left) (West, Straight) (West, Left) (West, Right) (South, Left)
First arriving AGV	(East, Left)	(West, Left)	(South, Left)	(North, Left)
Approaching AGVs that need to stop	(West, Straight) (West, Right) (South, Straight) (South, Left) (North, Straight) (North, Left)	(East, Straight) (East, Right) (South, Straight) (South, Left) (North, Straight) (North, Left)	(East, Straight) (East, Left) (West, Straight) (West, Left) (North, Straight) (North, Right)	(East, Straight) (East, Left) (West, Straight) (West, Left) (South, Straight) (South, Right)
First arriving AGV	(East, Right)	(West, Right)	(South, Right)	(North, Right)
Approaching AGVs that need to stop	(West, Left) (South, Straight)	(East, Left) (North, Straight)	(West, Straight) (North, Left)	(East, Straight) (South, Left)

<u>2) Traveling along the same path with different speeds.</u> Another possible situation where collisions may occur is when AGVs are traveling along the same path with different speeds in the same transit lane. This situation is possible as loaded AGVs are assumed to have a lower speed than the ones that carry no load. To prevent this kind of collision, we use *Low Speed Zone(s)* in the portion(s) of the transit lanes where two or more AGVs with different traveling speeds may exist [26]. When a particular AGV enters the Low Speed Zone, it simply reduces its speed down to that of the loaded AGV. For the container yard under consideration, the Low Speed Zone is the portion of the horizontal transit lane in Figure 6.1, which is located adjacent to the berth area.

<u>3).An AGV stops ahead in the moving direction.</u> The intervehicle spacing between the AGVs traveling in the same direction in the same lane is chosen to be 45 ft so that if a particular AGV stops in order to perform a task or due to an emergency the following AGVs have enough time to stop without colliding with each other.

The control logic that dictates the motion of the AGVs in order to perform tasks 1 to 3 without collision, conflicts and deadlocks for the proposed AGV-ACT system is described by the flowcharts shown in Figures 6.4, 6.5.

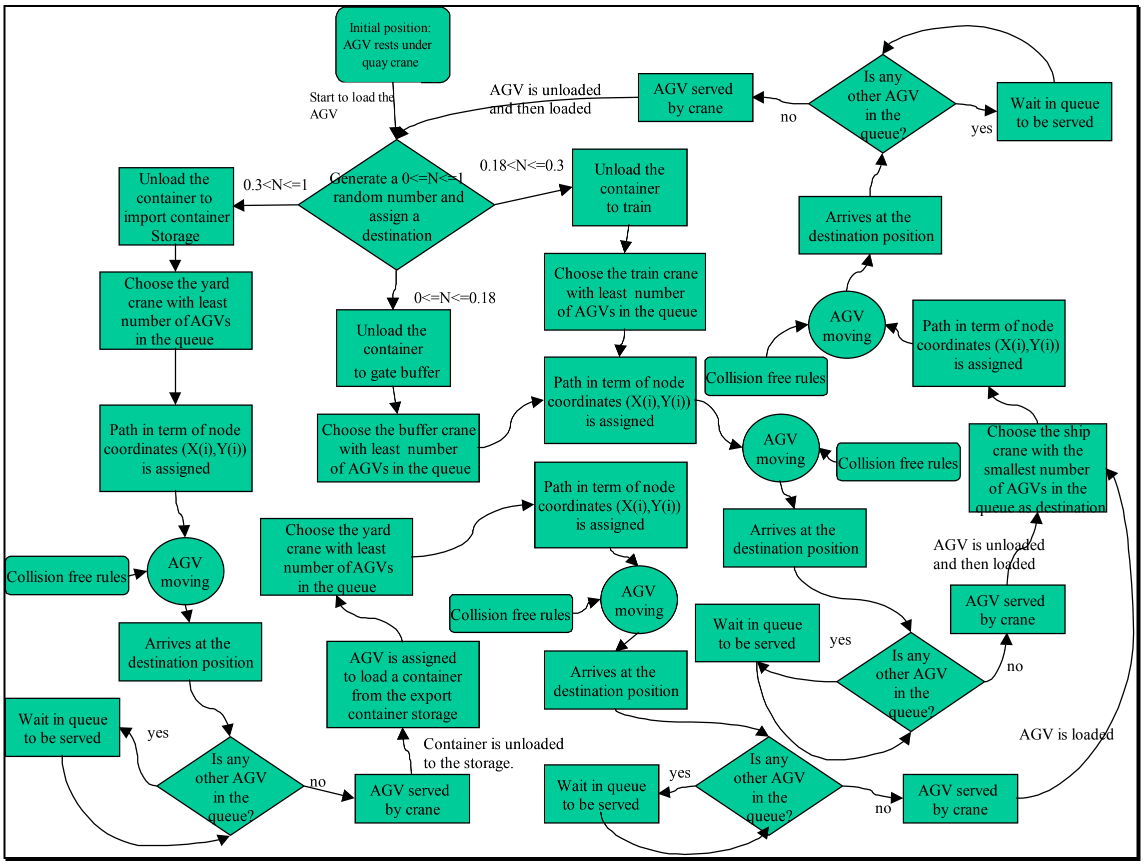

Figure 6.4: Control logic of AGVs for task 1

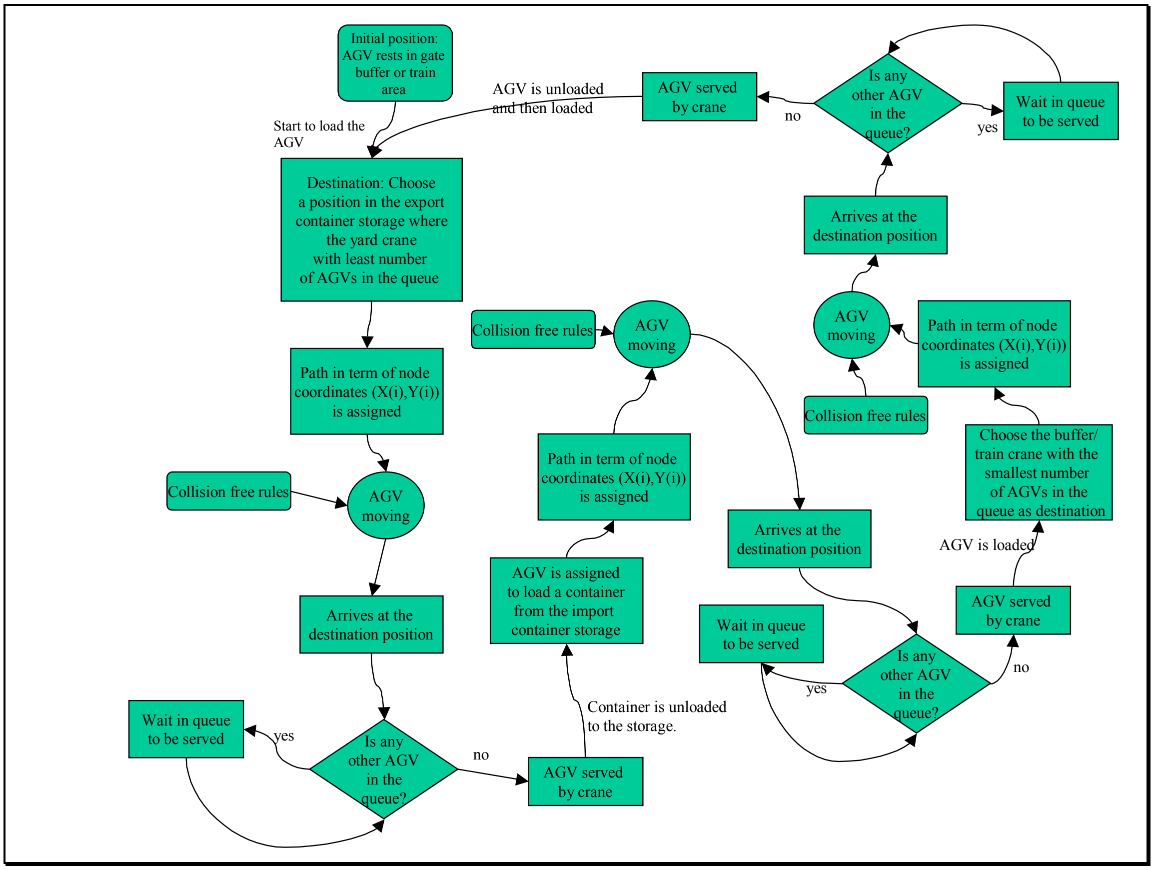

Figure 6.5: Control logic of AGVs for tasks 2 and 3

6.2 Characteristics of Equipment

The characteristics of equipment used by the AGV-ACT system are considered to be the same as those described in section 4.6 for the general ACT layout. The additional equipment specific to the AGV-ACT system is that associated with the storage yard and is discussed below:

Yard cranes for import, export storage yard: The yard crane's speed is assumed to be 5 mph. It takes 15 seconds to line up with the stack, and an average time of 45 seconds to unload or load an AGV. We assume that one yard crane is used for each stack that is a total of 36 yard cranes are used in the yard. The assumption of one crane per stack is made mainly to simplify the control logic of AGVs and cranes. Therefore the number of yard cranes has not been optimized in this study.

Speed of AGVs: We assumed that an empty AGV travels with a speed of 10 mph while a loaded AGV travels with the speed of 5 mph. These speeds are compatible with current AGVs used for the same application at the Port of Rotterdam. As indicated in section 2, however, these speeds can be considerably increased, especially for loaded AGVs.

Number of AGVs: The minimum number of AGVs that are required to meet the demand of the AGV-ACT system is determined by exercising the simulation model of the terminal for different combinations of AGVs. The objective is to have a sufficient number of AGVs to feed the quay cranes fast enough so that the cranes operate close to their maximum capacity. This in turn will guarantee that the ship turnaround time is minimized. We assume that the system is loaded, i.e., there are always containers ready to be processed by the AGVs at each buffer. While this scenario may not be true all the time, the system should have sufficient number of AGVs to deal with such possible extreme situation. The results of the simulations are presented in Figure 6.6.

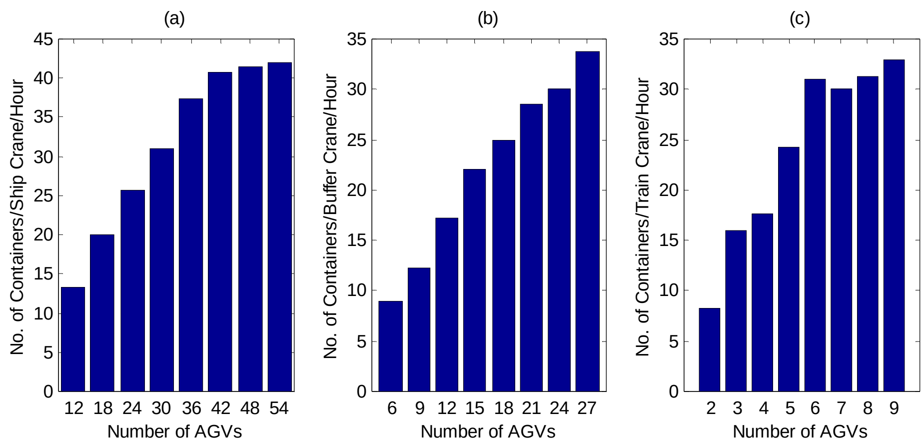

Figure 6.6: (a) throughput of quay crane, (b) throughput of buffer crane and (c) throughput of train crane versus the number of AGVs used

In Figure 6.6, the number of AGVs for tasks 1, 2 and 3 satisfy the ratio 6:3:1. For example, the simulation run that has 24 AGVs serving the quay crane buffer is the same simulation run for 12 AGVs serving the gate buffer and 4 AGVs serving the train buffer.

As shown in Figure 6.6(a), 42 AGVs are sufficient to meet the maximum expected capacity of the quay cranes, which is 42 moves per hour per quay crane (double mode i.e. combined loading and unloading). Figure 6.6(b) and (c) show the throughputs of the cranes at the gate and train buffers. The throughput increases as the number of AGVs increases. Figure 6.6(c) shows that as the number of AGVs serving the train buffers increases from 6 to 7, the throughput of the train buffers drops slightly. The reason for this drop is the effect of noise that is assumed to be present in the cranes' operating characteristics. The number of AGVs for each task is calculated by choosing the combination with the minimum total number of AGVs that meet the expected maximum demand for Tasks 1, 2 and 3. Considering that the maximum average throughput of the cranes at the gate and train buffers (calculated earlier) is 34 and 28.3 moves per hour per crane, it follows from Figure 6.6 that the combination (48, 26, 6) - i.e. 48 AGVs for Task 1, 26 for Task 2, and 6 for Task 3, a total of 80 AGVs - will meet the demand for the AGV-ACT system. Note that in addition to the 80 AGVs needed to meet the expected demand we assume an additional 5 AGVs to be used as spares in order to handle emergencies and meet maintenance schedules.

6.2.1 Summary of Characteristics of Equipment

Table 6.2 summarizes the characteristics of the AGV-ACT system that are described in detail above:

Table 6.2: AGV-ACT: Summary of the physical characteristics of the terminal

Size of the terminal	1,633*1,875 ft^2 (70.29 acres)
Storage Capacity	22, 464 TEUs
No. of Berths	1
Capacity of quay cranes	42 moves per hour (combined loading and unloading)
No. of quay cranes	5
Gates service time	3 min inbound-gate, 2 min outbound-gate
No. of gate lanes	9 inbound, 6 outbound
Capacity of yard cranes at buffers	Yard crane's speed is 5 mph, takes 15 sec. to line up with the container, and an average time of 65 seconds to unload/load an AGV.
No. of yard cranes at gate buffer	6
No. of yard cranes at Train buffer	2
Capacity of yard cranes at storage yard	Yard crane's speed is 5 mph, takes 15 sec. to line up with the container, and an average time of 45 seconds to unload or load an AGV.
No. of yard cranes at Import and Export storage yard	36
Speed of AGVs	10 mph for empty, 5 mph for loaded AGVs
No. of AGVs	85 (48 for Task 1, 26 for Task 2, 6 for Task 3 plus 5 spare)

A variance of 10% is assumed in all values associated with speeds and time with the exception of the speed of the quay cranes where a variance of 15% is assumed.

6.3 Performance Analysis

The characteristics of the AGV-ACT system are used as inputs to the simulation model together with the arrival/departure patterns of containers brought in and taken out by ships/trucks/trains as shown in Tables 4.1 to 4.5. We assume that the patterns of container arrivals and departures to/from the terminal by ship, trucks and train are repeated every 24 hours so that a 24-hour simulation was sufficient to make projections about annual productivity. This assumption may not be valid today due to the randomness that exists in the system. The use of automation and information technologies however coupled with optimum dispatching and scheduling techniques will lead to scenarios that are very close to the assumed one. The results of a one-day (24-hour) simulation are shown in Table 6.3.

Table 6.3: AGV-ACT: Performance results for one-day (24-hour) simulation

Ship turnaround time	16.81 hours
Throughput	40.45 containers/ship crane/hour
Throughput Per acre	0.576 containers/ship crane/acre/hour
Annual Throughput per acre	35,310 TEUs/acre/year
Gate utilization	66.03%
Truck turnaround time (doesn't include time at the gate)	126.75 seconds
Throughput (train crane)	29.42 containers/hour/crane
Throughput (buffer crane)	33.7 containers/hour/crane
Idle rate of AGVs over 24 hours	36.3%
Idle rate of yard cranes over 24 hours	70.2%
Idle rate of buffer cranes over 24 hours	12.7%
Idle rate of train cranes over 24 hours	23.0%
Idle rate of ship cranes over 24 hours	31.7%
Container dwell time	19.1 hours

The ship turnaround time obtained from the simulations is 16.81 hours, which is close to the desired 16 hours. We should note that for a maximum speed of 42 moves per hour per crane the best ship turnaround time possible is 16.2 hours. The difference between the simulated and the best possible ship turnaround time is mainly due to the variance introduced in simulations for the characteristics of the quay cranes and other equipment.

It should be noted that the idle rate of the cranes is calculated over a period of 24 hours. Since the ship was at the berth for only 16.81 hours, it means that the quay cranes were idled for 24-16.81=7.19 hours, which is 30.0% of the time that is close to the 31.73% obtained from simulations indicating that while the ship was at the birth the quay cranes were operating very close to maximum capacity. Similarly, after the ship is serviced the AGVs responsible for the task of serving the ship will be idle until the next ship arrives about 7 hours later. This accounts for most of the 36.3% idle rate for the AGVs.

The throughput of the terminal is close to the maximum possible indicating that the AGVs met the service demand imposed by the quay cranes' speeds.

The idle rate of the yard cranes was found to be high. This is due to two reasons: First reshuffling has not been considered in our simulation, which implies that the cranes had it easy -- something that may not be true in a real situation. One however could argue that the use of automation could improve yard planning to the point that the number of reshufflings or unproductive moves is negligible. The second reason, which was stated earlier, is that the number of yard cranes has not been optimized. Instead, one yard crane was assumed for each stack in order to simplify the operations and the control logic of the AGVs. A smaller number of yard cranes could be used to achieve the same throughput. This can be achieved by having yard cranes serving two stacks instead of one. In such case, the crane may have to cross roads used by the AGVs and therefore their motion relative to that of the AGVs has to be controlled and synchronized in order to avoid collisions, delays and deadlocks. Another way is to change the configuration of the stacks so that a single crane can serve more than one stack without crossing roads used by the AGVs. These possibilities have not been explored in this study.

6.4 Cost Analysis

The simulation results obtained in subsection 6.3 together with the characteristics of the terminal are used to calculate the average cost of moving a container through the terminal, i.e. the ACC value, by exercising the cost model for the AGV-ACT system presented in Appendix I. In addition to these data the model is fed with several other parameters and data that are necessary for the operation of the terminal. These include number of people, salaries and cost data regarding equipment, land, facilities etc. Most of the cost data are collected from the open literature [28], [37] and modified after discussions with experts in the field such as terminal operators [7], [9], [10] and researchers from August Design, Inc.

