

ABSTRACT

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Since the start of the containerization revolution in 1950's, not only the TEU capacity of the vessels has been increasing constantly, but also the number of fully cellular container ships has expanded substantially. Because of the tense competition among ports in recent years, improving the operational efficiency of ports has become an important issue in containership operations. Arrangement of containers both within the container terminal and on the containership play an important role in determining the berthing time. The berthing time of a containership is mainly composed of the unloading and loading time of containers. Containers in a containership are stored in stacks, making a container directly accessible only if it is on the top of one stack. The task of determining a good container arrangement to minimize the number of re-handlings while maintaining the ship's stability over several ports is called stowage planning, which is an everyday problem solved by ship planners.

The horizontal distribution of the containers over the bays affects crane utilization and overall ship berthing time. In order to increase the terminal productivity and reduce the turnaround time, the stowage planning must conform to the berth design. Given the configuration of berths and cranes at each visiting port, the stowage planning must take into account the utilization of quay cranes as well as the reduction of unnecessary shifts to minimize the total time at all ports over the voyage. This dissertation introduces an optimization model to solve the stowage planning problem with crane utilization considerations. The optimization model covers a wide range of operational and structural constraints for containership load planning.

In order to solve real-size problems, a meta-heuristic approach based on genetic algorithms is designed and implemented which embeds a crane split approximation routine. The genetic encoding is ultra-compact and represents grouping, sorting and assignment strategies that might be applied to form the stowage pattern. The evaluation procedure accounts for technical specification of the cranes as well as the crane split. Numerical results show that timely solution for ultra large size containerships can be obtained under different scenarios.

CONTAINERSHIP LOAD PLANNING WITH CRANE OPERATIONS

By

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Dedication

To my wife Nina, the love of my life,
and to my daughter Mana, the joy of our lives

Acknowledgements

During my long years at the University of Maryland I had the opportunity to work and collaborate with many wonderful people that without their help and support this journey would not have been possible. My deepest and sincerest thanks is devoted to my advisor, professor Ali Haghani, for his guidance, advice, support, and especially his extraordinary patience and trust in me. I would also like to thank my dissertation committee members for all their helpful guidance and discussions throughout the course of my research.

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Last but not least, I am deeply grateful to my parents, my family and my wife. My parents made many sacrifices to ensure I get the best possible education and lovingly guided me every step of the way. My wife is the most important reason in the success of my PhD. She has provided me with unconditional love, support, and understanding. I have been very lucky, beyond anything I could have wished for, to have her by my side. It would be impossible for me to express my gratitude towards her and my parents in mere words.

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Chapter 1: Introduction

1.1. Containerization

Containerization is an intermodal transportation system in which the containers as cargo units can be loaded on containerships, railroad cars and trucks without handling the contents. Containerization revolution that began in 1950s increased ocean carries productivity dramatically. Prior to containerization all goods other than bulk cargo were carried in break bulk format. Pieces of cargo were loaded one by one into trucks and at the marine port they were unloaded and loaded into the hold of a ship. At the destination individual pieces were unloaded and put on truck or train for delivery. In addition to inefficiency cargo was exposed to potential damage. Loading numerous pieces of cargo into a standard sealed metal box carried by truck or train to the seaport where it would be lifted and stored aboard ship sped up the process. At the destination the process would be reversed. The simple solution improved the delivery time, decreased transportation cost and made intermodal transportation far more feasible. On April 26th 1956 Ideal-X, the first cargo ship carrying containers left the port of Newark to the Port of Houston (Cudahy 2006). Soon the concept of containerization proved to be faster, safer and cheaper than the existing methods. By making the exchange of commodities easier it opened new markets for import and export.

The vast majority of international trade travels by ship and over that past two decades, container utilization has grown dramatically, helping the idea of a global intermodal economy. “Today over 60% of the world’s deep sea general cargo is

transported in containers whereas some routes, especially between economically strong and stable countries, are containerized up to 100%” (Steenkan et al. 2004). The globalization would have been impossible without containers. Because the demand for transportation is different across the ports, different sizes of containerships have been designed.

Container handling technology has also evolved over the years, not only in terms of size, type and capacity but also in ways that the containers are moved. In the beginning, ships were equipped with cranes to load and unload the containers themselves or traditional shore equipment was used. However as the container revolution went on, specialized equipment was developed allowing for a faster handling of containers. Nowadays, automated guided vehicles and cranes are in use in some ports to handle containers. The port of Rotterdam was the first one to develop and use this technology (Ben-Jaap 2005).

1.2. Container port terminal

A container terminal is the interface between land side and the quayside transshipment of the containers. Import containers arrive by containerships at the terminal where they are stored temporarily before being loaded onto the ground modes of transportation i.e. trains or trucks and dispatched to their final destination. The export containers arrive by rail or truck and are stored in a similar manner before being loaded to the ship and leave the port. Transshipment containers on the other hand are unloaded from the ship and stored in the yard, but eventually leave the port

on a different containership. The container terminal is the point at which containers change their mode of travel.

Container terminals can be looked at as three relatively independent subsystems.

- Quay-side interface
- Storage yard
- Land-side interface

Figure 1.1 shows a schematic of a container terminal system.

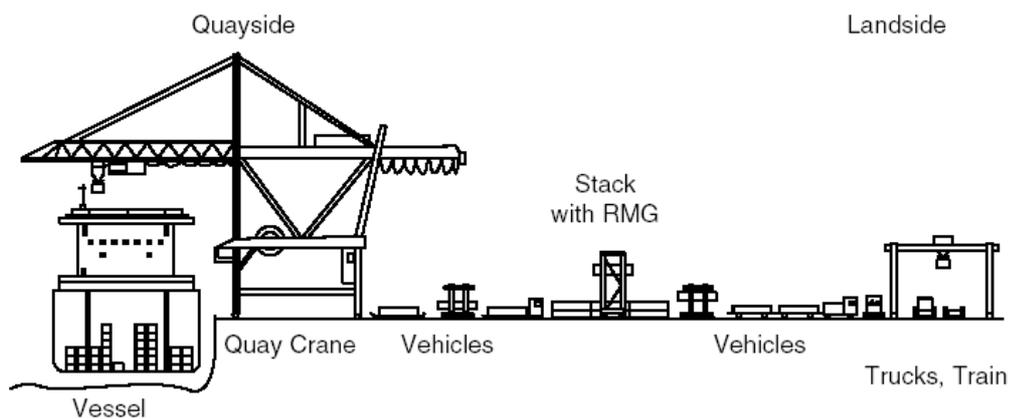


Figure 1.1: General schematic of a container terminal (Steenkan et al. 2004)

There are several decisions to be made in order to create a smooth and efficient flow of the containers in the system. The major tactical decision makers are terminal managers and the ship planners while at the operational level decisions might be made by crane operators or straddle carriers drivers. The hierarchy and timeline of the decisions for incoming and outgoing ships are depicted in figure 1.2.

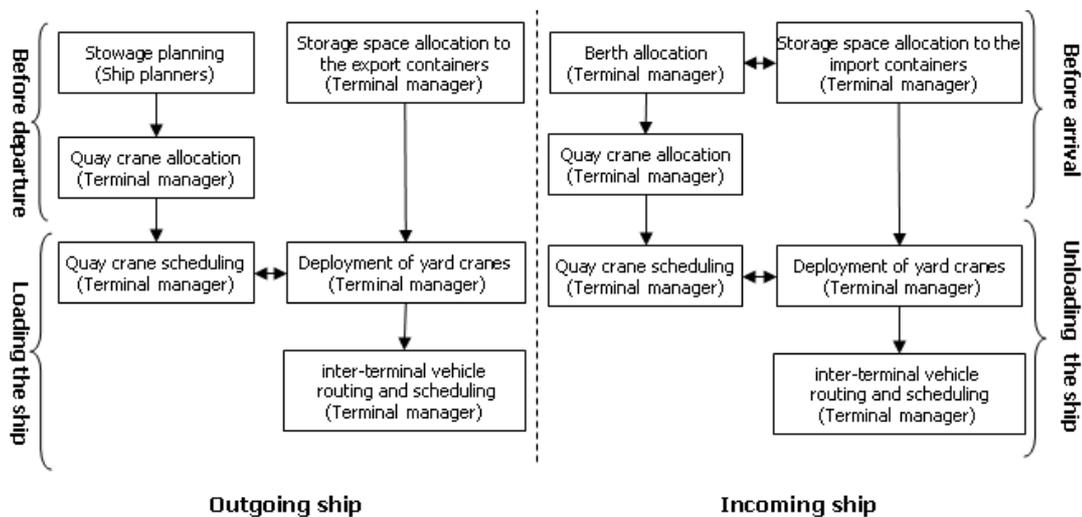


Figure 1.2: Hierarchy of the main decisions for incoming and outgoing ships

1.2.1. Quay-side interface

Before a ship calls for a port, her specifications and berth requirements as well as estimated time of arrival will be transmitted to the port. Based on the availability of the berths and the schedules of the incoming vessels, the terminal operators allocate a berth, berthing time and other resources (i.e. quay cranes) to the vessel. Although the shipping lines expect prompt berthing upon arrival, this might not be possible due to the limitation of the wharfs and congestion at the sea side of the port. Vessels of the priority customers might be granted berth-on arrival service if they have contracts with terminal operators.