The equipment characteristics used by the model are the same as those listed in Table 6.2. Appendix I shows the various inputs and data used to obtain the following calculations shown in Table 6.4.

Table 6.4: AGV-ACT: Cost results

Annual projected volume	2,482,000 TEUs
Annual Variable cost	$28,408,000
Annual Fixed cost	$39,046,000
Annual Land cost	$7,930,000
Annual Labor cost	$20,113,000
Total Annual cost	$95,498,000
Average Cost per container (ACC)	$77.0

The results obtained from the cost model presented in Appendix I, like all models, depend on the validity of the input variables. For instance, one may argue that the price of the land differs based on the geographical location, which will affect the cost results presented above. Figure 6.7 illustrates the sensitivity of the average cost per container (ACC) with respect to land cost per acre. In Appendix I, the initial cost of land per acre depreciated over 25 years is considered to be $0.5 million, which leads to the ACC value of $77.0. Figure 6.7 shows how the ACC value varies with the initial land cost per acre. The arrow indicates the value used in the calculations of Table 6.4. The Figure shows that changes in the land price have a smaller effect on the ACC value. For instance, increasing the value of the land price per acre by 50% (a $0.5 Million increase) causes less than 9% increase in the ACC value, i.e. the ACC value becomes $83.3. Since we are dealing with many containers that may be an important factor, as it translates to an annual cost increase of $7.9 million for the AGV-ACT terminal.

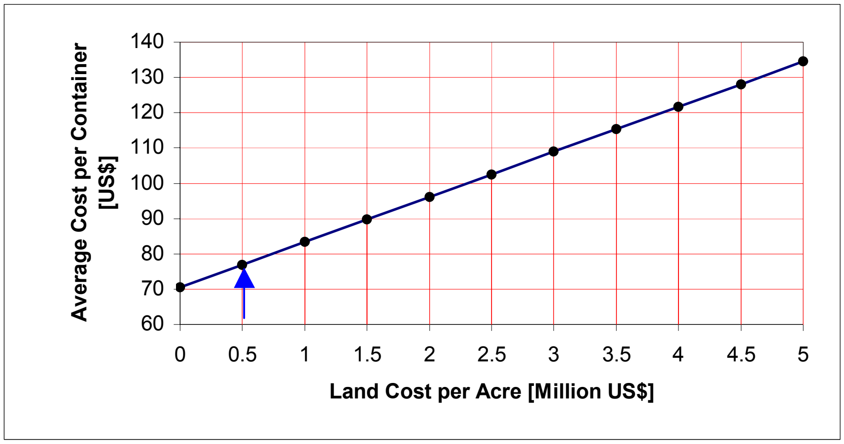

Figure 6.7: AGV-ACT: Average Cost per Container (ACC) vs. land cost per acre (arrow indicates the value assumed in the results of Table 6.4)

Figure 6.8 illustrates the effect of the changes in the price of AGVs and its infrastructure on the ACC value. In our analysis in Table 6.4, the price of AGVs together with its infrastructure was assumed to be \$200k per unit (column 8, row 2 of sheet I.3). The sensitivity analysis in Figure 6.8 shows that a 50% increase in the price of AGVs leads to less than 2.5% increase in the value of ACC.

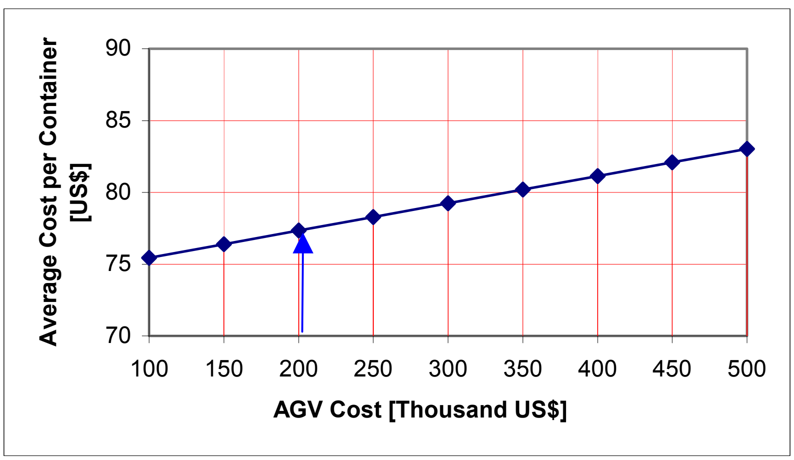

Figure 6.8: AGV-ACT: Average Cost per Container (ACC) vs. an AGV cost (arrow indicates the value assumed in the results of Table 6.4)

7. AUTOMATED CONTAINER TERMINAL USING A LINEAR MOTOR CONVEYANCE SYSTEM

Linear Motor Conveyance Systems (LMCS) are among the technologies that have recently been considered for cargo handling. A prototype of a linear motor conveyance system has been constructed and successfully tested in Eurokai Container Terminal, Hamburg [26]. The promise of employing linear motor technologies lies in its very high positioning accuracy, reliability and robustness of equipment. Figure 7.1 shows part of a conceptual container yard using LMCS. A linear induction motor operates on the same basic principles as a conventional, rotary induction motor, except that instead of the coils being wound around a shaft, the entire assembly is "unwound" into a linear configuration. Running current through the unrolled, flattened stator moves a metal flat blank, which is placed above the stator, as though it is a rotor [13]. By controlling an array of linear motors that are placed underneath a platform, one can accurately move the platform (given that it is on a sliding or rolling surface).

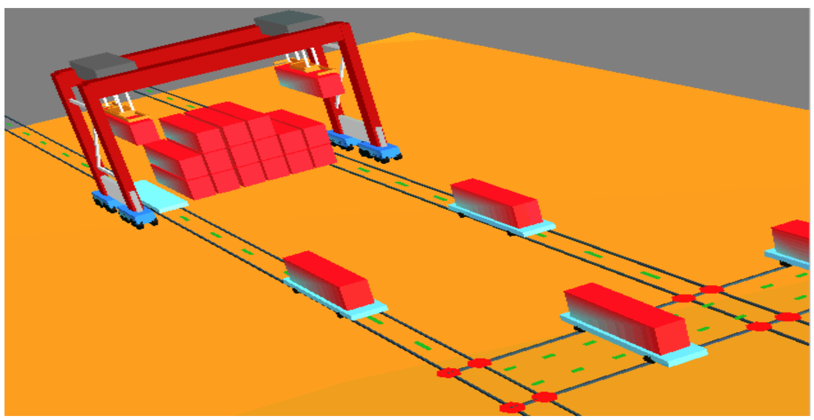

Figure 7.1: Transfer of containers in a yard using LMCS

Linear motor systems have several attractive characteristics: The motors are very reliable and last a long time. Platforms, which are conveyed via linear motor technology, are unmanned and have very few moving parts. The wheel assembly on the platform is the only moving part. In addition, no power is required onboard the platform. Linear motors are currently used widely for smaller scale, manufacturing applications, such as conveyance systems for sorting systems or assembly plants. However, the technology is scalable to larger tasks. A system such as this could be ideally suited for port and terminal operations. Once the necessary infrastructure is in place, and the shuttles to carry the containers are constructed, the system could be operated autonomously without any constraints on the hours of operation, and at an expected lower maintenance cost.

7.1 Terminal Layout

As shown in Figure 7.2, the LMCS yard layout is identical to that of the AGV-ACT system of Figure 6.1 except that the paths are pre-built guide ways. For instance, a two-lane road in the AGV–ACT system becomes a two- guide way tracks that allow shuttles to travel in opposite directions.

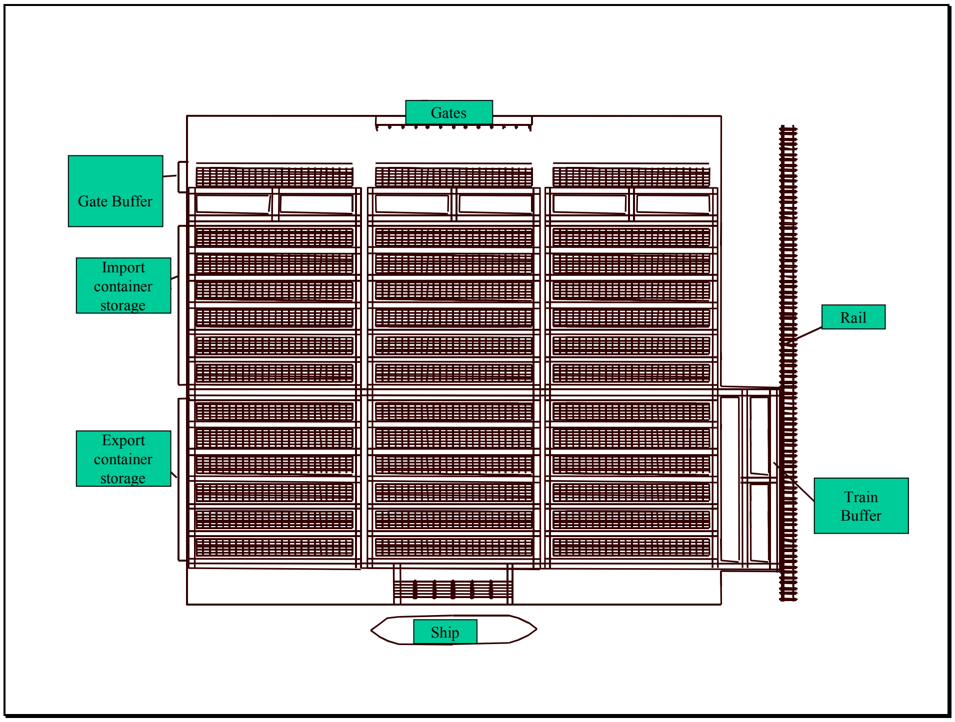

Figure 7.2: Automated container terminal layout using LMCS

The AGVs are replaced with shuttles that are moving on the linear motors conveyance system. The shuttles can be considered as AGVs moving on a fixed path. Consequently, the control logic of the shuttles is similar to that of AGVs described in the previous subsection and is not repeated. The number of shuttles and other equipment is calculated in subsection 7.2 in order to meet the demand and operational scenario described in section 5.

7.2 Characteristics of Equipment

The characteristics of equipment used for the LMCS-ACT system to meet the demand are the same as those of the general ACT described in section 4. The characteristics and the number of yard cranes are the same as in the AGV-ACT system. The speed of empty shuttles and loaded shuttles are assumed to be the same as those in AGVS. We assumed that at each corner of the guide way, it takes 5 seconds for the shuttle to change its direction of movement. Despite this change, the number of shuttles needed to meet the demand was calculated to be the same as the number of AGVs used in the AGV-ACT system. Table 7.1 summarizes the characteristics of the LMCS-ACT system.

Table 7.1:LMCS-ACT: Summary of the physical characteristics of the terminal.

Size of the terminal	1,633*1,875 ft^2 (70.29 acres)
Storage Capacity	22, 464 TEUs
No. of Berths	1
Capacity of quay cranes	42 moves per hour (combined loading and unloading)
No. of quay cranes	5
Gates service time	3 min inbound-gate, 2 min outbound-gate
No. of gate lanes	9 inbound, 6 outbound
Capacity of yard cranes at buffers	Yard crane's speed is 5 mph, takes 15 sec. to line up with the container, and an average time of 65 seconds to unload/load an AGV.
No. of yard cranes at gate buffers	6
No. of yard cranes at Train buffer	2
Capacity of yard cranes at storage yard	Yard crane's speed is 5 mph, takes 15 sec. to line up with the container, and an average time of 45 seconds to unload or load an AGV.
No. of yard cranes at Import and Export storage yard	36
Speed of shuttles	10 mph empty, 5 mph loaded
No. of shuttles	82 (48 for Task 1, 26 for Task 2, 6 for Task 3, and plus 2 spare)

A variance of 10% is assumed in all values associated with speeds and time with the exception of the speed of the quay cranes for which a variance of 15% is assumed.

7.3 Performance Analysis

A simulation model for the LMCS-ACT system is developed and used to simulate the terminal based on the operation scenario given in section 4.7. The results are shown in Table 7.2.

Table 7.2: LMCS-ACT: Performance results for one-day (24-hour) simulation.

Ship turnaround time	16.83 hours
Throughput	40.40 containers/ship crane/hour
Throughput Per acre	0.575 containers/ship crane/acre/hour
Annual Throughput per acre	35,310 TEUs/acre/year
Gate utilization	66.03%
Truck turnaround time (doesn't include time at the gate)	126.8 seconds
Throughput (train crane)	29.42 containers/hour/crane
Throughput (buffer crane)	33.7 containers/hour/crane
Idle rate of shuttles over 24 hours	36.2%
Idle rate of yard cranes over 24 hours	70.2%
Idle rate of buffer cranes over 24 hours	12.7%
Idle rate of train cranes over 24 hours	23.0%
Idle rate of ship cranes over 24 hours	31.8%
Container dwell time	19.1 hours

Since the terminal yard layout, control logic of vehicles, speed of the vehicles, and the characteristics of the yard equipment are exactly the same for both AGV-ACT and LMCS-ACT systems, the performance of the two terminals is almost identical. The difference is that AGVs are moving freely in the yard, while LMCS shuttles are traveling on fixed guide paths. The differences between the AGV-ACT and the LMCS-ACT systems are in the cost as shown in the following section.

7.4 Cost Analysis

The cost data for the LMCS-ACT system was much more difficult to obtain as no such system of the scale under consideration is in operation. Researchers at August Design, Inc. provided most of the data related to the cost of the shuttles, rail system and infrastructure that controls and manages the movement of shuttles based on their experience with similar systems and knowledge about costs of equipment. The cost model and cost analysis for the LMCS-ACT system is presented in Appendix II and the results are summarized in Table 7.3.

Table 7.3: LMCS-ACT: Cost results

Annual projected volume	2,482,000 TEUs
Annual Variable cost	$30,008,000
Annual Fixed cost	$124,486,000
Annual Land cost	$7,930,000
Annual Labor cost	$20,113,000
Total Annual cost	$182,539,000
Average Cost per container (ACC)	$147.1

The cost of the LMCS infrastructure accounts mostly for the high LMCS-ACT total annual cost. The initial infrastructure cost is assumed to be $500 Million. The cost was computed based on a cost of $50,000 per yard of the LMCS [7]. This cost includes preparation of the ground, cost of the rails and installation cost. Due to the reliability of the LMCS system, however, and low maintenance requirements, the LMCS is depreciated over 30 years instead of the 15 years that was used for the AGVs. The ACC value is very sensitive to the infrastructure cost as indicated in Figure 7.3. A 20% increase in the cost of the LMCS infrastructure increases the ACC value by 10%.

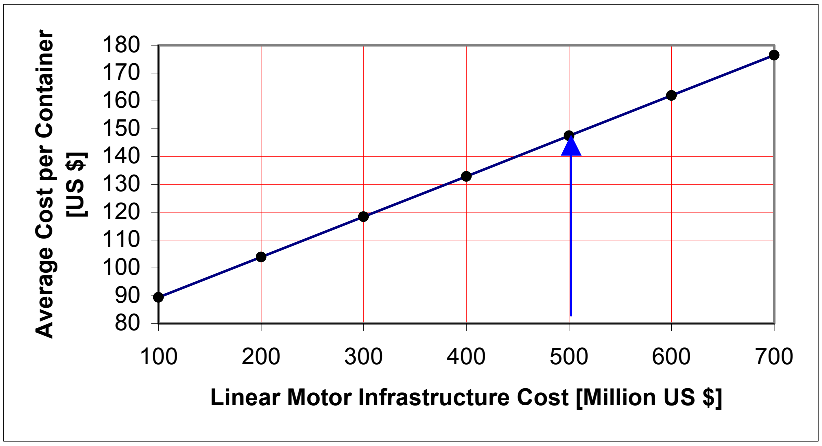

Figure 7.3: LMCS-ACT: Average Cost per Container (ACC) vs. the LMCS infrastructure cost (arrow indicates the value assumed in cost results of Table 7.3)

Figure 7.4 shows how the ACC value varies with the land cost per acre.

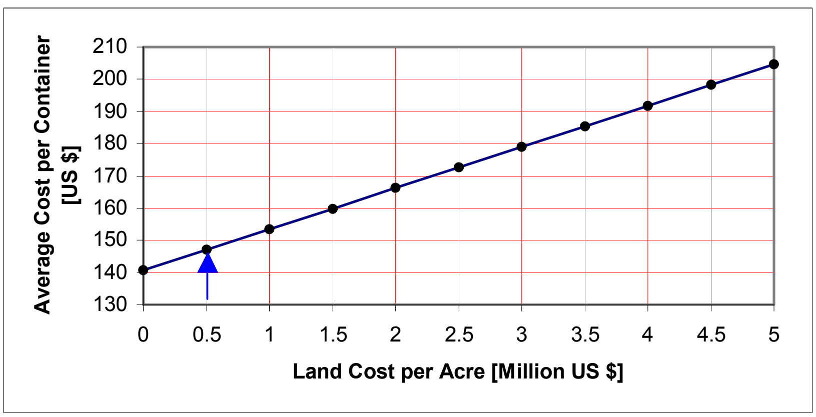

Figure 7.4: LMCS-ACT: Average Cost per Container (ACC) vs. land cost per acre (arrow indicates the value assumed in cost results of Table 7.3)

Our cost analysis shows that the LMCS-ACT system is costly compared with the AGV-ACT system that has almost identical throughput and performance. The difference in cost comes mainly from the cost of installing a LMCS in the terminal, which at the cost of $50,000 per linear yard is considerable. To make the LMCS-ACT comparable to the AGV-ACT system in terms of cost, the cost of the LMCS has to be reduced to about $20,000 per linear yard. The possibility for such a drastic reduction has not been explored in this work.

8. AUTOMATED CONTAINER TERMINAL USING A GRID RAIL (GR) SYSTEM

The concept of loading and unloading containers in the yard using overhead rail and shuttles is another attractive way of utilizing yard space more efficiently. Figure 8.1 shows an example of this concept known as GRAIL designed by Sea-Land and August-Design. It uses linear induction motors, located on overhead shuttles that move along a monorail above the terminal. The containers are stacked beneath the monorail and can be accessed and brought to the ship as needed. Sea-Land has a portion of this system running in its highly successful Hong Kong terminal but the shuttles are driven manually.