After the containership docks at one of the available berths of the port, the containers will be loaded to, and unloaded from the containership using quay cranes. Quay cranes are the most expensive pieces of equipment at the container terminal and play a crucial role in loading and unloading operations. In the case of fully cellular containerships where no cranes are mounted on the vessel, quay cranes are the only

means of moving containers to/from the ship. Quay cranes are rail mounted and can move horizontally alongside the ship. The required time for moving a crane from one bay to the next depends on the type of the equipment and the underlying technology, but typically it is on the order of a one container move which ranges from one to three minutes. The crane operator uses the spreader arm to handle the container to/from the vessel. Maximum performance of the quay cranes depends on the crane type. While the technical performance is in the range of 50-60 box/hr, the operational performance is in the range of 22-30 box/hr (Steenken et. al. 2004). A quay crane typically has four legs. The space between the legs accommodates up to five truck lanes which is used by the internal trucks. Trucks stop in the lanes under the cranes to either feed the export containers to the crane or take the import containers from the crane and transport them to the yard. Import containers might directly leave the port by road or rail without going to the storage yard; however this is not very common.

1.2.2. Storage yard

Storage yard is an intermediate system between the quay and the land side of the port system. Both import and export containers are stacked in the columns at the storage yard. The yard handling equipment retrieve the export containers within the yard and take them to the quay cranes and bring back the import containers unloaded at the berth for storage in the yard.

There are two types of storage yards: those that stack the containers on the ground and those that store the containers on chassis. Although the containers on chassis can be retrieved and moved quickly and easily, this option is only available to the ports that do not have space limitations. When the land becomes expensive or simply

unavailable and the flow of the containers grows rapidly, similar to the situation in major Asian ports, stacking becomes the only viable option. Saving the space by using stacks comes at the price of increased time and effort for accessing the containers. The yard area in this case is divided into different blocks with several rows and tiers at each block. Some blocks or stack sections are reserved for special containers such as reefer containers which need electric plugs, hazardous cargo or overweight containers. Usually yard managers do not mix the import and export containers and store them in separate stacks. This is because the import containers arrive in the yard, in large batches but leave the port one by one in random order. On the contrary, the departure of export containers is predictable but their arrival happens in a random order. Empty containers also are stacked in different sections where they can be stacked higher than the normal containers.

There are several types of equipment for handling and transporting the containers within the storage yard. Straddle carriers are individual independent units that are capable of both lifting and transporting standard containers. When the maximum storage density at the container yard is required, a combination of Rubber Tyre Gantry Cranes (RTCG) and trucks is usually preferred to straddle carriers. Each storage block in this case consists of several rows of containers and a truck lane. RTCG's are capable of lifting a container from the truck waiting in the truck lane and store it in the stack or retrieve an outbound container and put it on the truck. They are very expensive equipment and planning for their proper utilization is crucial to the throughput of the yard. RTCG' are not fixed within the block and may move to

adjacent blocks, their movement however is slow and it is even slower if making a 90° turn for reaching the adjacent block is necessary.

When using straddle carriers no other vehicles are necessary for horizontal transportation of the containers within the storage yard. On the other hand when RTGC's are employed, trucks with trailer, multi-trailers or Automatic Guided vehicles (AGV) are needed for moving the containers. AGV's are computer controlled robots which operate on a grid of pre-designed wired routes with sensors and transponders. The deployment of AGV's is driven by economic reasons where the labor costs are high. Although they call for high investment they are already in operation at ECT/Rotterdam and at the HHLA/Hamburg in combination with automatic gantry cranes (Steenkan et. al. 2004). Figure 1.3 shows an aerial photo of the port of Rotterdam.



Figure 1.3: Port of Rotterdam in Netherlands (www.zpmc.com)

1.2.2. Land-side interface

The land-side interface is the transshipment point between the storage yard and the inland transportation system which can be truck, rail or both. The landside operation starts at gates where two main activities happen: export delivery and import receiving. Export delivery begins with checking the documentation and inspection of the containers which is brought in by freight forwarders. A storage location will be assigned to the container and the truck will be routed to the destination area at the yard where the container will be lifted and stored. Import receiving process initiates by a request from the customer at the gate. The location of the container then is reported by the computer system and the truck will be guided to the specific yard area to load the container.

To maximize the throughput of the port system and to avoid congestion, the processes of the above subsystems must be synchronized and optimized.

1.3. The containership

The size of a containership is normally stated as the number of TEU sized containers that it can carry (TEU is the abbreviation for twenty foot equivalent unit which is the standard container size by International Organization for Standardization). The first containerships were built by modifying bulk vessels in order to accommodate containers. These ships had their own on board cranes to handle the containers. As containers became more popular in 1970's, a new generation of the fully cellular containerships were introduced to the market. On board cranes were removed from these vessels so they had more space to dedicate to the stack of containers. Until the

mid 1980's containership size was limited by the dimensional constraint of the Panama canal. The economies of scale (increased capacity at higher speeds with lower costs per TEU) encouraged ship builders to design larger vessels until the Panama Canal limit of 13 containers across a 32.2m wide deck was reached. The result was a new generation of containerships known as post Panamax that started in 1988. Figure 1.4 shows different generations of the containerships and Figure 1.5 shows the maximum containership size by the year of build as well as the projected trend of the size growth.

Since then, the development of the post-Panamax fleet has been dramatic. According to the Lloyd's register fact sheets (Lloyd's 2003) the world post-Panamax container fleet has risen to 25% of the total containership fleet by capacity in 2003 and with the current trend a jump to 58% is expected. The new Panamax vessels will fit the third line of docks of the Panama Canal which will be operational in 2014 (Rodrigue et al. 2009).

United Nations reports that average carrying capacity per ship for the world containership fleet has increased from 3,489 TEUs in 2008 to 4,016 TEUs in 2010 as a result of building larger vessels to achieve economies of scale. Data shows that well-defined trend towards large container vessels is continuing unabated. The largest fully cellular vessel in early 2010 had a nominal capacity of 14,770 TEU. The largest vessels delivered in 2009 were two 13,880 TEU ships for CMA CGM shipping lines (UNCTAD 2010).

		Length	Draft	TEU
First (1956-1970)	 Converted Cargo Vessel	135 m	< 9 m < 30 ft	500
	 Converted Tanker	200 m		800
Second (1970-1980)	 Cellular Containership	215 m	10 m 33 ft	1,000 – 2,500
Third (1980-1988)	 Panamax Class	250 m	11-12 m 36-40 ft	3,000
	 Panamax Class	290 m		4,000
Fourth (1988-2000)	 Post Panamax	275 – 305 m	11-13 m 36-43 ft	4,000 – 5,000
Fifth (2000-2005)	 Post Panamax Plus	335 m	13-14 m 43-46 ft	5,000 – 8,000
Sixth (2006-)	 New Panamax	397 m	15.5 m 50 ft	11,000 – 14,500

Figure 1.4: Containership sizes (Source: The geography of transport systems)

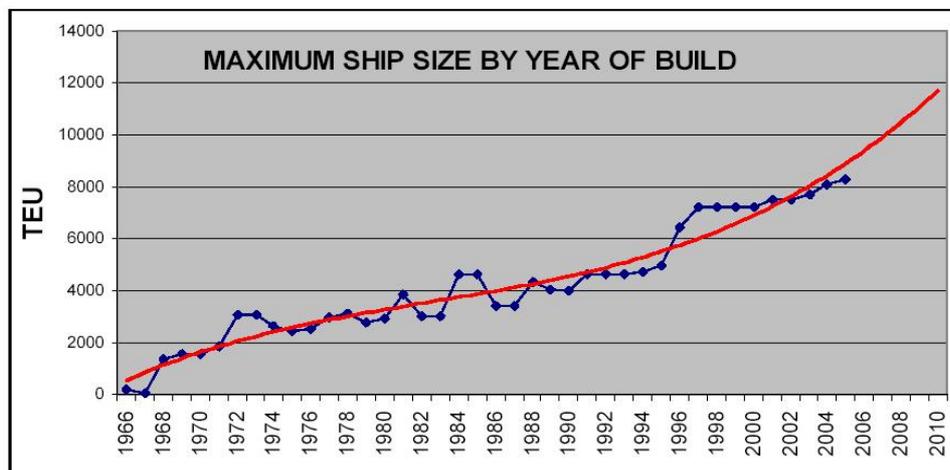


Figure 1.5: Maximum containership size by the year of build (Lloyd's 2003)

Not only the TEU capacity of the vessels has increased, but also the number of fully cellular containerships has expanded substantially. Studies show that by the beginning of 2010 there were 4,677 ships with a combined total capacity of 12.8

million TEUs (UNCTAD 2010). Overall there was an increase from of 8.9 percent in the number of ships and 12.9 percent in TEU capacity over the previous year. Figure 1.6 demonstrates the world fleet by principal vessel types for selected years.