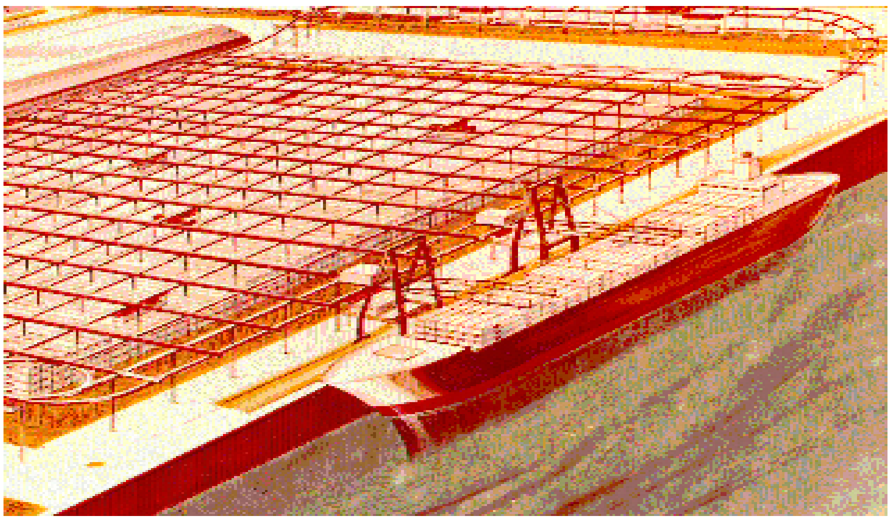

Figure 8.1: The Sea-Land/August Design, Inc. GRAIL system

In Task 1.2.6.2 under CCDoTT the concept of the overhead grid rail (GR) system was used to design, simulate and evaluate a GR based ACT (GR-ACT) system [27]. The GR system is modular in the sense that it is a collection of grid rail units similar to the GRAIL. In [27] each unit is optimized by using a new dispatching algorithm for assigning shuttles to containers within the unit. The results developed in [27] are used in this report in order to compare the GR-ACT system with other automated systems.

8.1 GR-ACT: Terminal Layout

The GR-ACT system shown in Figure 8.2 is similar to that of the AGV-ACT system with the only difference that the storage yard is replaced with 8 GR units. The use of several GR units instead of a large one is done for robustness and reliability purposes as well as for simplifying the operations as explained in [27]. The number 8 of units is chosen so that the storage capacity of the GR-ACT system is the same as that of the AGV-ACT and LMCS-ACT systems. Due to the high density of the GR units, however, less land is needed to obtain the same storage capacity. As a result, the total size of the terminal is

1,472*1,875 ft^2 (63.36 acres) versus 70.29 acres for the AGV-ACT and LMCS-ACT systems for the same storage capacity of about 22,000 TEUs.

The 8 GR units communicate with the other parts of the yard through the GR Gate/Train (G/T) buffers: 1a, 2a,..., 8a and the GR quay buffers: 1b, 2b, …8b. There are vertical transit roads between each two units. These transit roads are used for transferring containers – using AGVs – to/from the gate buffer directly to the berth area. The containers that have to stay in the yard are stored in the GR units. The units number 1, 2 and 7, 8 are used for storing import containers to be taken away by trucks and trains. The units 3, 4 and 5, 6 are used to store export containers brought in by trucks and trains. Note that in each unit only one operation can take place at each time. For example, the shuttles within GR unit 1 can serve either the buffer 1a or 1b but not both at the same time. The interaction of the GR unit buffers with AGVs is as follows:

One AGV in one cycle goes from gate or train buffer with an export container, unloads the container at the G/T buffer (either 3a or 4a) and travels empty to the G/T buffer (either 1a or 2a) where it is loaded by an import container and travels back loaded to the gate or train buffer. The AGVs at the rest four units are operating as follows: When the ship is present, an AGV in one cycle goes from the quay buffer (either 5b or 6b) with an export container, unloads the container at the quay crane, loads an import container from the quay crane and travels to the GR quay buffer (either 7b or 8b) where it unloads the container to the quay buffer and travels empty back to the GR buffers 5b or 6b. In the case where there are no import containers available at the quay crane the AGV returns empty to GR buffers 5b or 6b where it is loaded with a new export container. Similarly, in the case where there are no export containers at the buffers 5b and 6b the AGV transfers containers from the quay crane to buffers 7b and 8b. When the ship is not present then the units 5, 6, 7, and 8 operate similar to the units 1, 2, 3, 4, i.e., one AGV in one cycle goes from the gate or train buffer with an export container, unloads the container at the G/T buffer (either 5a or 6a) and travels empty to the G/T buffer (either 7a or 8a) where it is loaded by an import container and travels back loaded to the gate or train buffer.

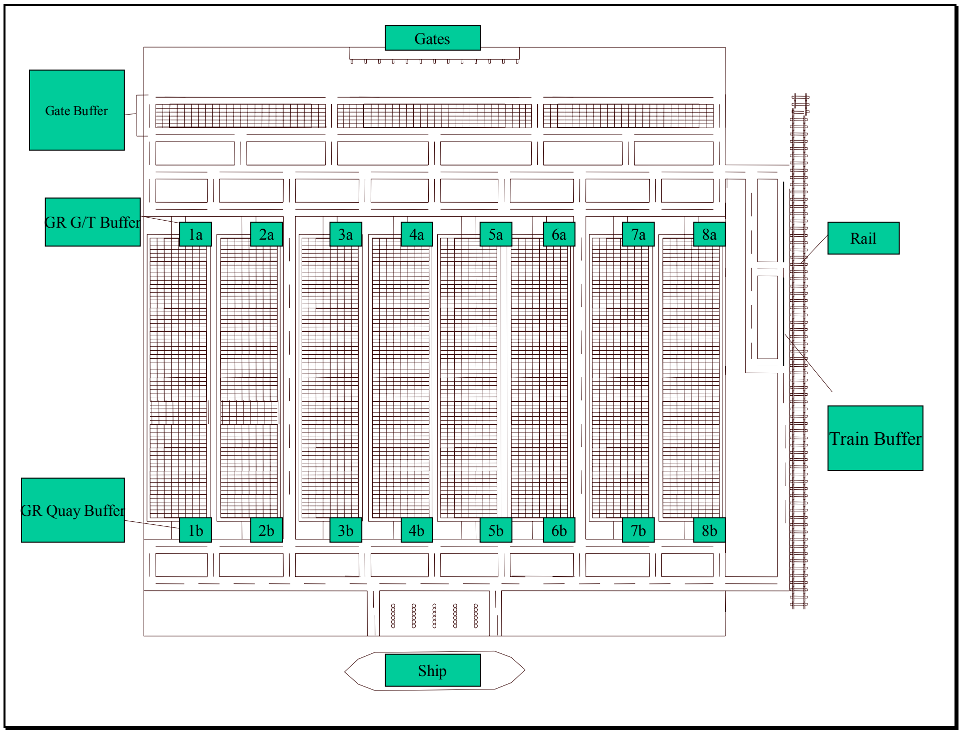

Figure 8.2: The GR Automated Container Terminal

8.2 Control Logic of AGVs for the GR-ACT System

The tasks to be performed by the AGVs in the GR-ACT system are the same as Task 1 to 3 given in section 6 for the AGV-ACT system. The only difference is that the GR units are replacing the storage yard (see Figure 8.3).

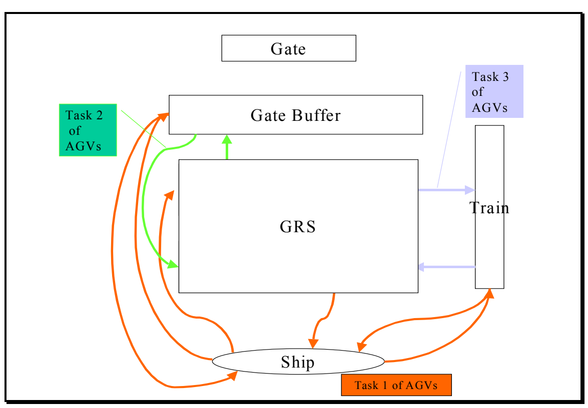

Figure 8.3: The tasks assigned to AGVs in the GR-ACT system

The control logic of the AGVs for the GR-ACT system is similar to that of the AGV-ACT system. The difference is that the AGVs in the GR-ACT system do not have to travel long distances, (exception is the case of JIT loading/unloading operations) since they only have to serve the buffers of the GR units. Because of that, the design of their logic is simplified by assuming the same speed for AGVs with and without a load. In particular all traffic roads are designed to be low speed zones i.e. the allowable speed of an AGV whether loaded or unloaded is the same as that of a loaded AGV. The flowcharts in Figures 8.4 and 8.5 summarize the modified control logic for the AGVs in the GR-ACT system.

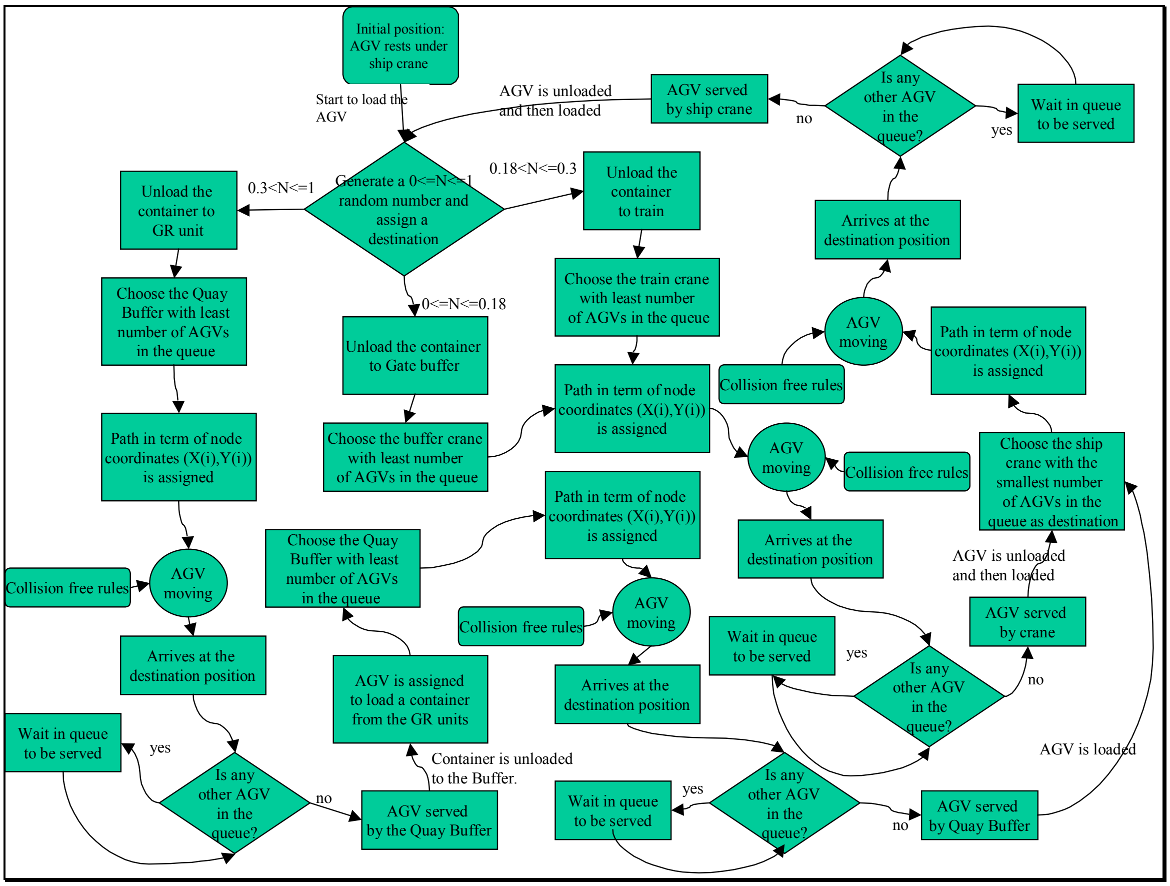

Figure 8.4: Control Logic of AGVs for Task 1

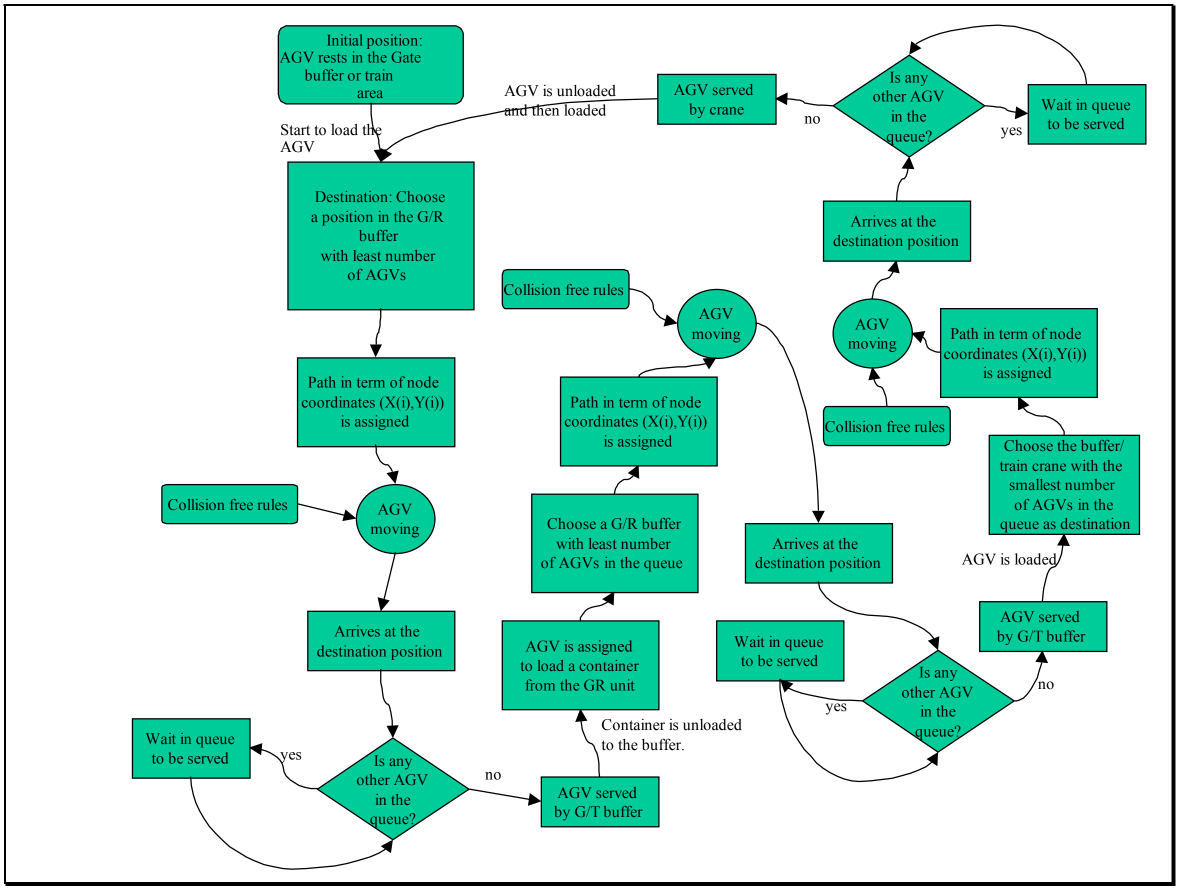

Figure 8.5: Control Logic of AGVs for Tasks 2 and 3

8.3 GR-ACT: Charcteristics of Equipment

According to [27], the characteristics of the equipment associated with the GR units are as follows:

Speed of loading and Unloading the GR buffers: We assume that a loading and unloading mechanism at the GR buffers serves the AGVs. It is assumed that it takes 30 seconds with a 10% variance to load or unload a container to/from an AGV.

Number of shuttles: The number of shuttles in each GR unit is15.

Speed of AGVs: The speed of AGVs serving the GR buffers and the quay cranes, gate and train buffers is 5 mph (loaded or empty).

Number of AGVs: Simulations were used to calculate the minimum number AGVs that are needed in order to meet the demand in the GR-ACT system. In Figure 8.6 the number of AGVs for tasks 1, 2 and 3 satisfy the ratio 6:3:1. The Figure shows that the combination (42, 21, 6) - i.e. 42 AGVs for Task 1, 21 for Task 2 and 6 for Task 3, a total of 69 AGVs - can meet the required demand for the GR-ACT system.

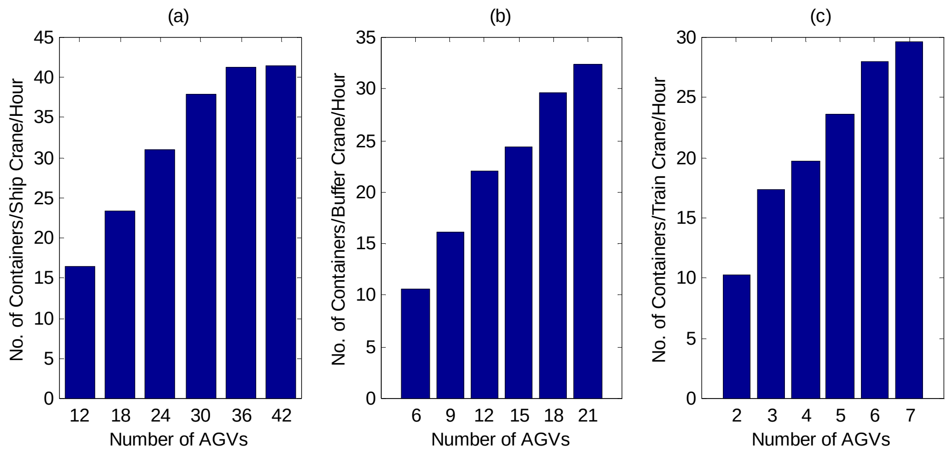

Figure 8.6: (a) throughput of quay crane vs. no. of AGVs, (b) throughput of crane at gate buffer vs. no. of AGVs and (c) throughput of train crane vs. no. of AGVs.