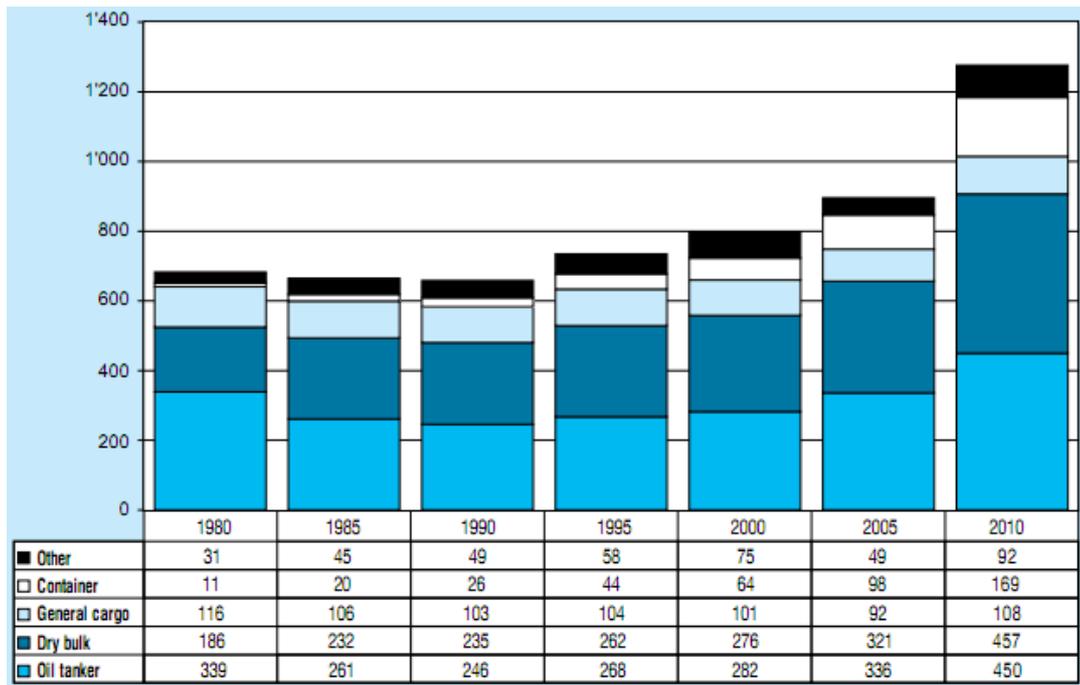


Figure 1.6: World fleet by principal types of vessel (UNCTAD 2010)

Containerization has revolutionized cargo shipping. Today, approximately 90% of non-bulk cargo worldwide moves by containers stacked on transport ships; 26% of all containers originate from China. As of 2005, some 18 million total containers make over 200 million trips per year (Levinson 2006).

Samsung Heavy Industries compared the cost of ship building between two 6200TEU vessels and one 12000TEU. The results suggest approximately 16% reduction in costs by building the latter vessel rather than the formers. The fuel cost per TEU for

12000TEU vessel compared to two 6200TEU is also approximately 17% lower (Yang 2004).

Today deployment of 15,000 TEU vessels on the routes between both east and west coast of North America and Southeast Asia is justified by the economies of scale. The containership "Emma Maersk" which is 396 m long was launched in August 2006. A study conducted at the Delft University (Wijnolst et al 1999) suggests that the maximum size for future containerships would be 18,000 TEU with a draft of 21m, given depth restrictions in the Malacca Strait which is a major shipping route between Europe and Asia. According to Levinson (2006) this so-called Malaccamax size constrains a ship to dimensions of 470 m in length and 60 m wide (1542 feet * 197 feet).

1.4. The container

Containers are large metal boxes used to transport commodities from one destination to another. The dimensions of the containers have been standardized. The term TEU¹ is used to refer to one container with a length of twenty feet, so a container of 40 ft is expressed by 2 TEU. Although the 20 foot containers are the most popular, the 40 footer are increasingly replacing them particularly since costs tend to be per container rather than per foot. The longer container types are also becoming more popular as the shorter containers (e.g. 10 foot containers) are rarely used. Table 1.1 shows the dimensions and weights for the three most common container types worldwide.

¹ Twenty feet equivalent unit

Table 1.1: Average dimensions and weights of popular container types²

		20' container		40' container		45' high-cube container	
		imperial	metric	imperial	metric	imperial	metric
external dimensions	length	20' 4"	6.198 m	40' 0"	12.192 m	45' 0"	13.716 m
	width	8' 0"	2.438 m	8' 0"	2.438 m	8' 0"	2.438 m
	height	8' 6"	2.591 m	8' 6"	2.591 m	9' 6"	2.896 m
interior dimensions	length	19' 4 13/16"	5.898 m	39' 5 45/64"	12.032 m	44' 4"	13.556 m
	width	7' 8 19/32"	2.352 m	7' 8 19/32"	2.352 m	7' 8 19/32"	2.352 m
	height	7' 9 57/64"	2.385 m	7' 9 57/64"	2.385 m	8' 9 15/16"	2.698 m
door aperture	width	7' 8 1/8"	2.343 m	7' 8 1/8"	2.343 m	7' 8 1/8"	2.343 m
	height	7' 5 3/4"	2.280 m	7' 5 3/4"	2.280 m	8' 5 49/64"	2.585 m
volume		1,169 ft ³	33.1 m ³	2,385 ft ³	67.5 m ³	3,040 ft ³	86.1 m ³
maximum gross mass		52,910 lb	24,000 kg	67,200 lb	30,480 kg	67,200 lb	30,480 kg
empty weight		5,140 lb	2,330 kg	8,820 lb	4,000 kg	10,580 lb	4,800 kg
net load		47,770 lb	21,670 kg	58,380 lb	26,480 kg	56,620 lb	25,680 kg

1.5. Containerization challenges

The global demand for containerized services has shown an increasing trend for the past decade. Table 1.2 shows double digit percentages of growth in container flow for Trans-Pacific and Asia-Europe routes between the years 2003-2004. The flow estimates used in this table are based on UNCTAD 2010 report. The decline of container flow in 2009 is attributed to the global recession which reduced the flow of containers from Asia to the United States and Europe.

² Container Handbook

Table 1.2: Estimated cargo flow along major trade routes (millions of TEU)

	Trans-Pacific		Asia-Europe		Transatlantic		Total
	Asia-US	US-Asia	Europe-Asia	Asia-Europe	US-Europe	Europe-US	
2009	11.5	6.9	5.5	11.5	2.5	5.3	43.2
2008	14.5	5.6	10.5	16.7	2.9	4.3	54.5
2007	15.2	5.0	10.1	17.2	2.7	4.5	54.7
2006	15.0	4.7	9.1	15.3	2.5	4.4	51
2005	12.4	4.4	5.5	10.8	2.1	3.8	39
2004	10.2	4.2	5.2	8.9	1.7	3.2	33.4
2003	8.8	4.1	4.9	7.3	1.7	2.9	29.7
2002	7.2	3.9	4.2	6.1	1.5	2.6	25.5
2001	5.6	3.9	4.0	5.9	2.7	3.6	25.7
2000	5.2	3.3	3.6	4.5	2.2	2.9	21.7

This ongoing growth has put an enormous pressure on ports and terminal operators to increase productivity in order to handle all these containers in a fast and smooth way. To maintain rapid dwell time for large vessels, ports need to invest in high speed container handling equipments and to accommodate large volumes of containers per vessel, expansion of landside storage facilities is necessary. Currently mega containerships can be served from one side of the vessel. Developing new berthing systems such as indented berths which make it possible to handle the containers from both sides of the ship can also speed up the process.

The key factors that shipping lines use to choose among competitive ports include handling cost per TEU, ship dwell time (total time spent at port), performance of quay

cranes, availability of the berths and the interface to the landside intermodal transportation system. To meet the challenges of today's competitive market it is crucial for each port to invest in state-of-the-art technologies and optimize the utilization of its expensive and limited facilities.

One of the major contributing factors in ship turnaround time is the pattern that the containers are stowed in the vessel. In general, a containership calls at a number of ports on her route and in each port, containers are unloaded and loaded. The containers will be stored in stacks that are only accessible from the top. In a favorable stowage pattern containers will be assigned to the positions in the ship such that the overall stability of the ship is maintained and the number of unnecessary movements is minimized. Unfavorable movements appear if at a certain port, containers have to be unloaded and reloaded again, since they are stored on top of containers destined for that port. Reducing the overall ship turnaround time by optimizing the stowage pattern and maximizing the utilization of the quay cranes during the load/unload process is the subject of this research.

1.6. Environmental issues of containerships

Stability of the vessel is a very important factor in cargo safety and maneuverability. Improper distribution and inadequate trimming of the containers causes horizontal as well as vertical imbalances to the vessel whether she is fully or partially loaded. One of the solutions to this problem is using ballast water to stabilize the vessel. Ballast in general is any material used to balance an object e.g. sandbags used to balance hot air balloons. Modern ships take ocean water into their ballast tanks instead of traditional solid ballasts like rocks and sands which have been used by old ships for a long time.