8.3.1 Summary of Characteristics of Equipment

Table 8.1 summarizes the characteristics of the GR-ACT system that are used in the simulation model.

Table 8.1: GR-ACT: Summary of the physical characteristics of the terminal.

Size of the terminal	1,472*1,875 ft^2 (63.36 acres)
Storage Capacity	22, 464 TEUs
No. of Berth	1
Capacity of quay cranes	42 moves per hour
No. of quay cranes	5
Gates service time	3 min inbound-gate, 2 min outbound-gate
No. of lanes at the gate	9 inbound, 6 outbound
Capacity of yard cranes at buffers	Yard crane's speed is 5 mph, takes 15 sec. to line up with the container, and an average time of 65 seconds to unload/load an AGV.
No. of yard cranes at gate buffer	6
No. of yard cranes at train buffer	2
Average service time for loading and unloading an AGV at the GR buffers	30 seconds
No. of shuttles in each GR unit	15
No. of GR units	8
Speed of AGVs	5 mph
No. of AGVs	72 (42 Task 1, 21 Task 2, 6 Task 3, and plus 3 spare AGVs)

A variance of 10% is assumed in all values associated with speeds and time with the exception of the speed of the quay cranes where a variance of 15% is assumed.

8.4 Performance Analysis

The characteristics of the GR-ACT system given in Table 8.1 together with those for each GR unit developed in [27] are fed into the simulation model for the GR-ACT system and simulated for the operational scenario described in section 4.7. In this simulation we assume that each GR unit performed as designed in the sense that in the case of outgoing containers from the GR units the GR buffers were always ready to deliver a container to an AGV and in the case of incoming containers to the GR units the GR buffer was always ready to receive a container. This property of the GR units was made possible in [27] by choosing an optimum number of shuttles and using a new dispatching algorithm to assign containers to shuttles within the unit and control their motion. The results of the simulation are shown in Table 8.2.

Table 8.2: GR-ACT: Performance results for one-day (24-hour) simulation

Ship turnaround time	16.47 hours
Throughput	41.68 containers/ship crane/hour
Throughput Per acre	0.652 containers/ship crane/acre/hour
Annual Throughput per acre	39,173 TEUs/acre/year
Gate utilization	65.7%
Truck turnaround time (doesn't include time at the gate)	120 seconds
Throughput (train crane)	28.6 containers/hour/crane
Throughput (buffer crane)	36.7 containers/hour/crane
Idle rate of AGVs over 24 hours	31.8%
Idle rate of buffer cranes over 24 hours	10.8%
Idle rate of train cranes over 24 hours	31.9%
Idle rate of quay cranes over 24 hours	31.8%
Container dwell time	19.0 hours

The simulation results indicate that the GR-ACT system performs efficiently by having the quay cranes operate close to maximum capacity and keeping the ship turnaround time close to the desired one. Similarly, the yard cranes at the train and gate buffer worked close to maximum capacity. The idle rate of the quay cranes is over a 24-hour period. This means that 31.38% of the time the quay cranes were idle because the ship was not at the berth. The same goes for the AGVs dealing with Task 1.

8.5 Cost Analysis

The performance characteristics of the GR-ACT system together with cost data are used as input to the cost model that calculates the ACC value for the proposed system. Since a GR system known as GRAIL (designed by August Design, Inc.) has already been installed by Sea-Land in Hong Kong, researchers at August Design, Inc. were able to provide fairly accurate cost data regarding the equipment associated with the GR units.

Table 8.3 summarizes the cost data generated by the cost model of the GR-ACT system presented in Appendix III.

Table 8.3: GR-ACT: Cost results

Annual projected volume	2,482,000
Annual Variable cost	$36,152,000
Annual Fixed cost	$47,880,000
Annual Land cost	$7,338,000
Annual Labor cost	$20,000,000
Total Annual cost	$111,370,000
Average Cost per container (ACC)	$89.74

Figure 8.7 shows how the ACC value varies with the initial cost of land per acre.

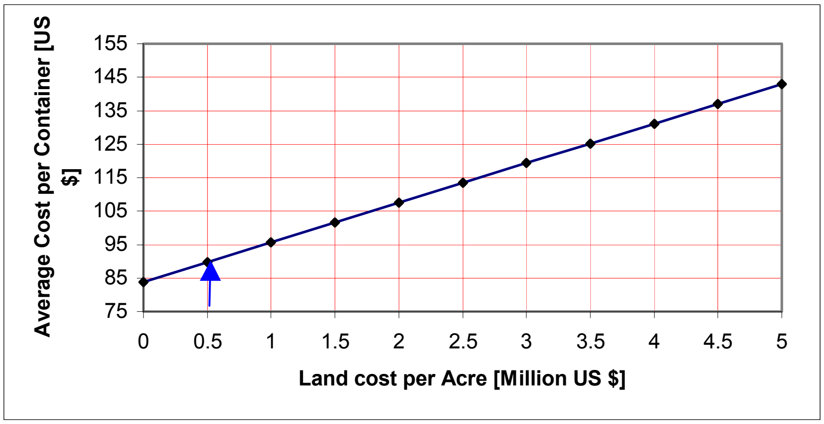

Figure 8.7: GR-ACT: Average Cost Container (ACC) vs. land cost per acre (arrow indicates the value assumed in cost analysis of Table 8.2)

The major fixed cost in the GR-ACT system is due to the cost of infrastructure and GRAIL shuttles. Figures 8.8 and 8.9 show how the ACC value varies with respect to the cost of shuttles and infrastructure, respectively.

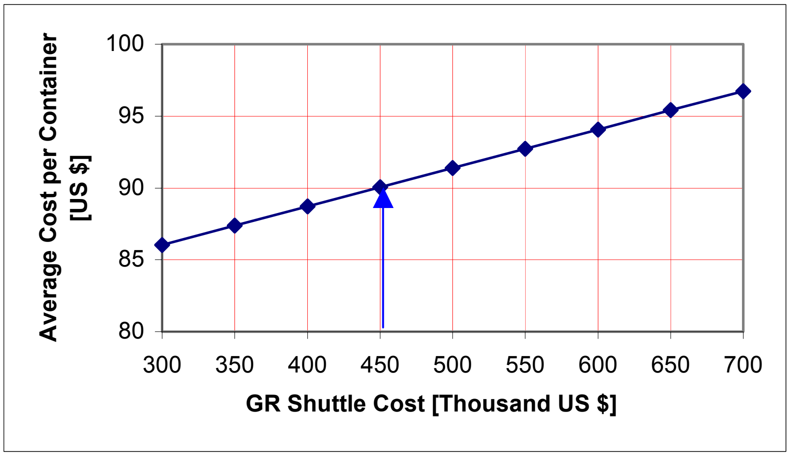

Figure 8.8: GR-ACT: Average Cost Container (ACC) vs. Cost of a GRAIL Shuttle (arrow indicates the value assumed in cost analysis of Table 8.2)

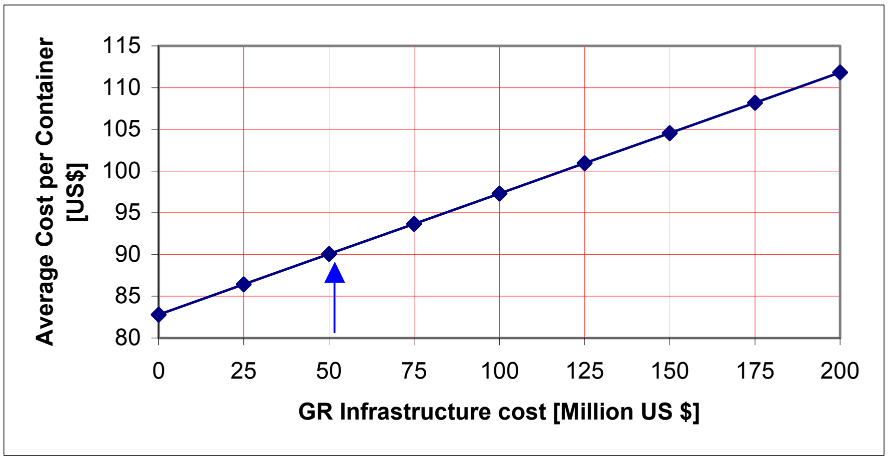

Figure 8.9: GR-ACT: Average Cost Container (ACC) vs. the GR infrastructure cost (arrow indicates the value assumed in cost analysis of Table 8.2)

9 AUTOMATED CONTAINER TERMINAL USING AUTOMATED STORAGE/RETRIEVAL SYSTEMS (AS/RS)

By the year 2020, it is projected that the amount of cargo transferred between container terminals will be doubled. The scarcity of land in many areas makes it almost impossible for many container terminals to respond to this increasing demand by expanding their yard facilities. AS/RS with high-density storage capabilities could play an important role in the future container terminal activities. AS/RS can store and retrieve containers automatically. It can be built on a small piece of land and add capacity by increasing the number of floors. The promise of the high productivity of the AS/RS lies in its capability to permit access to any container within the storage structure randomly (random access), without having to reshuffle containers. This high productivity property together with the ability to have a high storage capacity makes the AS/RS concept very attractive in places where land is very limited or very costly.

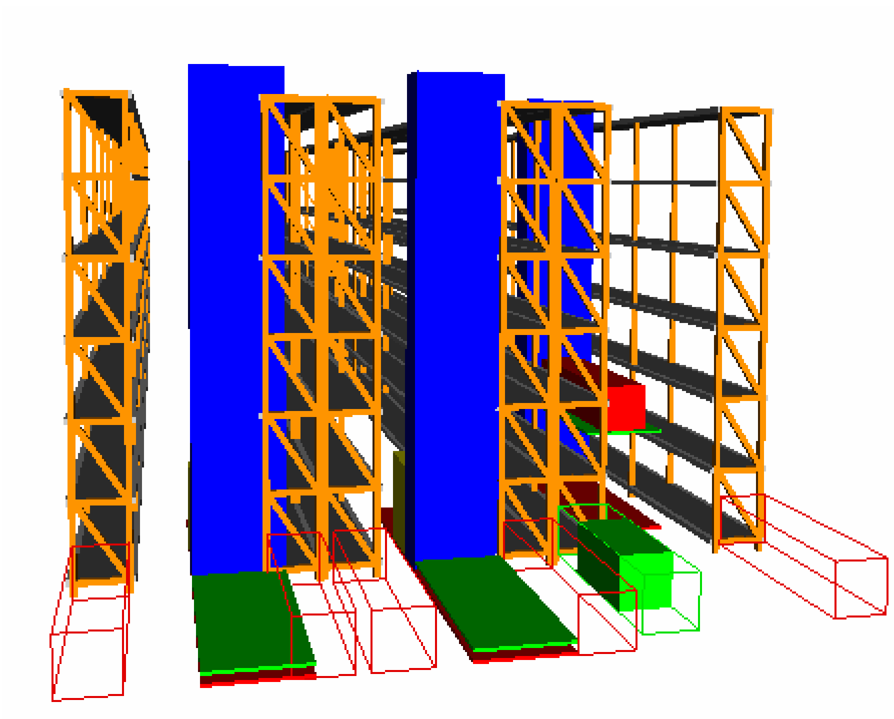

Figure 9.1: Automated Storage/Retrieval System (AS/RS) Module

Shown in Figure 9.1, an AS/RS module has four major components: the Storage and Retrieval Machine (SRM), the rack structure, the horizontal material handling system, and the planning and control system. The SRM simultaneously moves horizontally and vertically to reach a certain location in the rack structure. It travels on floor-mounted rails guided by electrical signals. The original design of the AS/RS module consisted of only two racks served by an SRM [12]. It was found however that one SRM for two racks (of the size considered) was more than needed to achieve a certain input/output throughput.

In an effort to meet demand and at the same time keep the cost low, we modified the original design so that one SRM can serve 6 racks. Therefore, in each AS/RS module served by a single SRM we have six rack structures that are built to hold and store containers. The SRM is designed to move from one set of two racks to another within the module. Each module has two buffers, one on each side. Each buffer has two slots, one for outgoing containers to be picked up by AGVs and one for incoming containers brought in by AGVs. These buffers are referred to as Pick-up and Delivery (P/D) point buffers.

9.1 Terminal Layout

In this concept, we replace the import and export container storage area in the AGV-ACT system by AS/RS modules. As shown in Figure 9.2, the layout of the proposed AS/RS-ACT system is very much similar to that of GR-ACT system discussed in section 8. The only difference is that instead of the GR units we use the AS/RS modules for storing the containers. The number of AS/RS modules is chosen so that the storage capacity of the AS/RS-ACT system is close to 22,000 TEUs as specified in section 4, a number assumed for all concepts under consideration.

Assuming that each rack can store 120 (12*10 cells) FEUs and each AS/RS module consists of 6 racks, the storage capacity requirement of 10,368 FEUs (same as the storage capacity of the GR units) can be achieved with 15 AS/RS modules. Each one of the modules has two P/D buffers on each side as shown in Figure 9.2. The total storage capacity of the AS/RS-ACT system is now equal to 15*6*120*2=21,600 TEUs which together with the 1,728 TEUs that could be stored at the gate buffer, it gives a total possible storage capacity of 23,328 TEUs. Given the dimensions of each AS/RS module the total size of the AS/RS-ACT system is calculated to be 1,265*1,875 ft^2 (54.45acres).

Figure 9.2 also shows the transit and working roads in the AS/RS container terminal. The lanes adjacent to the gate buffer and P/D buffers and the roads adjacent to the train/AGV interface are considered to be working roads, while all the other roads are transit roads. The two transit roads located on both sides of the AS/RS structure allow the direct transfer of containers that change modes of transportation without having to be stored in the yard. The containers that need to be stored (retrieved) in (from) the AS/RS structure are transferred by AGVs from (to) quay crane, gate and train buffers. A special loading/unloading machine that is part of the AS/RS module does the loading and unloading of AGVs at the P/D buffers. One AGV in one cycle carries an export container from the gate buffer to an AS/RS module P/D buffer where it unloads the container and gets loaded with an import container that it transfers back to the gate buffer. Similarly, one AGV in one cycle goes from the berth area to a specific P/D buffer (on the ship side) with an import container, delivers it to the P/D buffer, and gets loaded with an export container, which it transfers back to the berth area.

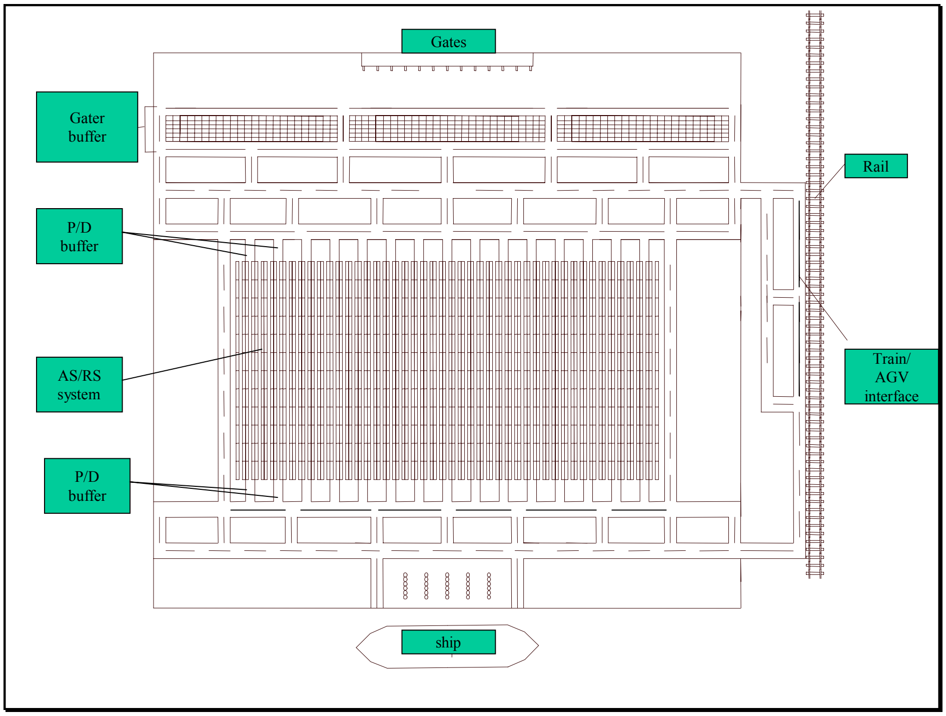

Figure 9.2: Automated terminal yard layout using AS/RS

9.2 Control Logic for AGVs

The control logic that dictates the motion of the AGVs within the AS/RS-ACT system is exactly the same as in the case of the GR-ACT system. Similarly, the tasks performed by the AGVs are the same as indicated in Figure 9.3.

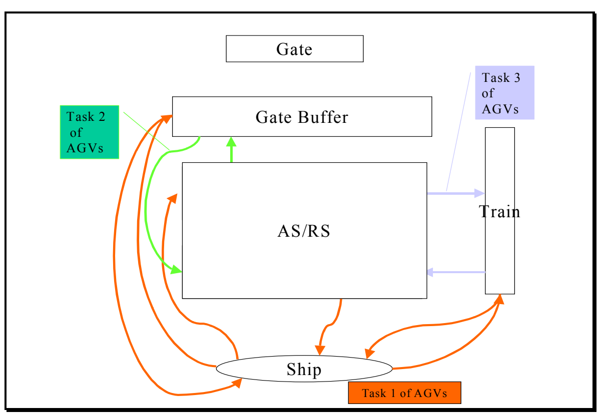

Figure 9.3: Three tasks of AGVs in the AS/RS-ACT system

9.3 Characteristics of Equipment

According to [12], the characteristics specific to the AS/RS-ACT system are the following:

Speed of loading unloading at the P/D buffers: In [12] the operations within the AS/RS module were optimized so that at the P/D buffers an AGV can be served (load it and unload it) within 45 seconds with 10% variance. Simulations of the system demonstrate that with such speed the P/D buffers will never be saturated due to the demand imposed by the AGVs.

Speed of AGVs: The speed of AGVs is 5 mph (loaded or empty).

Number of AGVs: The AS/RS-ACT system was simulated with different combinations of AGVs performing tasks 1 to 3 in order to calculate the minimum number of AGVs that is necessary to keep the quay cranes operating close to maximum capacity.

Figure 9.4 shows that the combination (36, 14, 5) - i.e. 36 AGVs for Task 1, 14 for Task 2 and 5 for Task 3, a total of 55 AGVs - can meet the required demand for the AS/RS-ACT system.

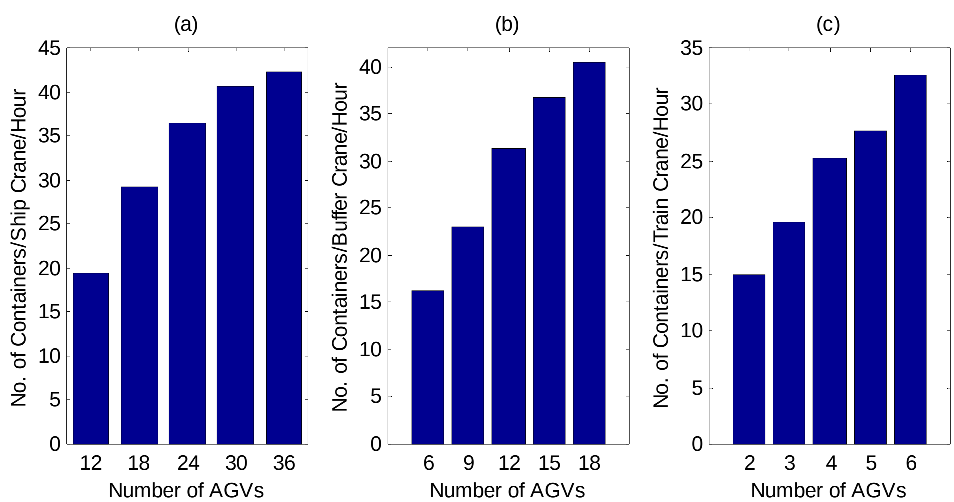

Figure 9.4: (a) throughput of quay crane vs. no. of AGVs, (b) throughput of buffer crane vs. no. of AGVs and (c) throughput of train crane vs. no. of AGVs

Despite the strong similarities between the GR-ACT and the AS/RS-ACT system, the AS/RS-ACT system requires 55 AGVs versus 69 for the GR-ACT system. The reason for this difference is that the AS/RS structure has 30 P/D buffers where loading and unloading can take place at the same buffer whereas the GR structure has only 16 buffers that alternate as pick-up and delivery buffers. Therefore, with the AS/RS structure the AGV cycle is shorter which in turn implies a smaller number of AGVs.

Figure 9.5 shows a snapshot of the AS/RS-ACT simulation with the number of equipment displaced in the yard.

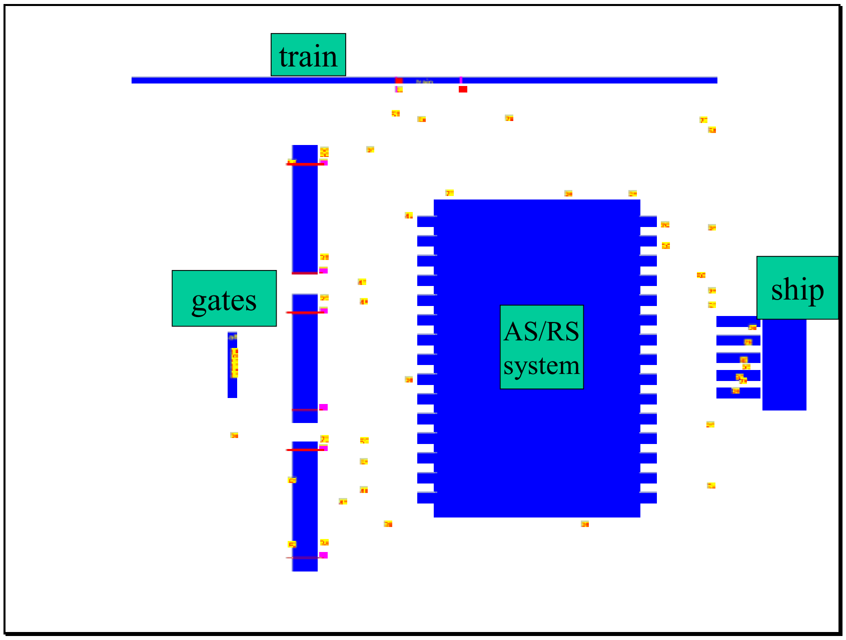

Figure 9.5: Snapshot of the AS/RS-ACT simulation

9.3.1 Summary of Characteristics

Table 9.1 summarizes the characteristics of the AS/RS-ACT system to be used in the simulation model.

Table 9.1: AS/RS-ACT: Summary of the physical characteristics of the terminal

Size of the terminal	1,265*1,875 ft^2 (54.45 acres)
Storage Capacity	23,328 TEUs
No. of Berth	1
Capacity of quay cranes	42 moves per hour
No. of quay cranes	5
Gates service time	3 min inbound-gate, 2 min outbound-gate
No. of lanes at the gate	9 inbound, 6 outbound
Capacity of yard cranes at buffers	Yard crane's speed is 5 mph, takes 15 sec. to line up with the container, and an average time of 65 seconds to unload/load an AGV.
No. of yard cranes at gate buffer	6
No. of yard cranes at Train buffer	2
Average service time at AS/RS buffers	45 seconds
No. of AS/RS Modules	15
Average service time for SRM	110 sec (double move) 80 sec (single move)
Speed of AGVs	5 mph
No. of AGVs	58 (36 Task 1, 14 Task 2, 5 Task 3, and plus 3 spare)

As with the other concepts a variance of 10% is assumed in all values associated with speeds and time with the exception of the speed of the quay cranes where a variance of 15% is assumed.

9.4 Performance Analysis:

The characteristics of the AS/RS-ACT system summarized in Table 9.1 are fed into the simulation model, which was then exercised for the operational scenario presented in section 4.7. The results of the simulation are shown in Table 9.2.

Table 9.2: AS/RS-ACT: Performance results for one-day (24-hour) simulation

Ship turnaround time	16.24 hours
Throughput	41.7 containers/ship crane/hour
Throughput Per acre	0.767 containers/ship crane/acre/hour
Annual Throughput per acre	45,583 TEUs/acre/year
Gate utilization	66.4 %
Truck turnaround time (doesn't include time at the gate)	110.75 seconds
Throughput (train crane)	30.6 containers/hour/crane
Throughput (buffer crane)	38.32 containers/hour/crane
Idle rate of AGVs over 24 hours	30.9%
Idle rate of buffer cranes over 24 hours	6.8%
Idle rate of train cranes over 24 hours	27.86%
Idle rate of ship cranes over 24 hours	32.33%
Container dwell time	18.9 hours

The performance of the AS/RS-ACT system is comparable with that obtained with the other concepts. The throughput per acre, however, is higher due to the less land required by the system.

9.5 Cost Analysis

The performance characteristics of the AS/RS-ACT system generated by the simulation model as well as cost data specific to the AS/RS structure obtained from another study [52] and by personal communication with the designer of the AS/RS structure [12] are used to perform a cost analysis. The cost model and analysis are presented in Appendix IV. The cost of one SRM is assumed to be $4 million. The cost of an AS/RS module is assumed to be $15 million, which results into a total cost of $225 million for the AS/RS structure, which is referred to as infrastructure cost in the cost model. The results of the cost analysis are summarized in Table 9.3.

Table 9.3: AS/RS-ACT: Cost results

Annual projected volume	2,482,000 TEUs
Annual Variable cost	$25,806,000
Annual Fixed cost	$82,427,000
Annual Land cost	$6,576,000
Annual Labor cost	$11,718,000
Total Annual cost	$126,528,000
Average Cost per Container (ACC)	$101.96

Figures 9.6, 9.7, and 9.8 show how the ACC value varies with land cost per acre, cost of the SRM and cost of the AS/RS structure (infrastructure) respectively.

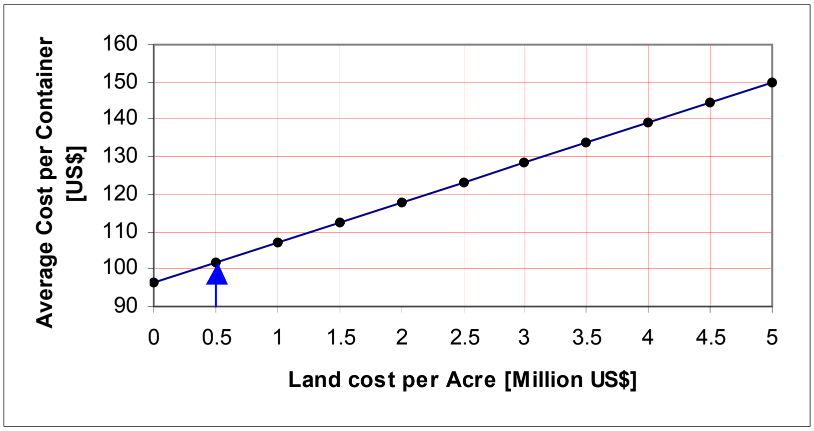

Figure 9.6: AS/RS-ACT: Average Cost of Container (ACC) vs. land cost per acre (arrow indicates the value assumed in cost results of Table 9.3)

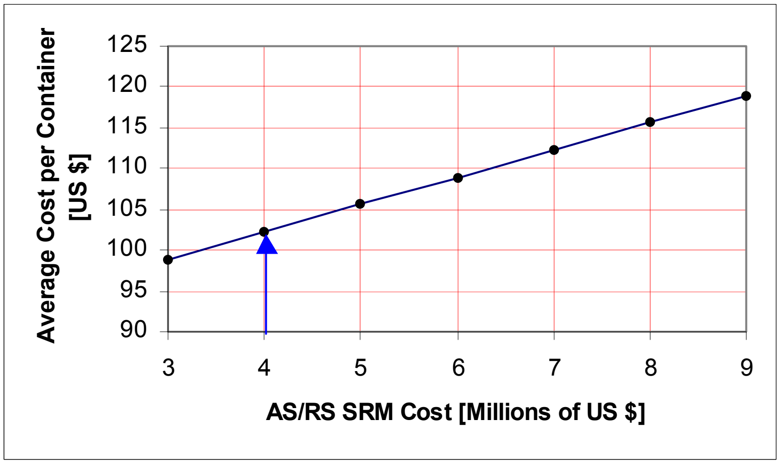

Figure 9.7: AS/RS-ACT Average Cost of Container (ACC) vs. SRM cost (arrow indicates the value assumed in cost results of Table 9.3)

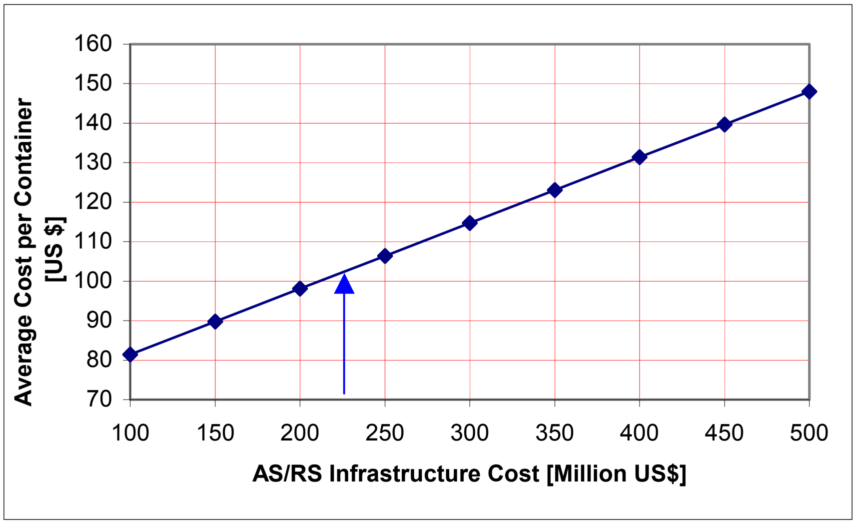

Figure 9.8: AS/RS-ACT: Average Cost of Container (ACC) vs. AS/RS structure (infrastructure) cost, (arrow indicates the value assumed in cost results of Table 9.3)

The sensitivity analysis indicates that the ACC value is more sensitive to the infrastructure and SRM cost than to land cost.

10. WHEELED TERMINAL OPERATION CONCEPT

In this section, we introduce and investigate a new concept for improving mobility in a RO/RO terminal. The concept involves the automatic guidance of manually driven vehicles to a particular assigned spot in the yard where they can be parked waiting to be loaded to the ship or driven inland at a later time. The guidance is achieved by using low cost automated carts that locked into the manually driven vehicles electronically and play the role of a lead vehicle or guide. This system could be very attractive for use during military deployments in underdeveloped ports or areas where drivers are not familiar with the yard or due to low visibility the assigned spots in the yard cannot be easily identified by the drivers. With the proposed concept, the assigned spots in the yard do not have to be physically marked. The automated carts are small, can be carried from one port to another, and can be easily deployed. The proposed concept is simulated and evaluated in the following subsections.

10.1 Automatic Guidance of Vehicles

We consider the yard layout shown in Figure 10.1 with total capacity of 2448 parking spots for vehicles. As shown in Figure 10.1, the yard consists of import vehicle storage area, export vehicle storage area, automated cart storage, ship berth, and two Transportation Automation Measurement Systems (TrAMS) at the gate and shipside. TrAMS, a system developed under CCDoTT funding, is used to provide automated measurements of the dimensions and weight characteristics of vehicles. Associated with TrAMS is a central control station that communicates with TrAMS and the automated carts deployed in the yard. The layout of the yard does not have to be physically marked. The geometry of the yard and coordinates of each parking spot and roads and empty areas are stored in the computer system. A yard planning system allocates parking spots to vehicles based on certain considerations and the information is stored in the central control system. When a vehicle goes through inspection and measurements by TrAMS, the central controller dispatches an Automated Cart (AC) to guide the vehicle to its pre-assigned position in the yard. Idle ACs are kept in a parking pool beside the yard for quick dispatching. The dispatched AC automatically positions itself in front of the vehicle at a small distance (about 4 feet) and locks on the vehicle electronically. This can be achieved using ranging sensors based on radar, sonar or optical sensors and a control system onboard the cart. The navigation of the cart through the yard can be done using dead reckoning combined with beacons at several points in the yard for correction of the dead reckoning measurements, GPS receivers, etc. Once the AC locks on the vehicle it moves with the vehicle by adjusting its speed to be close to that of the vehicle so that the distance between the AC and the vehicle is maintained close to the desired one about 4 feet. When the AC reaches the assigned parking spot it stops and signals to the driver to park his/her vehicle. When the driver parks the vehicle, the AC would carry him/her back to a passenger area away from the parking area and go back to the AC queue waiting for the next assignment.

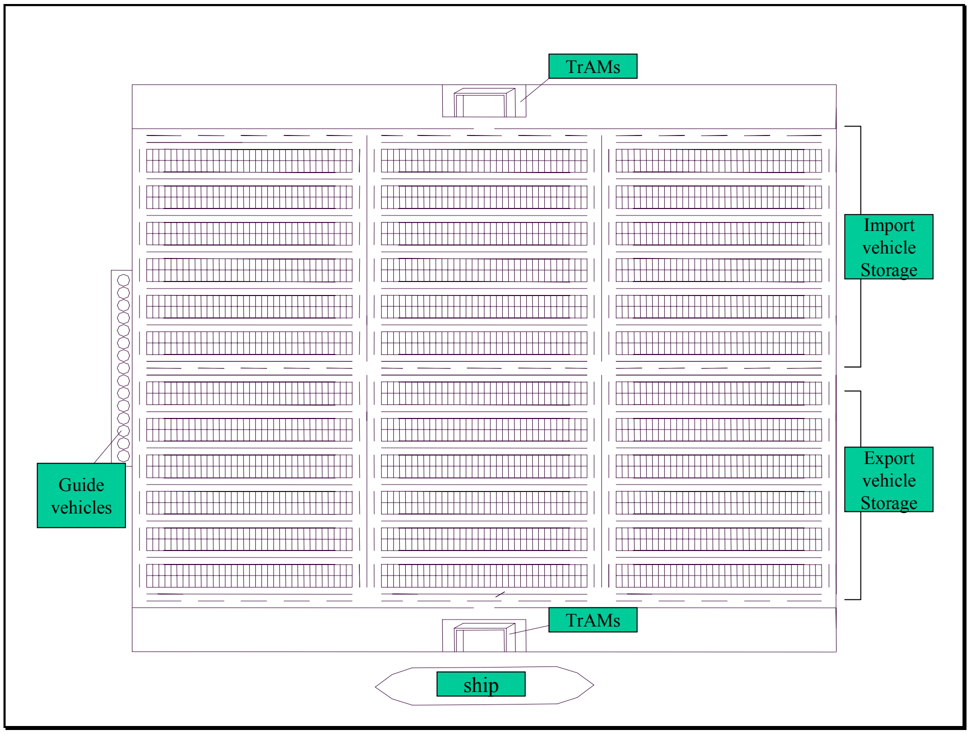

Figure 10.1: Virtual terminal yard layout for wheeled operation

The control logic that dictates the motion of the ACs in order to avoid conflicts, collisions and deadlocks is described in the next subsection.

10.2 Control Logic of Automated Carts

Since the guiding AC is locked to the following vehicle electronically, both can be considered as one automated Moving Vehicle (MV) in the yard. Therefore, we can assume that in the yard we have two classes of vehicles, the MVs and the ACs. The MVs and ACs are allowed to travel on the right lane of a two-lane road in their moving directions. Thus, once the starting and ending points are determined, the *path* for an MV or AC is uniquely determined by using the intermediate nodes.

The control logic algorithm must be able to resolve any possible conflicts between moving vehicles in the yard. A conflict between two or more vehicles may occur during the following situations:

1) <u>Arriving at an intersection from different path segments at the same time.</u>
   The same rules as in the case of AGVs considered in section 6.1 are used to avoid collision in this situation. The leading AC in such cases will signal to the driver of the following vehicle so that the MV can respond as dictated by the control logic.