Figure 1.7 shows the ballast water status in a typical vessel at different points of the voyage.

Containerships discharge their existing ballast water as the cargo is loaded. Ballast is primarily composed of water but it also contains sediment and thousands of living species which will be disposed in foreign waters. These species known as alien or invasive species can affect the native marine food chain and cause environmental damages. Rigby et al. 1995 estimate that about 10 billion tones of ballast water is transported around the world each year. The role of ballast water in introducing exotic species has received extensive attention recently and governments have established guidelines for discharge and treatment of the ballast water.

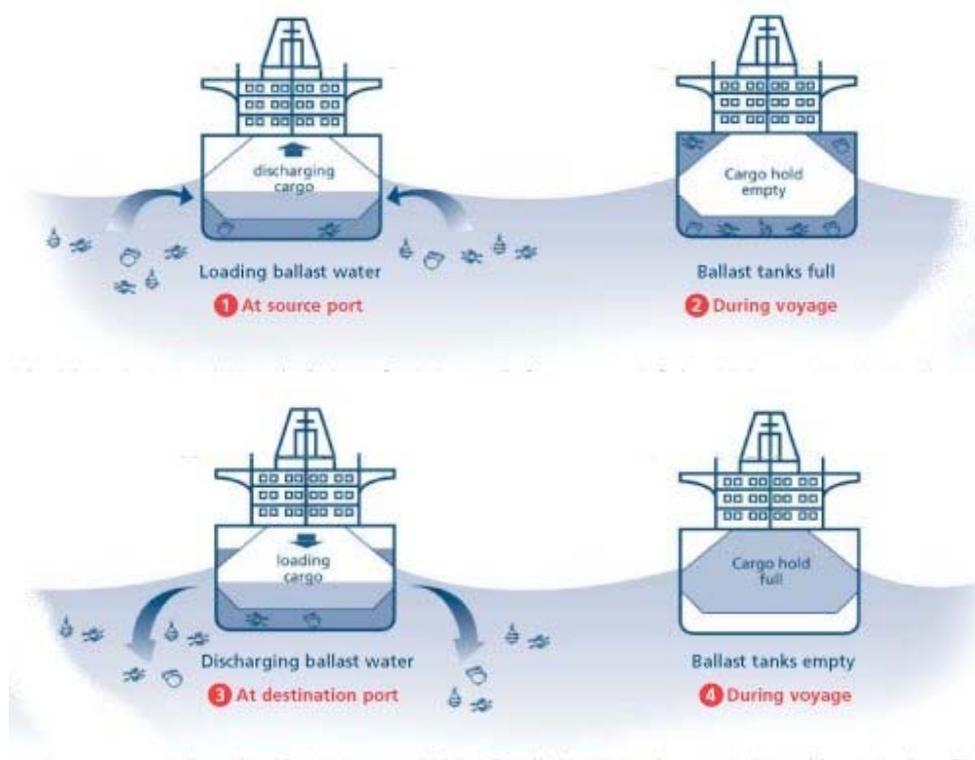


Figure 1.7: Cross section of a ship showing ballast tanks and ballast water cycle

(Source: International Marine Organization's website www.imo.org)

The more the imbalance in a containership, the more ballast water is required to stabilize it. In summary a proper stowage plan helps to make the containership operations more environmentally friendly in two ways. First it reduces the amount of ballast water needed to be carried which consequently lowers the risk of polluting the forthcoming ports with the exogenous species. Second it reduces the energy required for the thrust because the thrust is proportionate to the load of the vessel.

1.7. Motivation of this research

Because of the tense competition among ports in recent years, improving the operational efficiency of ports has become an important issue in containership operations. One of the major performance measures is the berthing time at a port. Arrangement of containers both within the container terminal and on the containership play an important role in determining the berthing time. The berthing time of a containership is mainly composed of the unloading and loading time of containers. Containers in a containership usually are stored in stacks. A container is directly accessible only if it is on the top of one stack (Last in First Out, LIFO). The ship visits several ports during a voyage and containers are loaded and unloaded at each port. The task of determining a good container arrangement to minimize the number of re-handlings while maintaining the ship's stability is called stowage planning, which is an everyday problem solved by ship planners.

Containers are loaded to and unloaded from the containership using quay cranes. The problem of allocating quay cranes to ship's sections is known as crane split. In some cases up to ten quay cranes might be allocated to a ship. Technical requirements determine the range in which each quay crane can operate. The ship's dwell time is

determined by the time that the latest crane finishes its job. Since the distribution of the containers over the bays affects crane utilization and overall ship berthing time, crane split and stowage problem are interrelated. Given the configuration of cranes at each visiting port, the stowage planning must take into account the utilization of quay cranes as well as the reduction of unnecessary shifts to minimize the total time at ports over the voyage. It seems that integration of the stowage plan and the crane split results in a more efficient working instruction which ultimately increases port utilization; however the joint optimization of these processes has not been discussed in the literature.

1.8. Structure of the dissertation

This dissertation is organized as follows. An introduction to the problem and the motivation for the research are presented in Chapter 1. Chapter 2 summarizes the existing literature that focus on containership loading/unloading operations and some other related problems. A mathematical programming model for solving the problem is developed and discussed in Chapter 3. Solution results of the aforementioned model for some sample problems are reported in Chapter 4. A general discussion on optimization techniques as well as a genetic algorithm framework for solving the containership loading problem is presented in Chapter 5. In Chapter 6 the parameters of the proposed genetic algorithm are analyzed and the performance of the method is discussed. Application of the solution algorithm for solving several scenarios and the effect of different policies on the loading/unloading process are shown in Chapter 7. The final chapter includes the concluding remarks and directions for future research.

Chapter 2: Literature review

2.1. Containership stowage planning

The stowage planning for a containership deals with the arrangement of containers within the ship. In general, a containership calls at a number of ports on her route and in each port, containers are unloaded and loaded. The stowage problem considers the assignment of containers to the positions in the ship such that the overall stability of the ship is maintained and the number of unnecessary movements is minimized.

These unfavorable movements appear if at a certain port, containers have to be unloaded and reloaded again, since they are stored on top of containers destined for that port.

Shields (1984) used a Monte Carlo method to solve the problem. Multiple parameters and constraints are considered in the research but the quality of the solution is not addressed. In this method the solution space is not searched systematically. Since then researchers have used mathematical programming and heuristics and artificial intelligence based optimization methods have been developed to solve large scale problems.

Aslidis (1990) solved a very special case of one uncapacitated column with constraints imposed on the vertical center of weight of the stack. He proved that exact optimal solution for the single column stack can be obtained in polynomial time.

Avriel and Penn (1993) and Avriel et al. (1998) formulated the problem as a binary linear programming model without considering stability constraints. All containers are assumed to have the same size. Since the stability is not taken into account the

weight of the containers is ignored. Due to the large number of variables needed, it was impossible to find the optimal solution for large size problems. Small examples were solved to optimality and alternative heuristics were proposed for larger problems. In their heuristic the authors broke the original transportation matrix into a sum of two sub matrices, one included the whole column and the other was a matrix of remainders. In a separate work Avriel et al. (2000) investigated the relation between the stowage problem and the coloring of circle of graphs problem. They showed that finding the minimum number of columns for which there is a zero shifts stowage plan is equivalent to finding the coloring number of circle graphs and through that they proved that the general stowage planning problem is NP-Complete. Haghani and Kaisar (2001) developed a mixed integer programming model and a heuristic algorithm for the simplified stowage planning to minimize container loading cost while maintaining the ship's stability within an acceptable range. They took longitudinal moment, trim and metacentric height (GM) into account and assumed that all containers have the same dimensions. In their two step heuristic approach they first assigned containers to stations and then to the individual cells within the station. Giemsch and Jellinghaus (2003) proposed a mixed integer programming model and a three step heuristic. Stability constraints are not considered in their work and results are not reported clearly. Imai et al. (2006) developed a multi-objective mathematical model for simultaneous stowage and load planning of a containership. They simplified the stowage part of the problem by considering only loading related rehandlings and single size containers. Since the effects of the unloading related reahndlings are ignored during the load planning, the burden will be carried to the

forthcoming ports. They used genetic algorithms to solve the joint problem of stowage and load planning to reduce the container rehandle in yard stacks.

In the aforementioned models an important simplification is the uniform container size. Multiple container sizes are considered in Ambrosino et al. (2004). They assumed that all the loading is done at the first port and the coming ports are only for discharge. This assumption reduces the stowage problem to an assignment problem with stability constraints at the master bay. They used a decomposition heuristic algorithm to solve the problem.