2) <u>Traveling along the same path with different speeds leading to potential collision</u>.
   Since the speeds of all the ACs and MVs in the yard are assumed to be about 10

mph, this type of conflict will not occur in the absence of emergency stopping. It is assumed that drivers will try to maintain the speed of 10 mph. The ACs, as part of guidance, could display signals to the driver to change speed in case of large deviations from the desired one.

3) A vehicle stops ahead in the moving direction. The distance between moving MVs or ACs in the same lane same direction is kept to about 45 ft so that in case of stopping the following MV or AC has enough time to stop without collision. The 45 ft was calculated based on vehicle dynamics and driver reaction times

The flowchart in Figure 10.2 summarizes the control logic that governs the movement of ACs and MVs in the yard.

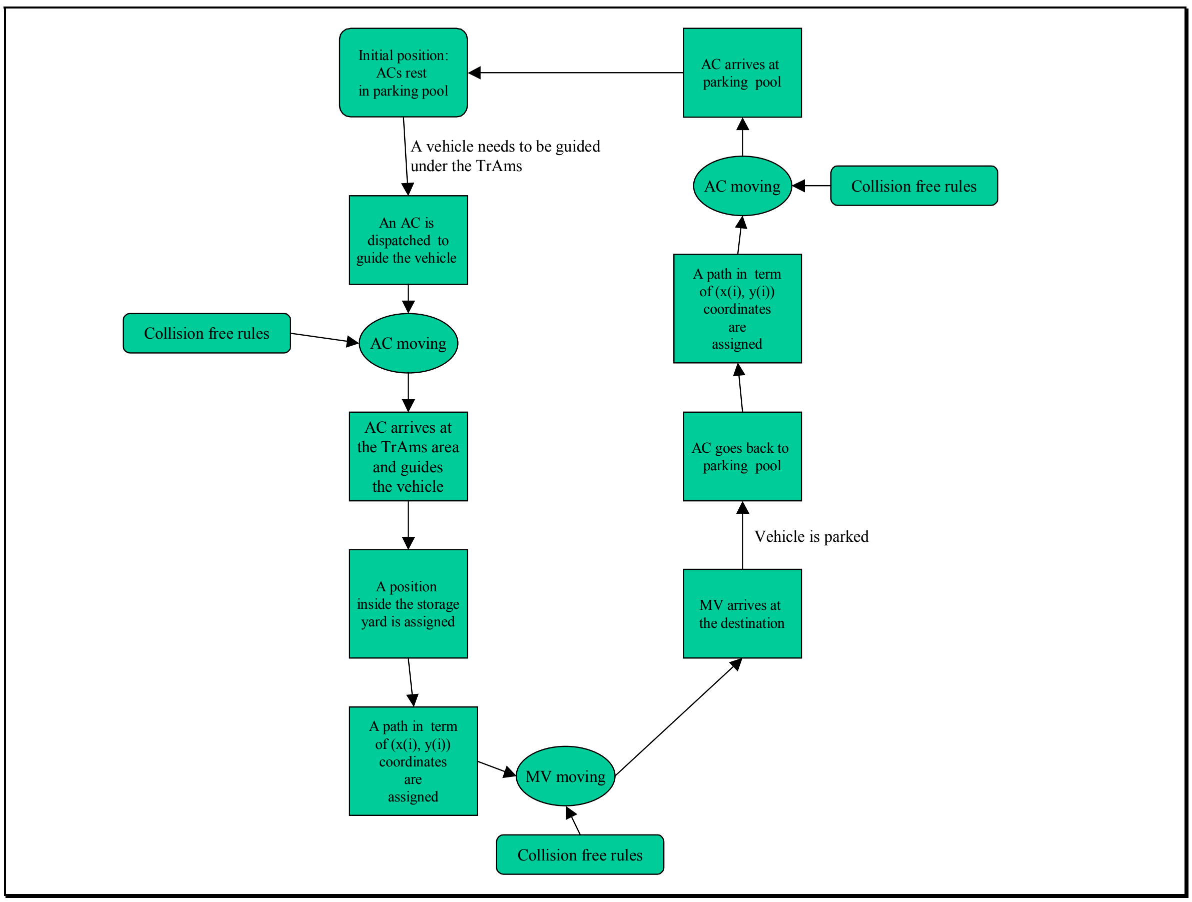

Figure 10.2: Flow chart of the control logic for ACs and MVs

10.3 Evaluation of Wheeled Operation Concept

A simulation model is developed to simulate the proposed concept for an unloading scenario. The number of ACs to be used in the simulation has to be decided first. This number depends on the processing speed of TrAMS as well as on the speed of the ACs and MVs. We assume that the speed of the MVs and ACs is about 10 mph, which is reasonable for the situation under consideration. The speed of TrAMS is considered to be a variable as in addition to TrAMS some other inspection of the vehicle may have to take place at the TrAMS location. We would like to choose the minimum number of ACs so that no vehicle has to wait for an AC after exiting TrAMS. Figure 10.3 shows the minimum number of ACs required as a function of the processing time at the TrAMS facility. Figure 10.3 also shows that as the processing time of TrAMS increases, the number of ACs required in the yard decreases almost exponentially.

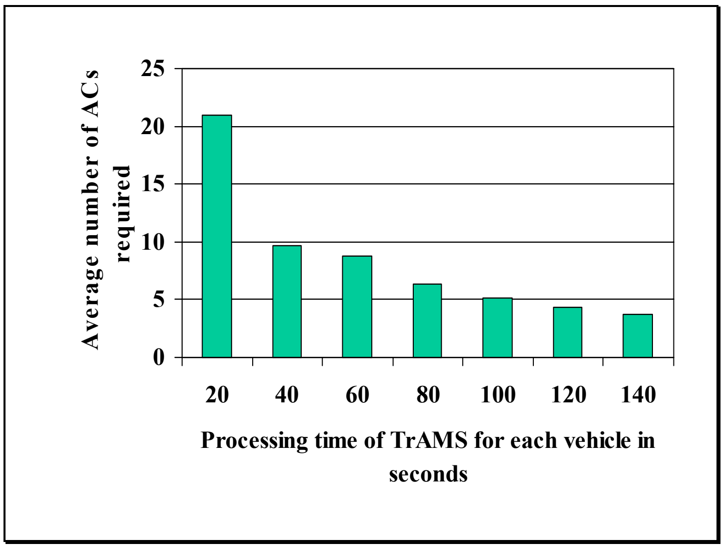

Figure 10.3: Number of AC's vs. processing time per vehicle

The following operational scenario is used to simulate the proposed concept. A RO/RO ship with 500 vehicles is to be unloaded; the vehicles should go through TrAMS before being parked in the yard according to a certain arrangement. The simulation model was exercised for different processing times of TrAMS. For each time the corresponding number of ACs obtained from Figure 10.3 is used in the simulations. The results are shown in Figure 10.4.

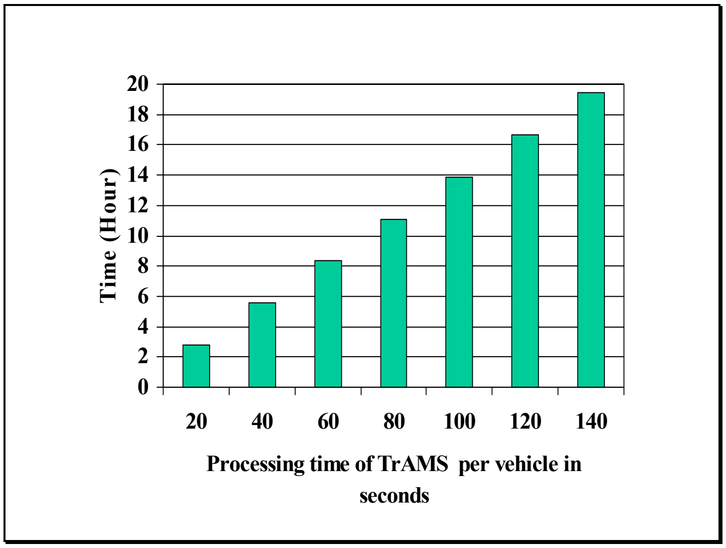

Figure 10.4: Time required to process 500 vehicles through TrAMS and guide them to assigned spots vs. processing time of TrAMS per vehicle

The results of Figure 10.4 indicate that the number of ACs required is relatively small. For a 100 seconds processing time of TrAMS, 14 ACs are sufficient to guide vehicles fast enough so that no vehicle has to wait for an AC after exiting TrAMS.

11. COMPARISONS AND RECOMMEDATIONS

The performance and cost results for each proposed ACT system are summarized in Table 11.1.

Table 11.1: Performance and Cost Results

	AGV-ACT	LMCS-ACT	GR-ACT	AS/RS-ACT
Ship turnaround time [hours]	16.81	16.83	16.47	16.24
Throughput, while the ship is at berth [moves/quay crane/hour]	40.45	40.40	41.68	41.7
Throughput per acre, while the ship is at berth [moves/quay crane/acre/hour]	0.579	0.575	0.652	0.767
Annual Throughput per acre [TEUs/acre/year]	35,310	35,310	39,173	45,583
Gate utilization	65.7%	66.03%	65.7%	66.4%
Truck turnaround time [seconds]	127	127	120	110.75
Throughput (train crane) [moves/hour/crane]	29.4	29.4	28.6	30.6
Throughput (buffer crane) [moves/hour/crane]	33.7	33.7	35.7	38.32
Idle rate of AGVs over 24 hours	36.3%	36.2%	31.81%	30.9%
Idle rate of gate buffer cranes over 24 hours	12.7%	12.7%	10.8%	6.8%
Idle rate of train cranes over 24 hours	23.0%	23.0%	31.9%	27.86%
Idle rate of quay cranes over 24 hours	31.7%	31.8%	31.8%	32.33%
Container dwell time [hours]	19.1	19.1	19	18.9
Average cost per container (U.S. $)	77.0	147.4	89.7	102.0

Since the amount of equipment and number of vehicles in each ACT system are chosen so that the ACT system can meet the same demand, it is not surprising that the performance for each system is almost identical for all measures with the exception of the throughput per acre. The highest throughput per acre was obtained for the AS/RS-ACT system since it requires less land to be implemented for the same storage capacity. Next comes the GR-ACT system that also requires less land for the same storage capacity. All the ACT systems operated close to the maximum possible capacity of the quay cranes that was assumed to be 42 moves per hour per crane for combined loading/unloading. This is much higher than the average of about 28 moves per hour measured in many of today's conventional terminals. The simulation model when exercised for a hypothetical conventional terminal of the same layout as the ACT with characteristics of equipment and operations based on data from an actual terminal generated a throughput of about 27 moves per hour per quay crane which is very close to the value of 28 that was actually measured in the terminal where the data were obtained from.

The significant difference between the various systems is the average cost per container. The LMCS-ACT was found to be the most expensive due to the high infrastructure cost associated with the LMCS. The second most expensive system is the AS/RS-ACT, due to the infrastructure cost of the AS/RS structure. The AGV-ACT system was found to be the most cost effective followed by the GR-ACT. The cost model was exercised for a hypothetical conventional terminal that has a performance similar to that observed in most of today's terminals. The average cost per container generated was $143.7, which is within the range ($130-$200) reported in the literature for some terminals.

The cost analysis was based on several assumptions regarding cost of equipment, land, labor etc. Most of these numbers were provided by professionals based on existing or very similar systems and are quite accurate. Others were estimates by the same professionals and their accuracy could be questioned when it involves equipment or systems that have not yet built and no detailed design is available. A sensitivity analysis is performed in order to calculate how cost per container varies with variations in the cost data assumed.

Figure 11.1 compares the ACC value with respect to land cost for different ACT systems. The Figure shows that irrespective of the land cost the LMCS-ACT system will always cost more in terms of the ACC value than any of the other systems. As indicated before this is mainly due to the high infrastructure cost associated with the LMCS-ACT system. The AGV-ACT system has the lowest ACC value until the cost of land reaches about $12 million per acre (see also Figure 11.2). When the cost of land exceeds $12 million per acre, the AS/RS-ACT system gives the lowest ACC value. When the land cost exceeds $13.5 million per acre the AS/RS-ACT system continues to have the lowest ACC value, followed by the GR-ACT and AGV-ACT systems.

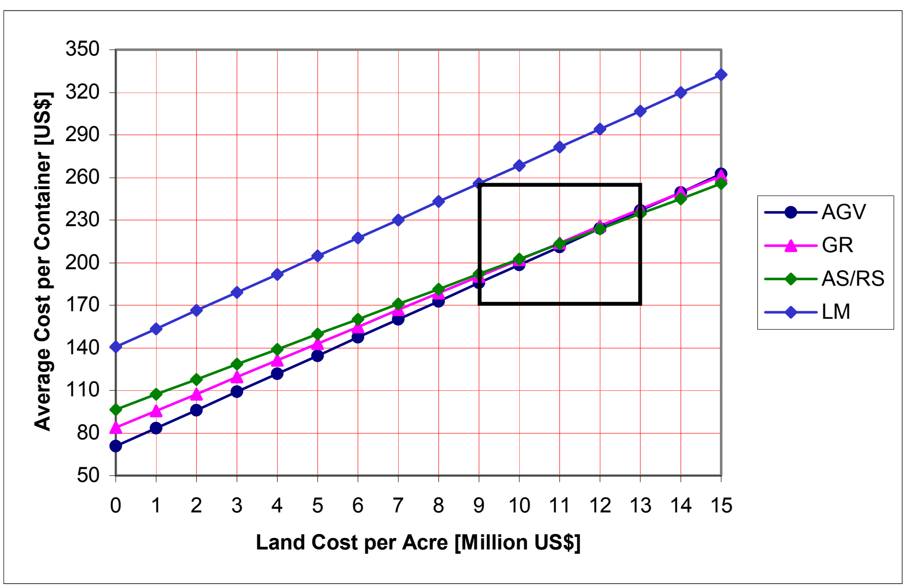

Figure 11.1: Average Cost of Container (ACC) for different agile concepts vs. land cost per acre, (the square area is expanded in Figure 11.2)

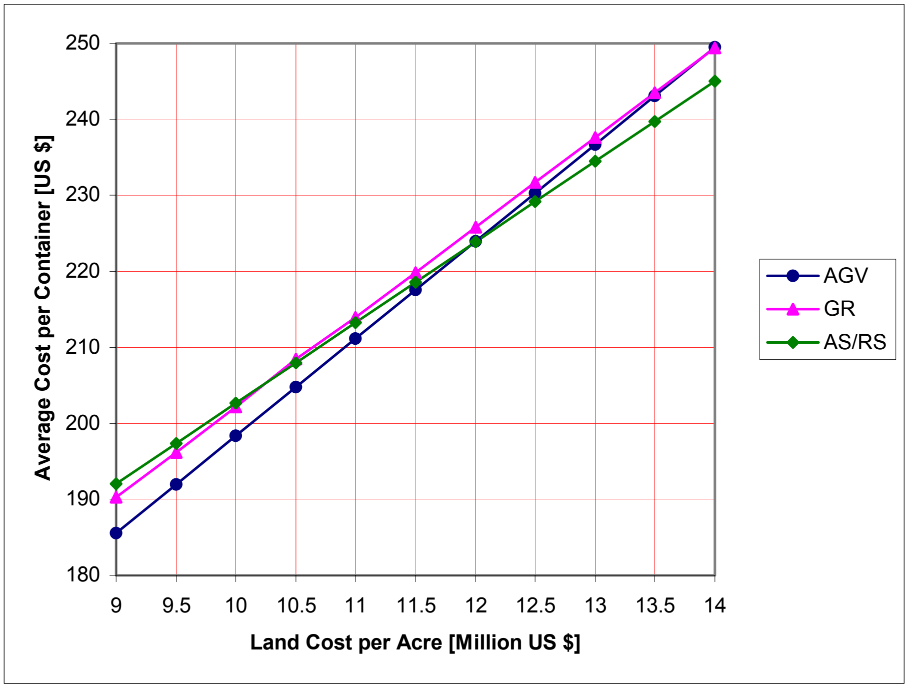

Figure 11.2: Average Cost of Container (ACC) for different agile concepts vs. land cost per acre. The figure corresponds to the square area in Figure 11.1

The ACT systems designed and evaluated in this project could be modified and improved further. The AGV-ACT and GR-ACT systems appear to have the strongest potential for a successful implementation when the land cost is less than about $11 million per acre. When the land cost exceeds $12 million the AS/RS-ACT system appears to be the most cost effective with respect to the ACC value. Further modifications to the ACT systems could reduce the cost further and the comparison presented here could change. AS/RS-ACT systems could become equally competitive if the cost of their infrastructure is reduced.

In addition to the four ACT systems discussed above a concept that is applicable to wheeled operations especially in areas with limited infrastructure is proposed, simulated and evaluated. The concept is based on automatic guidance of manually driven vehicles coming off the ship or entering the yard from the gate using low cost automated carts to lead and guide these vehicles to assigned spots in the yard. This concept can be proven useful during military operations in under-developed ports as well as during adverse conditions where visibility is limited.

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APPENDICES: COST TABLES

Cost Tables for Different Automated Terminal Concepts.

Appendix I: AGV-ACT SYSTEM

I.1) Activity

								0.030	0.010	0.100		
Activity Center	Working Hours	Electricity consumption Whirs per hour	electricity cost per KWHR	**Total electricity cost per activity**	Investment	Accounting life	Depreciation per year	Repair per year 3%	Insurance 1%	Interest 10%	**Total Fixed Costs**	**Total Costs**
Inbound gate	8,760	1,500	0.1410	1,852,740	1,000,000	25	40,000	30,000	10,000	100,000	180,000	2,032,740
Customs	5,840	1,500	0.1410	1,235,160	1,000,000	25	40,000	30,000	10,000	100,000	180,000	1,415,160
Outbound gate	8,760	1,500	0.1410	1,852,740	1,000,000	25	40,000	30,000	10,000	100,000	180,000	2,032,740
Gate buffer	8,760	1,500	0.1410	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
EXPORT Storage Area	8,760	1,500	0.1410	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
IMPORT Storage Area	8,760	1,500	0.1410	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
Train/AGV buffer	8,760	1,500	0.1410	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
Berth	5,840	3,000	0.1410	2,470,320	2,000,000	25	80,000	60,000	20,000	200,000	360,000	2,830,320
Maintenance area	4,160	1,500	0.1410	879,840	1,500,000	25	60,000	45,000	15,000	150,000	270,000	1,149,840
Central controller	8,760	1,500	0.1410	1,852,740	3,000,000	10	300,000	90,000	30,000	300,000	720,000	2,572,740

VC	FC	TC
17,554,500	2,250,000	19,804,500

I.2) Land

0.100

Land	Area (Acre)	Investment(U.S.$)	Accounting life(year)	Annual Land Cost (considering Inflation rate)	Interest 10%	**Total Costs(U.S.$)**
Storage Area	44.6284	22,314,200	25	1,583,247.32	2,231,420	3,814,667
Berth	5.6222	14,055,500	25	997,272.26	1,405,550	2,402,822
Train Area	6.9728	3,486,400	25	247,368.65	348,640	596,009
Gate Area	13.0667	6,533,350	25	463,557.24	653,335	1,116,892

Cost per Acre	500,000

Land Inflation Rate	0.05

Total Annual Land Cost
7,930,390

I.3) Equipment

	Working hours	Number of Equipment	Utilization Factor	Fuel, electricity, ..per equipment per hour($)	Fuel, electricity, …per equipment per year($)	**Fuel, electricity, … per year($)**	Investment	Accounting life	Depreciation per year	Repair per year 10% of investment cost	Insurance 1%	Interest 10%	Total Fixed Costs per equipment	**Total Fixed Cost**	**Total Costs**
										0.100	0.010	0.100			
AGV/AGV Infrastructure	8,760	85	0.640	15.00	84,096	7,148,160	200,000	15	13,333	20,000	2,000	20,000	55,333	4,703,333	11,851,493
Yard crane	8,760	44	0.350	20.00	61,320	2,698,080	1,500,000	15	100,000	150,000	15,000	150,000	415,000	18,260,000	20,958,080
Quay crane	5,840	5	0.690	50.00	201,480	1,007,400	10,000,000	15	666,667	1,000,000	100,000	1,000,000	2,766,667	13,833,333	14,840,733

VC	FC	TC
10,853,640	36,796,667	47,650,307

I.4) Labor Costs

GATES			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
5,084,400.00	Inbound gate	checkers	27	8,760.00	30.00	45.00	2,520.00	1,684,800.00	113,400.00	1,798,200.00
		supervisor	0	8,760.00	61.00	91.50	0.00	0.00	0.00	0.00
		clerical	15	8,760.00	30.00	45.00	2,520.00	936,000.00	113,400.00	1,049,400.00
		custodial	0	8,760.00	24.00	36.00	0.00	0.00	0.00	0.00
	Customs	checkers	0	5,840.00	45.00	67.50	0.00	0.00	0.00	0.00
		supervisor	0	5,840.00	61.00	91.50	0.00	0.00	0.00	0.00
		clerical	4	5,840.00	30.00	45.00	1,680.00	249,600.00	75,600.00	325,200.00
		custodial	0	5,840.00	24.00	36.00	0.00	0.00	0.00	0.00
	Outbound gate	checkers	18	8,760.00	30.00	45.00	2,520.00	1,123,200.00	113,400.00	1,236,600.00
		supervisor	0	8,760.00	61.00	91.50	0.00	0.00	0.00	0.00
		clerical	9	8,760.00	30.00	45.00	2,520.00	561,600.00	113,400.00	675,000.00
		custodial	0	8,760.00	24.00	36.00	0.00	0.00	0.00	0.00

YARD			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
5,282,460.00	Gate-buffer	supervisor	3	8,760.00	61.00	91.50	2,520.00	380,640.00	230,580.00	611,220.00
		yard worker	12	8,760.00	30.00	45.00	2,520.00	748,800.00	113,400.00	862,200.00
	EXPORT Storage Area	supervisor	3	8,760.00	61.00	91.50	2,520.00	380,640.00	230,580.00	611,220.00
		yard worker	12	8,760.00	30.00	45.00	2,520.00	748,800.00	113,400.00	862,200.00
	IMPORT Storage Area	supervisor	0	8,760.00	61.00	91.50	0.00	0.00	0.00	0.00
		yard worker	12	8,760.00	30.00	45.00	2,520.00	748,800.00	113,400.00	862,200.00
	Train/AGV interface	supervisor	3	8,760.00	61.00	91.50	2,520.00	380,640.00	230,580.00	611,220.00
		yard worker	12	8,760.00	30.00	45.00	2,520.00	748,800.00	113,400.00	862,200.00

BERTH			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
5,414,280.00	Berth	dock foremen	2	5,840	83.00	124.50	1,680.00	345,280.00	209,160.00	554,440.00

		marine planner	4	5,840	83.00	124.50	1,680.00	690,560.00	209,160.00	899,720.00
		operator	30	5,840	61.00	91.50	1,680.00	3,806,400.00	153,720.00	3,960,120.00
MAINTENANCE			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
2,408,640.00	Maintenance Area	repairmen	16	4,160.00	58.00	87.00	0.00	1,930,240.00	0.00	1,930,240.00
		supervisor	2	4,160.00	61.00	91.50	0.00	253,760.00	0.00	253,760.00
		clerical	2	4,160.00	30.00	45.00	0.00	124,800.00	0.00	124,800.00
		custodial	2	4,160.00	24.00	36.00	0.00	99,840.00	0.00	99,840.00
CONTROLLER			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
1,923,840.00	Central controller	programmer	3	8,760.00	72.00	108.00	2,520.00	449,280.00	272,160.00	721,440.00
		manager	3	8,760.00	120.00	180.00	2,520.00	748,800.00	453,600.00	1,202,400.00

Total Labor Cost
20,113,620.00

I.5) Summary

Activity					
	Variable Costs	Fixed Costs	**Total Costs**		
	17,554,500	2,250,000	**19,804,500**		
Equipment					
	Variable Costs	Fixed Costs	**Total Costs**		
	10,853,640	36,796,667	**47,650,307**		
Total					
	Variable Costs	**Fixed Costs**	**Land Costs**	**Labor Costs**	**Total Costs**
	28,408,140	**39,046,667**	**7,930,390**	**20,113,620**	**95,498,817**

Projected annual TEUs handling	2,482,000
verage Cost per ontainer	76.95

Appendix II: LMCS-ACT SYSTEM

II.1) Activity

Activity Center	Working Hours	Electricity consumption Whirs per hour	electricity cost per KWHR	**Total electricity cost per activity**	Investment	Accounting life	Depreciation per year	Repair per year 3%	Insurance 1%	Interest 10%	**Total Fixed Costs**	Total Costs
								0.030	0.010	0.100		
Inbound gate	8,760	1,500	0.14	1,852,740	1,000,000	25	40,000	30,000	10,000	100,000	180,000	2,032,740
Customs	5,840	1,500	0.14	1,235,160	1,000,000	25	40,000	30,000	10,000	100,000	180,000	1,415,160
Outbound gate	8,760	1,500	0.14	1,852,740	1,000,000	25	40,000	30,000	10,000	100,000	180,000	2,032,740
Gate buffer-buffer	8,760	1,500	0.14	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
EXPORT Storage Area	8,760	1,500	0.14	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
IMPORT Storage Area	8,760	1,500	0.14	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
Train/AGV buffer	8,760	1,500	0.14	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
Berth	5,840	3,000	0.14	2,470,320	2,000,000	25	80,000	60,000	20,000	200,000	360,000	2,830,320
Maintenance area	4,160	1,500	0.14	879,840	1,500,000	25	60,000	45,000	15,000	150,000	270,000	1,149,840
Central controller	8,760	1,500	0.14	1,852,740	3,000,000	10	300,000	90,000	30,000	300,000	720,000	2,572,740
LM Infrastructure	8,760	1,500	0.14	1,852,740	500,000,000	25	20,000,000	15,000,000	5,000,000	50,000,000	90,000,000	91,852,740

VC	FC	TC
19,407,240	92,250,000	111,657,240

II.2) Land

0.100

Land	Area (Acre)	Investment(U.S.$)	Accounting life (year)	Annual Land Cost (considering Inflation rate)	Interest 10%	**Total Costs (U.S.$)**
Storage Area	44.6284	22,314,200	25	1,583,247.32	2,231,420	3,814,667
Berth	5.6222	14,055,500	25	997,272.26	1,405,550	2,402,822
Train Area	6.9728	3,486,400	25	247,368.65	348,640	596,009
Gate Area	13.0667	6,533,350	25	463,557.24	653,335	1,116,892

Cost per Acre	500,000

Land Inflation Rate	0.05

Total Annual Land Cost
7,930,390

II.3) Equipment

										0.100	0.010	0.100			
	Working hours	Number of Equipment	Utilization Factor	Fuel, electricity, per equipment per hour ($)	Fuel, electricity, …per equipment per year ($)	**Fuel, electricity, … per year ($)**	Investment	Accounting life	Depreciation per year	Repair per year 10% of investment cost	Insurance 1%	Interest 10%	Total Fixed Costs per equipment	**Total Fixed Cost**	**Total Costs**
Linear Motor	8,760	82	0.640	15.00	84,096	6,895,872	7,000	25	280	700	70	700	1,750	143,500	7,039,372
Yard crane	8,760	44	0.750	20.00	131,400	5,781,600	5,000,000	15	333,333	500,000	50,000	500,000	1,383,333	60,866,667	66,648,267
Quay crane	5,840	5	0.650	50.00	189,800	949,000	10,000,000	15	666,667	1,000,000	100,000	1,000,000	2,766,667	13,833,333	14,782,333

VC	FC	TC
10,601,352	32,236,833	42,838,185

II.4) Labor Costs

GATES			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
5,084,400.00	Inbound gate	checkers	27	8,760.00	30.00	45.00	2,520.00	1,684,800.00	113,400.00	1,798,200.00
		supervisor	0	8,760.00	61.00	91.50	0.00	0.00	0.00	0.00
		clerical	15	8,760.00	30.00	45.00	2,520.00	936,000.00	113,400.00	1,049,400.00
		custodial	0	8,760.00	24.00	36.00	0.00	0.00	0.00	0.00
	Customs	checkers	0	5,840.00	45.00	67.50	0.00	0.00	0.00	0.00
		supervisor	0	5,840.00	61.00	91.50	0.00	0.00	0.00	0.00
		clerical	4	5,840.00	30.00	45.00	1,680.00	249,600.00	75,600.00	325,200.00
		custodial	0	5,840.00	24.00	36.00	0.00	0.00	0.00	0.00
	Outbound gate	checkers	18	8,760.00	30.00	45.00	2,520.00	1,123,200.00	113,400.00	1,236,600.00
		supervisor	0	8,760.00	61.00	91.50	0.00	0.00	0.00	0.00
		clerical	9	8,760.00	30.00	45.00	2,520.00	561,600.00	113,400.00	675,000.00
		custodial	0	8,760.00	24.00	36.00	0.00	0.00	0.00	0.00

YARD			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
5,282,460.00	Gate-buffer	supervisor	3	8,760.00	61.00	91.50	2,520.00	380,640.00	230,580.00	611,220.00
		yard worker	12	8,760.00	30.00	45.00	2,520.00	748,800.00	113,400.00	862,200.00
	EXPORT Storage Area	supervisor	3	8,760.00	61.00	91.50	2,520.00	380,640.00	230,580.00	611,220.00
		yard worker	12	8,760.00	30.00	45.00	2,520.00	748,800.00	113,400.00	862,200.00
	IMPORT Storage Area	supervisor	0	8,760.00	61.00	91.50	0.00	0.00	0.00	0.00
		yard worker	12	8,760.00	30.00	45.00	2,520.00	748,800.00	113,400.00	862,200.00
	Train/AGV buffer	supervisor	3	8,760.00	61.00	91.50	2,520.00	380,640.00	230,580.00	611,220.00
		yard worker	12	8,760.00	30.00	45.00	2,520.00	748,800.00	113,400.00	862,200.00

BERTH			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
5,414,280.00	Berth	dock foremen	2	5,840	83.00	124.50	1,680.00	345,280.00	209,160.00	554,440.00

		marine planner	4	5,840	83.00	124.50	1,680.00	690,560.00	209,160.00	899,720.00
		operator	30	5,840	61.00	91.50	1,680.00	3,806,400.00	153,720.00	3,960,120.00

MAINTENANCE			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
2,408,640.00	Maintenance Area	repairmen	16	4,160.00	58.00	87.00	0.00	1,930,240.00	0.00	1,930,240.00
		supervisor	2	4,160.00	61.00	91.50	0.00	253,760.00	0.00	253,760.00
		clerical	2	4,160.00	30.00	45.00	0.00	124,800.00	0.00	124,800.00
		custodial	2	4,160.00	24.00	36.00	0.00	99,840.00	0.00	99,840.00

CONTROLLER			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
1,923,840.00	Central controller	programmer	3	8,760.00	72.00	108.00	2,520.00	449,280.00	272,160.00	721,440.00
		manager	3	8,760.00	120.00	180.00	2,520.00	748,800.00	453,600.00	1,202,400.00

Total Labor Cost
20,113,620.00

II.5) Summary

Activity					
	Variable Costs	Fixed Costs	Total Costs		
	19,407,240	92,250,000	**111,657,240**		
Equipment					
	Variable Costs	Fixed Costs	Total Costs		
	10,601,352	32,236,833	**42,838,185**		
Total					
	Variable Costs	**Fixed Costs**	**Land Costs**	**Labor Costs**	**Total Costs**
	30,008,592	**124,486,833**	**7,930,390**	**20,113,620**	**182,539,436**

Projected annual TEUs handling	2,482,000
verage Cost per ontainer	147.09

Appendix III: GR-ACT SYSTEM

III.1) Activity

Activity Center	Working Hours	Electricity consumption Whirs per hour	electricity cost per KWHR	**Total electricity cost per activity**	Investment	Accounting life	Depreciation per year	Repair per year 3%	Insurance 1%	Interest 10%	**Total Fixed Costs**	**Total Costs**
								0.030	0.010	0.100		
Inbound gate	8,760	1,500	0.14	1,852,740	1,000,000	25	40,000	30,000	10,000	100,000	180,000	2,032,740
Customs	5,840	1,500	0.14	1,235,160	1,000,000	25	40,000	30,000	10,000	100,000	180,000	1,415,160
Outbound gate	8,760	1,500	0.14	1,852,740	1,000,000	25	40,000	30,000	10,000	100,000	180,000	2,032,740
Gate Buffer	8,760	1,500	0.14	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
GR Units	8,760	1,500	0.14	1,852,740	50,000,000	25	2,000,000	1,500,000	500,000	5,000,000	9,000,000	10,852,740
Storage Area	8,760	1,500	0.14	1,852,740	1,000,000	25	40,000	30,000	10,000	100,000	180,000	2,032,740
Train/AGV interface	8,760	1,500	0.14	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
Berth	5,840	3,000	0.14	2,470,320	2,000,000	25	80,000	60,000	20,000	200,000	360,000	2,830,320
Maintenance area	4,160	1,500	0.14	879,840	1,500,000	25	60,000	45,000	15,000	150,000	270,000	1,149,840
Central controller	8,760	1,500	0.14	1,852,740	3,000,000	10	300,000	90,000	30,000	300,000	720,000	2,572,740

VC	FC	TC
17,554,500	11,250,000	28,804,500

III.2) Land

0.100

Land	Area (Acre)	Investment(U.S.$)	Accounting life(year)	Annual Land Cost (considering Inflation rate)	Interest 10%	**Total Costs(U.S.$)**
Storage Area	34.8187	17,409,350	25	1,235,236.16	1,740,935	2,976,171
Berth	5.6222	14,055,500	25	997,272.26	1,405,550	2,402,822
Train Area	6.2853	3,142,650	25	222,978.74	314,265	537,244
Gate Area	16.6339	8,316,950	25	590,108.04	831,695	1,421,803

Cost per Acre	500,000

Land Inflation Rate	0.05

Total Annual Land Cost
7,338,040

III.3) Equipment

	Working hours	Number of Equipment	Utilization Factor	Fuel, electricity, ..per equipment per hour($)	Fuel, electricity, …per equipment per year($)	**Fuel, electricity, … per year($)**	Investment	Accounting life	Depreciation per year	Repair per year 10% of investment cost	Insurance 1%	Interest 10%	Total Fixed Costs per equipment	**Total Fixed Cost**	**Total Costs**
										0.100	0.010	0.100			
Yard Truck or AGV	8,760	72	0.680	15.00	89,352	6,433,344	200,000	15	13,333	20,000	2,000	20,000	55,333	3,984,000	10,417,344
GR shuttles	8,760	120	0.630	15.00	82,782	9,933,840	450,000	15	30,000	45,000	4,500	45,000	124,500	14,940,000	24,873,840
Yard crane	8,760	8	0.880	20.00	154,176	1,233,408	1,500,000	15	100,000	150,000	15,000	150,000	415,000	3,320,000	4,553,408
Quay crane	5,840	5	0.680	50.00	198,560	992,800	10,000,000	15	666,667	1,000,000	100,000	1,000,000	2,766,667	13,833,333	14,826,133
Maintenance Instrument	4,160	1	0.200	5.00	4,160	4,160	2,000,000	15	133,333	200,000	20,000	200,000	553,333	553,333	557,493