In the area of meta-heuristics, genetic algorithms and tabu search are used as solution approaches to stowage planning problem. Wilson and Roach (1999), (2000) used a hybrid heuristic composed of branch and bound and tabu search. They considered multiple type containers and stability and solved the problems in two steps. In the first step blocks or cargo are allocated to the bays in the vessel by branch and bound and in the second step tabu search assigns individual containers to each block. They reported that results are as good as the ones by human planners; however the size of the solved example was small and details of the solution approach were not presented.

Later Wilson et al (2001) used genetic algorithms instead of tabu search to progressively refine the arrangement of containers within the cargo space of a containership until each container is specifically allocated to a stowage location. No mathematical model was presented in the papers by Wilson et al.

Todd and Sen (1997) developed a multi criteria genetic algorithm. They call their genetic encoding a complete encoding because the whole assignment pattern at each port is stored in chromosomes which is both memory consuming and computationally

expensive. Besides that the crossover operator does not guarantee the feasibility of the resulting off-springs. To address this issue they apply a repair procedure to the results which interferes with the natural inheritance mechanism of genetic algorithm and destroys useful information which are crucial for evolution. Instead of saving the complete layout, Dubrovsky et al. (2002) used a genetic algorithm with a compact solution encoding by recording only the changes of the layout from port to port which result from loading and unloading the containers along the route. This method significantly reduces the search space and speeds up the convergence. However it does not take into account the effect of crane utilization and multiple containers sizes. To demonstrate the stability concerns they presented an example with horizontal equilibrium constraint. A parallel implementation of their genetic algorithm promises shorter running times when the number of CPU's is more than one.

Most recently Delgado et al. (2009) proposed a constrained programming approach for stowage planning. They assumed that containers must form a stack, 20-foot containers cannot be stacked on top of 40-foot containers, reefer containers must be assigned to reefer slots, and sum of the heights and weights of containers in each stack must stay within the stack limits. The objective of their approach was to minimize overstows, keep stacks empty if possible and avoid loading non reefer container into reefer cells. Results for some small scale cases shows that this method outperforms integer programming as well as column generation based approaches for the problem. Cranes are not considered in this research.

2.2. Container loading problem

Container loading problem is the problem of loading a subset of small items (e.g. rectangular boxes) into a large container. Depending on the field of application, the objective function and the side constraints, several variants of the container loading problem have been discussed in the literature. One classification is the problem of packing all given items into the least possible number of containers vs. packing as many items as possible into a given number of containers. Two, three and four dimensional packing models are discussed in the literature. Restrictions include but not limited to container capacity. Dyckhoff (1990) classifies such problems.

2.2.1. Bin packing

The problem of packing a set of boxes with different dimensions into a set of bins is called the bin packing problem. The objective is to use minimum number of bins to accommodate all the boxes. This problem has been discussed in the computer science and operations research literature extensively. Among them Scheithauser (1991) studied three-dimensional bin packing problem and Martello et al. (2000) considered exact methods for the solution. A review on the approximation algorithms for the bin packing problem can be found in Coffman et al. (1996). Giemsch and Jellinghaus (2003) discussed the possibilities of extending the three-dimensional bin packing problem to the containership stowage problem and Giemsch (2004) studied the stowage problem as a 4-D packing problem.

2.2.2. Strip packing

The strip packing problem also known as pallet loading problem involves the packing of a set of rectangles into a strip of given width and infinite height so that no rectangles are overlapping and the height of the strip is minimized. It is a generalization of bin packing because if we restrict all input boxes to be of the same height, then strip packing is equivalent to bin packing. It has applications in manufacturing industry, job scheduling, etc. The problem also has applications in multi-drop situations where the load should be divided into distinct sections for different destinations as it is discussed in Bischoff and Ratcliff (1995). A survey on two-dimensional packing problems is available in Lodi et al. (2002).

2.2.3. Multi-Container loading

Multi-Container Loading is a variation of the bin packing where the containers can have different dimensions. The objective is to choose a subset of the containers such that the shipping costs are minimized. An analytical model for the problem is described in Chen et al. (1995) and LP-based bounds are found in Scheithauser (1999).

2.2.4. Knapsack loading

Given a profit for each box, the knapsack loading problem is the problem of loading a subset of rectangular boxes into a container to maximize the loading profit subject to the container capacity. Minimization of the unused space can also be an objective function if the profit of each box is associated to its volume. Pisinger et al. (2004) covers many methods and techniques available for the solution of the Knapsack problem and its variations.

2.3. Stacking problem

A storage system in general is composed of the structure and the rules for adding and retrieving items in a storage area. Based on the application, a storage system can be anything like rail shunting yard, parking garage, computer memory, book library, a warehouse inventory, etc. The storage system may accommodate single type or multiple-type items. In the parking garage example the items are cars while in a hardware warehouse inventory items might be different kind of tools. The term stacking usually appears in the context of storage systems. Although it might be referred to the general situation in which items are stored on top of one another, it usually implies that the method of retrieval from the storage area is last in first out (LIFO). In a LIFO system the last item that is stored in the system is the first item to be retrieved. If the items can be retrieved regardless of their entering sequence the system will be randomly accessible. An Example is an inventory shelf where items can be stored vertically, but can be taken in any desired order. While stacks can be found in physical form in environments such as warehouses, their conceptual form is extensively used in the computer science and queuing theory. The storage rules in both forms are similar, but the purpose of stacking is different.

In physical systems stacking is usually used because the storage area is limited and also because it is cheaper to put the items of approximately the same size on top of each other rather than building shelving systems and cellular structures.

In computer systems however this is not the case. Stacks can be found in every level of a computer system not because it is cheaper to store data in a LIFO fashion, but because it is an efficient and powerful method to implement specific applications. In

the low level layers of a computer they are used for interrupt handling and system function call management. In the higher levels stacks have applications in expression evaluation and syntax parsing, runtime memory management, backtracking, etc. Using stacks for expression evaluation was first proposed by the early German computer scientist Friedrich L. Bauer and patented in 1957. He received IEEE Computer Society Pioneer Award in 1988 for his work on Computer Stacks (Broy 2002).

2.3.1. Overstowage

Stacking the items might seem to be a cheap alternative at first, but it might come at the cost of overstowage. Overstowage happens when there is need to retrieve an item which is not located on the top of the stack. In that case the items must be temporarily retrieved one by one until the designated item becomes accessible. After that, the temporarily removed items must be put back into the stack. Overstowage happens in everyday life. For example in an overcrowded elevator some people might have to temporarily exit the elevator in order to let people who have reached their desired floor out of the elevator. While packing a suitcase for a trip, one usually tries to put the items that are needed more frequently on top to avoid overstowage. Drivers of the pick up and delivery service trucks like UPS and FedEx may experience overstowage if the packages that they want to reach far inside the truck are blocked by the recently loaded ones.

Another example is the multiple-car carrier truck which, based on the size of the vehicles, can transport up to 12 vehicles in their stack shaped structure. Figure 2.1 shows a schematic design of such trucks. There are two independent stacks in this

example each having capacity of five cars. For unloading the leftmost car in the top tier it is necessary to first unload all the other cars in that tier. So if all the cars are not destined to the same destination and enough attention is not paid while loading the cars, the operator may have to go through the process of unloading and loading the overstowed cars. This is both time consuming and expensive. Overstowing is not always a result of bad planning; it might be inevitable due to technical and operational constraints. In the case of multiple-car carrier there might be a situation that for example only sedan cars are allowed on the leftmost position. In that case if the truck has to transport 9 SUV's and 1 sedan to two dealerships and the sedan happens to belong to the first dealership, then 4 SUV's on top ought to be overstowed.

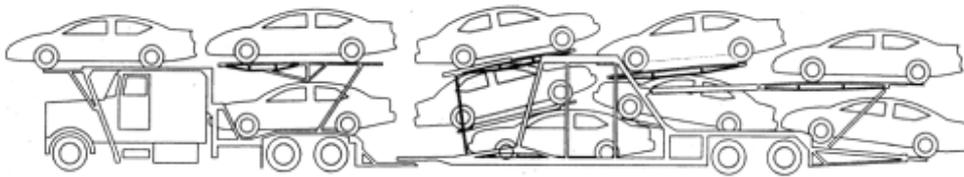


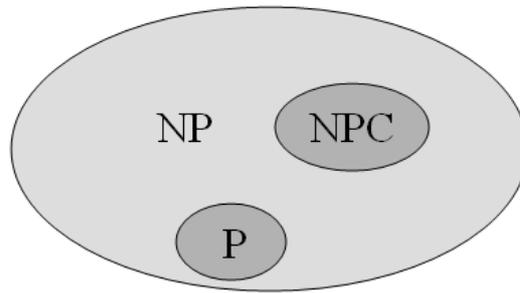
Figure 2.1: Schematic of a multiple-car carrier truck

Similar to the other stacking problems, stacking containers into the cellular columns of a containership or in the storage area of the container yard terminals may result in overstockage. The containers are stored in the yard before moving to the bays in the vessel. In order to prevent the situations like a container in the yard has to be moved so that the container below can be accessed; the terminal managers try to match the yard arrangement to the stowage plan. However some containers arrive while the loading process has already begun and that makes the overstockage in the yard

inevitable. The overstocking in containership occurs mainly because of the stability, technical and operational considerations.