VC	FC	TC
18,597,552	36,630,667	55,228,219

III.4) Labor Costs

GATES			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
5,084,400.00	Inbound gate	checkers	27	8,760.00	30.00	45.00	2,520.00	1,684,800.00	113,400.00	1,798,200.00
		supervisor	0	8,760.00	61.00	91.50	0.00	0.00	0.00	0.00
		clerical	15	8,760.00	30.00	45.00	2,520.00	936,000.00	113,400.00	1,049,400.00
		custodial	0	8,760.00	24.00	36.00	0.00	0.00	0.00	0.00
	Customs	checkers	0	5,840.00	45.00	67.50	0.00	0.00	0.00	0.00
		supervisor	0	5,840.00	61.00	91.50	0.00	0.00	0.00	0.00
		clerical	4	5,840.00	30.00	45.00	1,680.00	249,600.00	75,600.00	325,200.00
		custodial	0	5,840.00	24.00	36.00	0.00	0.00	0.00	0.00
	Outbound gate	checkers	18	8,760.00	30.00	45.00	2,520.00	1,123,200.00	113,400.00	1,236,600.00
		supervisor	0	8,760.00	61.00	91.50	0.00	0.00	0.00	0.00
		clerical	9	8,760.00	30.00	45.00	2,520.00	561,600.00	113,400.00	675,000.00
		custodial	0	8,760.00	24.00	36.00	0.00	0.00	0.00	0.00

YARD			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
5,169,060.00	Gate Buffer	supervisor	3	8,760.00	61.00	91.50	2,520.00	380,640.00	230,580.00	611,220.00
		yard worker	12	8,760.00	30.00	45.00	2,520.00	748,800.00	113,400.00	862,200.00
	Storage Area	supervisor	3	8,760.00	61.00	91.50	2,520.00	380,640.00	230,580.00	611,220.00
		yard worker	24	8,760.00	30.00	45.00	2,520.00	1,497,600.00	113,400.00	1,611,000.00
	Train/AGV Buffer	supervisor	3	8,760.00	61.00	91.50	2,520.00	380,640.00	230,580.00	611,220.00
		yard worker	12	8,760.00	30.00	45.00	2,520.00	748,800.00	113,400.00	862,200.00

BERTH			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
5,414,280.00	Berth	dock foremen	2	5,840	83.00	124.50	1,680.00	345,280.00	209,160.00	554,440.00
		marine planner	4	5,840	83.00	124.50	1,680.00	690,560.00	209,160.00	899,720.00
		operator	30	5,840	61.00	91.50	1,680.00	3,806,400.00	153,720.00	3,960,120.00

MAINTENANCE			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
2,408,640.00	Maintenance Area	repairmen	16	4,160.00	58.00	87.00	0.00	1,930,240.00	0.00	1,930,240.00
		supervisor	2	4,160.00	61.00	91.50	0.00	253,760.00	0.00	253,760.00
		clerical	2	4,160.00	30.00	45.00	0.00	124,800.00	0.00	124,800.00
		custodial	2	4,160.00	24.00	36.00	0.00	99,840.00	0.00	99,840.00

CONTROLLER			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
1,923,840.00	Central controller	programmer	3	8,760.00	72.00	108.00	2,520.00	449,280.00	272,160.00	721,440.00
		manager	3	8,760.00	120.00	180.00	2,520.00	748,800.00	453,600.00	1,202,400.00

Total Labor Cost
20,000,220

III.5) Summary

Activity					
	Variable Costs	Fixed Costs	Total Costs		
	17,554,500	11,250,000	**28,804,500**		
Equipment					
	Variable Costs	Fixed Costs	Total Costs		
	18,597,552	36,630,667	**55,228,219**		
Total					
	Variable Costs	**Fixed Costs**	**Land Costs**	**Labor Costs**	**Total Costs**
	36,152,052	**47,880,667**	**7,338,040**	**20,000,220**	**111,370,979**

Projected annual TEUs handling	2,482,000
verage Cost per ontainer	89.74

Appendix IV: AS/RS-ACT SYSTEM

IV.1) Activity

Activity Center	Working Hours	Electricity consumption Whirs per hour	electricity cost per KWHR	**Total electricity cost per activity**	Investment	Accounting life	Depreciation per year	Repair per year 3%	Insurance 1%	Interest 10%	**Total Fixed Costs**	**Total Costs**
								0.030	0.010	0.100		
Inbound gate	8,760	1,500	0.1410	1,852,740	1,000,000	25	40,000	30,000	10,000	100,000	180,000	2,032,740
Customs	5,840	1,500	0.1410	1,235,160	1,000,000	25	40,000	30,000	10,000	100,000	180,000	1,415,160
Outbound gate	8,760	1,500	0.1410	1,852,740	1,000,000	25	40,000	30,000	10,000	100,000	180,000	2,032,740
AS/RS buffer	8,760	1,500	0.1410	1,852,740	1,500,000	25	60,000	45,000	15,000	150,000	270,000	2,122,740
Storage Area	8,760	1,500	0.1410	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
Train/AGV buffer	8,760	1,500	0.1410	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
Berth	5,840	3,000	0.1410	2,470,320	2,000,000	25	80,000	60,000	20,000	200,000	360,000	2,830,320
Maintenance area	4,160	1,500	0.1410	879,840	1,500,000	25	60,000	45,000	15,000	150,000	270,000	1,149,840
Central controller	8,760	1,500	0.1410	1,852,740	3,000,000	10	300,000	90,000	30,000	300,000	720,000	2,572,740
AS/RS Infrastructure	8,760	1,500	0.1410	1,852,740	225,000,000	15	15,000,000	6,750,000	2,250,000	22,500,000	46,500,000	48,352,740

VC	FC	TC
17,554,500	48,840,000	66,394,500

IV.2) Land

					0.100	
Land	Area (Acre)	Investment(U.S.$)	Accounting life(year)	Annual Land Cost (considering Inflation rate)	Interest 10%	**Total Costs(U.S.$)**
Storage Area	26.7925	13,396,250	25	950,496.86	1,339,625	2,290,122
Berth	5.6222	14,055,500	25	997,272.26	1,405,550	2,402,822
Train Area	5.4014	2,700,700	25	191,621.30	270,070	461,691
Gate Area	16.6339	8,316,950	25	590,108.04	831,695	1,421,803

Cost per Acre	500,000

Land Inflation Rate	0.05

Total Annual Land Cost
6,576,438

IV.3)
Equipment

	Working hours	Number of Equipment	Utilization Factor	Fuel, electricity, ..per equipment per hour($)	Fuel, electricity, …per equipment per year($)	**Fuel, electricity, … per year($)**	Investment	Accounting life	Depreciation per year	Repair per year 10% of investment cost	Insurance 1%	Interest 10%	Total Fixed Costs per equipment	**Total Fixed Cost**	**Total Costs**
										0.100	0.010	0.100			
Yard Truck or AGV	8,760	57	0.690	15.00	90,666	5,167,962	200,000	15	13,333	20,000	2,000	20,000	55,333	3,154,000	8,321,962
AS/RS SRM	8,760	15	0.650	25.00	142,350	2,135,250	4,000,000	15	266,667	400,000	40,000	400,000	1,106,667	16,600,000	18,735,250
Quay crane	5,840	5	0.650	50.00	189,800	949,000	10,000,000	15	666,667	1,000,000	100,000	1,000,000	2,766,667	13,833,333	14,782,333

VC	FC	TC
8,252,212	33,587,333	41,839,545

IV.4) Labor Costs

GATES			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
4,237,000.00	Inbound gate	checkers	27	8,760.00	25.00	37.50	2,520.00	1,404,000.00	94,500.00	1,498,500.00
		supervisor	0	8,760.00	51.00	76.50	0.00	0.00	0.00	0.00
		clerical	15	8,760.00	25.00	37.50	2,520.00	780,000.00	94,500.00	874,500.00
		custodial	0	8,760.00	19.00	28.50	0.00	0.00	0.00	0.00
	Customs	checkers	0	5,840.00	38.00	57.00	0.00	0.00	0.00	0.00
		supervisor	0	5,840.00	51.00	76.50	0.00	0.00	0.00	0.00
		clerical	4	5,840.00	25.00	37.50	1,680.00	208,000.00	63,000.00	271,000.00
		custodial	0	5,840.00	19.00	28.50	0.00	0.00	0.00	0.00
	Outbound gate	checkers	18	8,760.00	25.00	37.50	2,520.00	936,000.00	94,500.00	1,030,500.00
		supervisor	0	8,760.00	51.00	76.50	0.00	0.00	0.00	0.00
		clerical	9	8,760.00	25.00	37.50	2,520.00	468,000.00	94,500.00	562,500.00
		custodial	0	8,760.00	19.00	28.50	0.00	0.00	0.00	0.00

YARD			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
1,073,520.00	AS/RS buffer	supervisor	3	8,760.00	51.00	76.50	2,520.00	318,240.00	192,780.00	511,020.00
		yard worker	9	8,760.00	25.00	37.50	2,520.00	468,000.00	94,500.00	562,500.00
	Storage Area	supervisor	0	8,760.00	51.00	76.50	0.00	0.00	0.00	0.00
		yard worker	0	8,760.00	25.00	37.50	0.00	0.00	0.00	0.00
	Train/AGV Buffer	supervisor	0	8,760.00	51.00	76.50	0.00	0.00	0.00	0.00
		yard worker	0	8,760.00	25.00	37.50	0.00	0.00	0.00	0.00

BERTH			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
3,610,760.00	Berth	dock foremen	2	5,840.00	69.00	103.50	1,680.00	287,040.00	173,880.00	460,920.00
		marine planner	4	5,840	83.00	124.50	1,680.00	690,560.00	209,160.00	899,720.00
		operator	20	5,840.00	51.00	76.50	1,680.00	2,121,600.00	128,520.00	2,250,120.00

MAINTENANCE			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
1,193,920.00	Maintenance Area	repairmen	8	4,160.00	48.00	72.00	0.00	798,720.00	0.00	798,720.00
		supervisor	2	4,160.00	51.00	76.50	0.00	212,160.00	0.00	212,160.00
		clerical	2	4,160.00	25.00	37.50	0.00	104,000.00	0.00	104,000.00
		custodial	2	4,160.00	19.00	28.50	0.00	79,040.00	0.00	79,040.00

CONTROLLER			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
1,923,840.00	Central controller	programmer	3	8,760.00	72.00	108.00	2,520.00	449,280.00	272,160.00	721,440.00
		manager	3	8,760.00	120.00	180.00	2,520.00	748,800.00	453,600.00	1,202,400.00

Total Labor Cost
11,718,400.00

IV.5) Summary

Activity					
	Variable Costs	Fixed Costs	Total Costs		
	17,554,500	48,840,000	**66,394,500**		
Equipment					
	Variable Costs	Fixed Costs	Total Costs		
	8,252,212	33,587,333	**41,839,545**		
Total					
	Variable Costs	**Fixed Costs**	**Land Costs**	**Labor Costs**	**Total Costs**
	25,806,712	**82,427,333**	**6,576,438**	**11,718,400**	**126,528,884**

Projected annual TEUs handling	2,482,000
verage Cost per ontainer	101.96

Appendix V: Base Scenario: Manual operations

V.1) Activity

Activity Center	Working Hours	Electricity consumption Whirs per hour	electricity cost per KWHR	**Total electricity cost per activity**	Investment	Accounting life	Depreciation per year	Repair per year 3%	Insurance 1%	Interest 10%	**Total Fixed Costs**	**Total Costs**
								0.030	0.010	0.100		
Inbound gate	8,760	1,500	0.14	1,852,740	1,000,000	25	40,000	30,000	10,000	100,000	180,000	2,032,740
Customs	5,840	1,500	0.14	1,235,160	1,000,000	25	40,000	30,000	10,000	100,000	180,000	1,415,160
Outbound gate	8,760	1,500	0.14	1,852,740	1,000,000	25	40,000	30,000	10,000	100,000	180,000	2,032,740
Gate buffer	8,760	1,500	0.14	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
EXPORT Storage Area	8,760	1,500	0.14	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
IMPORT Storage Area	8,760	1,500	0.14	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
Train buffer	8,760	1,500	0.14	1,852,740	500,000	25	20,000	15,000	5,000	50,000	90,000	1,942,740
Berth	5,840	3,000	0.14	2,470,320	2,000,000	25	80,000	60,000	20,000	200,000	360,000	2,830,320
Maintenance area	4,160	1,500	0.14	879,840	1,500,000	25	60,000	45,000	15,000	150,000	270,000	1,149,840
Central controller	8,760	1,500	0.14	1,852,740	3,000,000	10	300,000	90,000	30,000	300,000	720,000	2,572,740

VC	FC	TC
17,554,500	2,250,000	19,804,500

V.2) Land

0.100

Land	Area (Acre)	Investment(U.S.$)	Accounting life(year)	Annual Land Cost (considering Inflation rate)	Interest 10%	**Total Costs(U.S.$)**
Storage Area	44.6284	22,314,200	25	1,583,247.32	2,231,420	3,814,667
Berth	5.6222	14,055,500	25	997,272.26	1,405,550	2,402,822
Train Area	6.9728	3,486,400	25	247,368.65	348,640	596,009
Gate Area	13.0667	6,533,350	25	463,557.24	653,335	1,116,892

Cost per Acre	500,000

Land Inflation Rate	0.05

Total Annual Land Cost	**7,930,390**

V.3) Equipment

										0.100	0.010	0.100			
	Working hours	Number of Equipment	Utilization Factor	Fuel, electricity, ..per equipment per hour($)	Fuel, electricity, …per equipment per year($)	**Fuel, electricity, … per year($)**	Investment	Accounting life	Depreciation per year	Repair per year 10% of investment cost	Insurance 1%	Interest 10%	Total Fixed Costs per equipment	**Total Fixed Cost**	**Total Costs**
Yard Truck	8,760	110	0.550	10.00	48,180	5,299,800	75,000	15	5,000	7,500	750	7,500	20,750	2,282,500	7,582,300
Yard crane	8,760	44	0.300	15.00	39,420	1,734,480	800,000	15	53,333	80,000	8,000	80,000	221,333	9,738,667	11,473,147
Quay crane	5,840	5	0.670	40.00	156,512	782,560	6,000,000	15	400,000	600,000	60,000	600,000	1,660,000	8,300,000	9,082,560

VC	FC	TC
7,816,840	20,321,167	28,138,007

V.4) Labor Costs

GATES			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
5,084,400	Inbound gate	checkers	27	8,760.00	30.00	45.00	2,520.00	1,684,800.00	113,400.00	1,798,200.00
		supervisor	0	8,760.00	61.00	91.50	0.00	0.00	0.00	0.00
		clerical	15	8,760.00	30.00	45.00	2,520.00	936,000.00	113,400.00	1,049,400.00
		custodial	0	8,760.00	24.00	36.00	0.00	0.00	0.00	0.00
	Customs	checkers	0	5,840.00	45.00	67.50	0.00	0.00	0.00	0.00
		supervisor	0	5,840.00	61.00	91.50	0.00	0.00	0.00	0.00
		clerical	4	5,840.00	30.00	45.00	1,680.00	249,600.00	75,600.00	325,200.00
		custodial	0	5,840.00	24.00	36.00	0.00	0.00	0.00	0.00
	Outbound gate	checkers	18	8,760.00	30.00	45.00	2,520.00	1,123,200.00	113,400.00	1,236,600.00
		supervisor	0	8,760.00	61.00	91.50	0.00	0.00	0.00	0.00
		clerical	9	8,760.00	30.00	45.00	2,520.00	561,600.00	113,400.00	675,000.00
		custodial	0	8,760.00	24.00	36.00	0.00	0.00	0.00	0.00

YARD			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
39,375,000	Truck/ITV Buffer	supervisor	36	8,760.00	61.00	91.50	2,520.00	4,567,680.00	230,580.00	4,798,260.00
		yard worker	72	8,760.00	30.00	45.00	2,520.00	4,492,800.00	113,400.00	4,606,200.00
	EXPORT Storage Area	supervisor	9	8,760.00	61.00	91.50	2,520.00	1,141,920.00	230,580.00	1,372,500.00
		yard worker	18	8,760.00	30.00	45.00	2,520.00	1,123,200.00	113,400.00	1,236,600.00
	IMPORT Storage Area	supervisor	9	8,760.00	61.00	91.50	2,520.00	1,141,920.00	230,580.00	1,372,500.00
		yard worker	18	8,760.00	30.00	45.00	2,520.00	1,123,200.00	113,400.00	1,236,600.00
	Train/AGV Buffer	supervisor	9	8,760.00	61.00	91.50	2,520.00	1,141,920.00	230,580.00	1,372,500.00
		yard worker	24	8,760.00	30.00	45.00	2,520.00	1,497,600.00	113,400.00	1,611,000.00
	ITV driver		306	8,760.00	34.00	51.00	2,520.00	21,640,320.00	128,520.00	21,768,840.00

BERTH			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total

12,328,200.00	Berth	dock foremen	20	5,840.00	83.00	124.50	1,680.00	3,452,800.00	209,160.00	3,661,960.00
		marine planner	4	5,840	83.00	124.50	1,680.00	690,560.00	209,160.00	899,720.00
		operator	60	5,840.00	61.00	91.50	1,680.00	7,612,800.00	153,720.00	7,766,520.00

MAINTENANCE			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
2,891,200.00	Maintenance Area	repairmen	20	4,160.00	58.00	87.00	0.00	2,412,800.00	0.00	2,412,800.00
		supervisor	2	4,160.00	61.00	91.50	0.00	253,760.00	0.00	253,760.00
		clerical	2	4,160.00	30.00	45.00	0.00	124,800.00	0.00	124,800.00
		custodial	2	4,160.00	24.00	36.00	0.00	99,840.00	0.00	99,840.00

CONTROLLER			# of people	sch. hours	$ per hour	$ per hour overtime	overtime	salary	salary overtime	salary Total
1,198,080.00	Central controller	operator	3	8,760.00	72.00	108.00	2,520.00	449,280.00	272,160.00	721,440.00
		manager	3	8,760.00	120.00	180.00	2,520.00	748,800.00	453,600.00	1,202,400.00

Total Labor Cost
61,602,640

V.5) Summary

Activity					
	Variable Costs	Fixed Costs	Total Costs		
	17,554,500	2,250,000	**19,804,500**		
Equipment					
	Variable Costs	Fixed Costs	Total Costs		
	7,816,840	20,321,166	28,138,006		
Total					
	Variable Costs	**Fixed Costs**	**Land Costs**	**Labor Costs**	**Total Costs**
	25,371,340	**22,571,166**	**7,930,390**	**61,602,640**	**117,475,537**

Projected annual TEUs handling	1,635,200
verage Cost per ontainer	143.68