2.4. Complexity of the containership stowage problem

In computing theory, the complexity of an algorithm is measured by the number of required operations in term of the size of the problem. For long time computer scientists and mathematicians have struggled to find the common features for some problems that could determine whether a polynomial time algorithm for solving them does or does not exist. Polynomial time refers to the computation time of an algorithm, where the running time is less than a polynomial function of the problem size. Nondeterministic Polynomial (NP) problems are problems that their solutions are verifiable in polynomial time. NP-complete problems are a subset of NP problems that are considered the hardest in the sense that no NP-complete problem can be solved by any known polynomial time algorithm. It is also proven that if there is a polynomial time algorithm for any NP-complete problem then there are polynomial algorithms for all NP-complete problems. Thousands of computer scientists have been unsuccessful for decades to design polynomial time algorithms for this class of problems. Based on the overwhelming empirical evidence many researchers have conjectured that there can be no polynomial time algorithm for any NP-complete problem; however nobody has been able to prove this. Optimization problems whose decision versions are NP-complete are called NP-hard (Papadimitriou and Steiglitz 1998). Figure 2.2 shows a venn diagram of the conjectured relationships of different classes.



$$P \subset NP, NPC \subset NP, P \cap NPC = \emptyset$$

Figure 2.2: Conjectured relationships between P, NP, and NP-complete

Researchers have taken different approaches to prove or at least show that the containership stowage planning problem with stability constraints is NP-Complete. These methods are summarized in this section.

2.4.1. Connection to capacitated multi-stack overstowage problem

Aslidis (1989) developed an exact analytical algorithm for solving the simplified case of single column and single size stacking problem to optimality. He shows that multi-stack overstowage problems (MSOP) are much harder than their single stack counterparts and identifies two possible sources of difficulties for that. First it is the problem of assigning the containers to stacks to avoid overstowage. Since the time for finding optimal overstowage solution to the one stack problem is non-linear the assignment problem alone can make the problem very hard. Secondly the possibility of container switching among stacks through the voyage is another complexity factor. He presented a model for MSOP and transformed it into a minimum network cost flow problem with integrality constraints. By using a decision version of the problem he then proves that MSOP belongs to the class of NP problems. To prove that MSOP

problem is NP-complete, a general method is to find a known NP-complete problem and transform it to MSOP in polynomial time. Although the author found strong connection between MSOP and some well known NP-complete problems, he could not find a polynomial transformation. Thus Aslidis (1989) failed to mathematically prove that MSOP is NP-complete. By bringing the stability and operational constraints into MSOP he concluded that there is a very high chance that the problem is NP-complete. Introducing different size containers, operational constraints and crane utilization considerations adds to the complexity of the problem and one can use the same reasoning to consider the extended version of the problem NP-complete as well.

2.4.2. Connection to tram dispatching problem

Given a set of arriving trams, a set of departure schedules and a set of depot positions consisting of horizontal capacitated stacks, the tram dispatching problem (TDP) is the problem of assigning the trams to the stacks such that the cost of operations is minimized. Winter (1999) proved that TDP is NP-complete. Using the binary programming model for containership stowage problem by Avriel and Penn (1993), the author established a connection between container stowage problem and the tram dispatch problem. It was assumed that shift operations for containers and shunting operations for trams are of the same nature but different. A transformation model from TDP to container stowage problem is presented. Results show that because of the NP-completeness of the problem if the stacks contain five or more positions, it is impossible to solve instances of more than fifteen trams in reasonable time. The

binary model by Avriel and Penn (1993) is developed for problem with uniform container size without considering the stability constraints. So based on its connection to TDP, it can be concluded that solution to the more comprehensive version of containership stowage problem cannot be obtained in polynomial time.

2.4.3. Connection to the coloring of circle of graphs

Graph coloring is a well known classical problem in graph theory. In general it is an assignment of colors to certain objects of a graph (e.g. edges or vertices) subject to certain constraints. Vertex coloring as a special case of graph coloring is the problem of coloring vertices of a graph such that no two adjacent vertices share the same color. Chromatic number of a graph is the least number of colors needed to color the graph. The problem of finding the minimum coloring of a graph is NP-hard and its corresponding decision problem is NP-complete (Jensen and Bjarne 1995).

Avriel et al. (1999) considered a containership consisting of a single bay and that has C vertical columns and R rows. They called the bay capacitated if each column has a finite number of rows and uncapacitated otherwise. Given the transportation matrix and uniform size containers they defined the minimum shift problem as the problem of finding the stowage plan with the smallest number of shifts. The decision problem is the uncapacitated s -shift problem which indicates whether given a transportation matrix, a stowage plan with a cost of at most s shifts exists. They established a connection between the zero-shift problem and the coloring of overlap graphs. They proved that the uncapacitated zero-shift problem is NP-complete and finally concluded that uncapacitated shift problem is NP-complete. Since the simplified

containership stowage planning problem is NP-complete, the more complicated variances which account for stability and other constraints are also NP-complete.

2.5. Crane scheduling and utilization

One of the important decisions to be made by terminal operators is the crane scheduling, also known as the crane split problem. Quay cranes are the most expensive single unit of handling equipment at container terminals. By improving quay crane efficiency, ports can increase their productivity and improve their throughput. Depending on the ship size, up to five cranes may simultaneously operate on the ship as this number may be doubled at the indented berth terminals. Crane scheduling problem is the problem of optimal assignment of quay cranes to the ships with respect to technical specifications of the cranes and the vessels. Daganzo(1989) proposed a MIP model for static crane allocation problem assuming that the berth length is not restricted. The objective function was to serve all the vessels and minimize their total delay cost. Exact and approximate solutions were presented. Furthermore, Peterkofsky and Daganzo (1990) used branch and bound to determine the departure time of multiple vessels and the number of cranes assigned to the bays while minimizing the total delay cost. Neither of the above works considered the interference among cranes and the precedence relationship among tasks. Lim et. al. (2004) introduced spatial constraints to the problem, assuming that cranes cannot cross each other. Dynamic programming algorithms, a probabilistic tabu search, and a heuristic was proposed to find a job to crane assignment that maximizes the throughput. Considered the quay cranes as processors and the vessels as jobs, Guan et. al. (2002) show a multiprocessor task scheduling model for berth allocation in

which the total weighted completion time of the jobs is minimized. They presented a heuristic for the problem and analyzed the worst case instances. More recently, Kim and Park (2004) described a mathematical model to determine the sequence of discharging and loading operations that a quay crane will perform so that turnaround time of a single vessel is minimized. They used branch and bound to obtain the optimal solution and developed a lower bound. To overcome the computational difficulty, they proposed a greedy randomized adaptive search procedure. Moccia et al. (2006) proposed modifications to the model by Kim and Park (2004) and formulated the problem as a vehicle routing problem with side constraints. They used a branch and cut algorithm for solving large instances of the problem and compared their results with the work by former authors. Imai et al. (2007) addressed the berth allocation problem with a consideration of serving simultaneously multiple small ships at an indented berth terminal. They conclude that although turnaround time of mega-ships was faster in such terminals, the total service time for all ships was longer than the one in a conventional terminal.

Other researchers have considered crane scheduling jointly with other decision problems at port. Schonfeld and Sharafeldien (1985) developed a model for minimizing the total port costs which accounts for the delay costs, mutual interference among the cranes, minimum work shifts and storage yard constraints. The results showed that total costs can be reduced by increasing the number of cranes per berth and berth utilization. Bish (2003) considered the crane scheduling along with storage assignment determination and vehicle dispatching problem and developed a heuristic to minimize the maximum turnaround time of all the ships in

the planning horizon. Park and Kim (2003) discussed an integer programming model for scheduling berth and quay cranes and presented a two-phase solution algorithm. In the first phase a near optimal solution for berthing times and positions of the vessels is determined and in the second phase the specific operating schedules for individual cranes are constructed.

All previous studies were based on the assumption that all relevant containers are first unloaded before any are loaded. Goodchild and Daganzo (2007) studied the benefits of crane double cycling where loading and unloading operations are performed simultaneously. They formulated the problem as a scheduling problem and solved it using commercial solvers for small instances. A fast greedy algorithm and a lower bound are developed for real size problems. Zhang and Kim (2009) proposed a mixed integer programming model and a gap-based local search approach to maximize the number of dual-cycle operations of quay cranes.

A comprehensive literature review on container terminal operations may be found in Steenkan et al.(2004). Previous useful literature reviews are presented in Iris and Rene (2003) and Meermans and Dekker (2001).

2.6. Conclusions

The containership stowage planning problem which is the problem of stacking containers into the cellular columns of a containership is an everyday problem solved by the ship planners. Overstowage which is both costly and time consuming occurs in containership loading and unloading operations because of inefficient planning, technical limitations or both. Researchers have approached the problem as a variation of bin packing problem with stability constraints, multi-column stacking problem and

assignment problem and have applied interesting techniques to minimize the overstockage. However the actual objective of stowage planning is to minimize the total time that the vessel spends at all ports. Although reducing overstockage may contribute to this goal, the role of other players in the loading and unloading operations such as quay cranes should not be ignored. Considering the quay crane assignment in containership stowage planning problem has not been addressed in the literature. Maximizing the utilization of quay side equipment while minimizing the number of overstocked containers can produce a better stowage plan which directly translates into cost saving and congestion reduction. This dissertation looks at the containership load planning problem from this new perspective.

Chapter 3: Problem formulation

3.1. Problem statement

Container port system consists of different subsystems. Because of the complexity of the operations, subsystems have been studied and analyzed individually. Recently researchers have paid more attention to the joint optimization of two or more subsystems. Containership load planning is an important part of the container transportation logistics. The growing competition among ports and increasing capacity of the containerships has resulted in congestion in major terminals and has put pressure on container terminal managers and shipping companies to improve their operations. At the quay side interface of the container port system, berthing time is the most important performance measure. Quay cranes are the most expensive equipment at port and they play a major role in the terminal productivity. Depending on the size of the vessel and availability of quay cranes, usually more than one crane will be assigned to a vessel. Assigning more cranes to a vessel might not improve the berthing time if the stowage plan of the vessel does not match the crane assignment. This research will combine the quay crane assignment with the traditional stowage planning problem in order to generate more efficient stowage plans. Instead of focusing on minimization of overstowage, the real objective function of the containership load planning which is the minimization of overall berthing time at all ports will be used. This will be done through maximizing the utilization of quay cranes while minimizing the unproductive container moves. Realistic stability and operational constraints as well as individual container characteristics are taken into account.

3.1.1. Modeling contribution

No optimization model exists in the literature that addresses joint optimization of quay crane utilization and stowage planning. Very few mathematical models exist for containership stowage planning optimization. Each of these models has its own simplifications and shortcomings. More details can be found in section 2.1. To the best of our knowledge this is the first mathematical model to minimize total berthing time and accounts for containers of different weight, size and type as well as stability and real life operational constraints. It also introduces the assignment pattern and technical specifications of the quay cranes to the optimization framework. So far almost everybody has directly translated the minimization of shifts to the minimization of time at port and the ones who have mentioned the necessity of paying attention to the horizontal distribution of the containers during stowage planning have not considered it in their models (Giemsch, Jellinghaus 2003). This research fills this gap.

3.2. Problem description

A containership has a cellular structure. The containers are held in bays along the length of the ship. The containers are stacked in tiers in each bay. Each of these tiers is made up of a number of cells. The position of the container within the ship is entirely specified by three indices: bay-row-tier. The layout of bays, rows and tiers differs from ship to ship because the location of engine rooms, accommodation sections and hull shapes are different in each ship. Figure 3.1 shows the cellular structure of a sample containership.

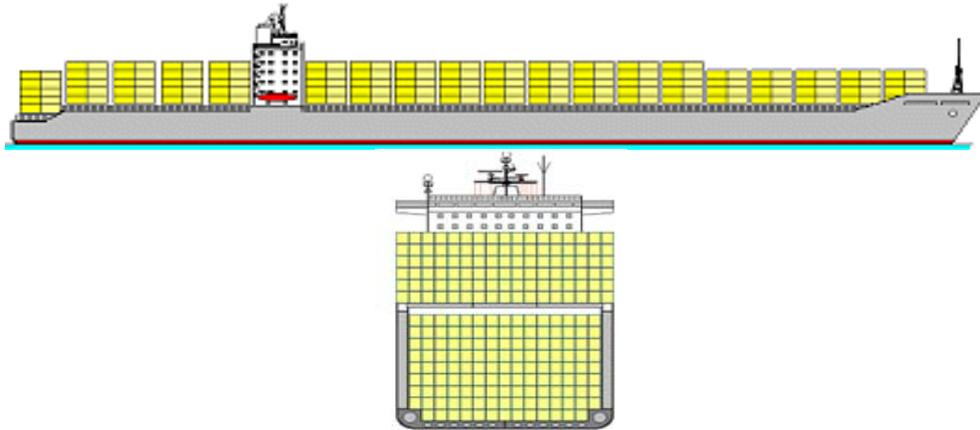


Figure 3.1: Cellular structure of a containership (www.containerhandbuch.de)

A general layout design can be looked at as a three dimensional matrix. Each element of the matrix corresponds to a cell in the vessel. This value might serve as the container number assigned to the corresponding cell or simply be a binary digit showing the availability of the cell. Specific hull shapes and design structures may be addressed by using predefined values in this way. Figure 3.2 shows the general layout.

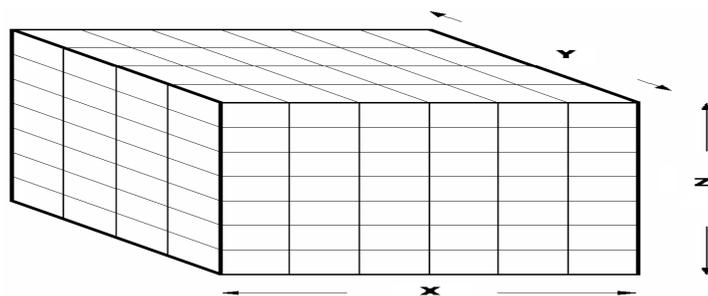


Figure 3.2: General cellular structure

Usually more than one quay crane operate on a containership at each port. Quay cranes move horizontally along the ship and load/unload containers to/from the vessel using a spreader arm. Horizontal moves are both slow and expensive, so they should be avoided as much as possible. These moves are also restricted by technical constraints such as no two cranes may work on the same bay simultaneously. Quay cranes are the most expensive single unit handling equipment in container terminals. Therefore, by improving crane utilization, ports can reduce ship dwell time, increase throughput of the system and improve port productivity. Utilization of each crane is determined by dividing the crane busy time over ship dwell time. Distribution pattern of containers along the bays plays a crucial role in crane utilization.

3.3 Containership stability

Safety of the sea vessels, whether they are cruise ships or cargo ships, goes hand in hand with their stability. For the cargo and containerships it is crucial that the weight is properly distributed through the ship so that the structure is not overstressed and the standard criteria of stability are met. A brief summary of Hydrostatic as well as experimental rules of stability for containerships is given in this section.

3.3.1. Hydrostatic rules of stability

Stability of a vessel is the ability to return to its upright position when disturbed, after the disturbing force is eliminated. Archimedes principle says that a body floating or submerged in a fluid is buoyed up by a force equal to the water it displaces. So a ship sinks if weight of water displaced by the underwater volume is less than the weight of the ship. One way to check for the stability of a ship is by measuring center of gravity (G) and the center of buoyancy (B) force. The former is the aggregation of all gravity forces acting downward

through ship's geometric center and the latter is all the buoyancy forces acting upward as on force through underwater geometric center. Location of G remains the same unless weight is added, removed or shifted. The location of B changes as the ship heels. Depending on the location of G and B there exist a righting moment which tends to return the ship to the upright position and an upsetting moment which tends to overturn the ship (Barrass and Derrett 2005). The meta-center of the ship (M) is the intersection of different lines of buoyancy as the ship heels through small angles. The relationship between M and G determines the stability status of the ship. According to the position of M and G three cases exist:

1. **G under M:** Ship is in stable equilibrium meaning that when inclined, it tends to return to the initial upright position
2. **G above M:** Unstable equilibrium exists. In this situation if the ship is inclined to a small angle, it tends to heel over even further.
3. **G coincides with M:** Ship is in neutral equilibrium and if inclined to a small angle, it will tend to stay in that angle until another external force is applied.

Figure 3.3 shows the forces on a sample vessel.

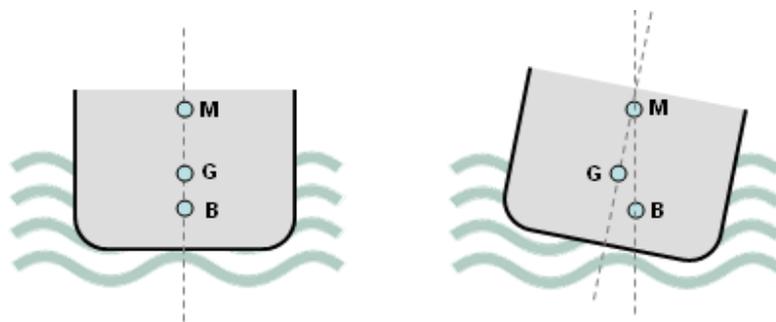


Figure 3.4: Gravity forces, Buoyancy forces and Meta-center of a ship

Another tool to measure the stability is the meta-centric height (GM) which is the distance between the meta-center and the center of gravity. The typical working value for GM for containerships is approximately 1.5 m. If the GM falls below this threshold the vessel will be unstable. Generally speaking the higher density containers must be stored in the lower holds of the vessel in order to increase the meta-centric height.

3.3.2. Experimental rules of stability

Since calculating the meta-centric height requires detailed information of the containership structure, experimental rules of stability have been created by ship planners which are applicable to typical containerships. These rules can be categorized as longitudinal, cross and vertical equilibrium.

Longitudinal equilibrium

Containers stowed at the bow side of the ship create a tilt which acts as an opposite force to the tilt created by the containers at the stern side. If these forces cancel out each other the bow and stern will have the same waterline height. Longitudinal equilibrium requires that the difference in the height of waterline between bow and stern does not exceed a given threshold. Besides safety considerations the longitudinal equilibrium affects the required propulsion and the fuel consumption by the engine. Figure 3.5 shows this equilibrium.



Figure 3.5: Longitudinal equilibrium

Cross equilibrium

Relating to the axis of symmetry going through bow to stern, the containers at the left side create a tilt opposite to the one by the containers at the right side. If these tilts are not equal the vessel will heel toward the heavier side. To ensure the stability the weight difference between the two sides must be kept within a predetermined range.

Figure 3.6 illustrates this situation.

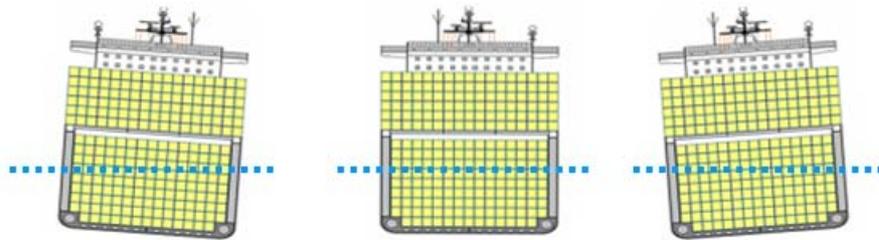


Figure 3.6: Cross equilibrium

Vertical equilibrium

According to the hydrostatic rules the location of center of gravity changes with the vertical shift of the weight in the vessel. However the vertical shift does not affect the center of buoyancy because the underwater portion of the containership does not change. This means that shifting the heavier containers to the lower compartments of the vessels increases the GM and improves the stability. This is the reason that empty containers are mostly stored above the deck area. The experimental rule of vertical stability requires that the total weight of each tier of containers to be less than or equal to the total weight of the tier underneath.

3.4 Operational consideration

In addition to the vessel stability constraints, a number of operational constraints must be satisfied. Generally these constraints relate to the placement restrictions with respect to the size, type, content and strength of the containers. Some of these constraints are presented below.

1. Weight of a single column: depending on the structural specification of the containership, there is a limit to the maximum weight of a single column of the containers that the deck structure can bear. So the weight of individual stacks may be restricted.
2. Racking strength: The containers below deck are stored in cells, however above deck there are no cell guides. In this case the containers on the lower tiers hold the containers stowed above them. The planners must make sure that the weight of the upper containers does not exceed the strength of the base containers. This is one of the reasons that empty containers are usually stored above deck.
3. Container support: standard cells are generally designed for twenty feet containers and 40 feet containers require two contiguous 20 feet cells. Each container needs to be fixed by four twisters to the upper corners of the containers below it, so smaller containers cannot be placed above larger ones.
4. Refrigerated containers: refrigerated containers (reefers) are used for transporting perishable goods. They need to stay connected to the electricity outlet for the safety of their contents. There are also containers that require ventilation. These containers must be placed in certain areas of the vessel where their requirements can be met.
5. Hazardous containers: the placement of the containers containing hazardous materials is governed by the hazardous materials safety regulations. According to Code of Federal Regulations hazmat containers must be separated from other hazmat

and reefer containers by a minimum distance (CFR, Title 49, Transportation, Parts 100-185).

On June 22nd 2007, a large number of containers carried by the Ital Florida – a 3450 TEU fully cellular containership - were damaged at the Port of Trieste because of improper lashing and weight distribution. Figure 3.7 shows the incident.



Figure 3.7: Damaged containers on Ital Florida (www.cargolaw.com)

3.5 Assumptions

Using the general cellular layout for the containership, each cell is identified using three indices: bay-row-tier. This address is a system of numerical coordinates relating to length, width and height of the containership. The route which the ship takes in her voyage and the sequence of the ports at which she stops are fixed and known. At each port a set of containers must be picked up and some containers must be unloaded. The number of containers to be loaded/unloaded at each port as well as the complete relevant information of the containers including weight, size, type and destination are also known. More than one quay crane may be assigned to a vessel at each port. The

number of available quay cranes, the range of bays in which they can operate on the ship as well as the technical parameters of the cranes are known.

3.6. Mathematical model

Based on the assumptions in the former section, a mathematical model that minimizes the ship's berthing time at all ports by minimizing the number of re-handlings and maximizing crane utilization is developed. The model is a binary integer programming model which observes the stability and operational constraints.

3.6.1. Parameters

C	Set of all containers
TF	Set of 20 ft containers
R	Set of refrigerated containers
H	Set of hazmat containers
N	Set of all ports
$O(c)$	Origin of container c
$D(c)$	Destination of container c
$W(c)$	Weight of container c
$T(c)$	Size of container c in TEU
NQ_t	Number of quay cranes at port t
$S(Q_{k,t})$	Start bay of crane k at port t
$E(Q_{k,t})$	End bay of crane k at port t
$W_{\max}(t)$	Ship weight capacity at port t
W_{column}	Maximum weight allowed for a column
P_k	Handling time of a container by crane k
LRB	Left-Right balance threshold
BSB	Bow-Stern balance threshold

Total weight limit of the ship might be different at different ports since the berthing depth limit is port specific and the ship draft must meet that limit.

3.6.2. Decision variables

$$\delta_{c,t}^{x,y,z} = \begin{cases} 1 & \text{If cell (x,y,z) is assigned to container c at port t;} \\ 0 & \text{Otherwise} \end{cases}$$

$$U_{c,t} = \begin{cases} 1 & \text{If container c is unloaded at port t;} \\ 0 & \text{Otherwise} \end{cases}$$

$$I_{c,d,t} = \begin{cases} 1 & \text{If container c is on top of container d at port t;} \\ 0 & \text{Otherwise} \end{cases}$$

$$J_{c,k,t} = \begin{cases} 1 & \text{If container c is handled by crane k at port t;} \\ 0 & \text{Otherwise} \end{cases}$$

δ 's serve as assignment variables. They determine whether a given cell is occupied by a given container at a given port. The specific hull shape and design of a given containership can be addressed by assigning dummy containers to the virtual cells which do not physically exist. Index variables I 's keep track of the relative location of each two containers at any port. Decision variables U 's show if the container has been unloaded at a port either because of rehandling or simply because it has reached the final destination. J 's are crane assignment variables and show the cranes that handle a container at each port.

3.6.3. Objective function

The difference between the time of which the ship is released and the arrival time at port is called dwell time. The objective function minimizes the total dwell time at all ports which is as follows:

$$\text{Min} \sum_{t=1}^N (T_t = \text{Max} \{ P_{k_1} \sum_{c=1}^C J_{c,k_1,t}, P_{k_2} \sum_{c=1}^C J_{c,k_2,t}, \dots, P_{k_{N_{Q_i}}} \sum_{c=1}^C J_{c,k_{N_{Q_i}},t} \}) \quad (3.1)$$

Since this objective function is nonlinear we transfer the crane utilization considerations to the constraints and use (3.2) as objective function.

$$\text{Min} \sum_{c=1}^C \sum_{t=1}^N U_{c,t} \quad (3.2)$$

This objective function minimizes the total number of unloading and rehandling activities over the voyage.

3.6.4. Cell assignment constraints

The cell assignment constraints are written as follows.

$$\sum_{x=1}^X \sum_{y=1}^Y \sum_{z=1}^Z \delta_{c,t}^{x,y,z} = 1 \quad \forall c, t \in [O(c)..D(c)-1] \quad (3.3)$$

$$\sum_{x=1}^X \sum_{y=1}^Y \sum_{z=1}^Z \sum_{t=D(c)}^N \delta_{c,t}^{x,y,z} = 0 \quad \forall c \quad (3.4)$$

$$\sum_{x=1}^X \sum_{y=1}^Y \sum_{z=1}^Z \sum_{t=1}^{O(c)-1} \delta_{c,t}^{x,y,z} = 0 \quad \forall c \quad (3.5)$$

$$\sum_{c=1}^C \delta_{c,t}^{x,y,z} \leq 1 \quad \forall x, y, z, t \quad (3.6)$$

$$\sum_{c=1}^C \delta_{c,t}^{x,y,z} - \sum_{c=1}^C \delta_{c,t}^{x,y,z+1} \geq 0 \quad \forall x, y, z \in [1..Z-1], t \quad (3.7)$$

Constraints (3.3) force a container to be assigned to a cell at its origin port and stay aboard up to its destination. Constraints (3.4) and (3.5) prohibit a container to be assigned to a cell before its origin or after its destination port. Constraints (3.6) ensure that an individual cell will be assigned to no more than one container at each time.

Constraints (3.7) ensure a container will not be put on top of an empty cell.

3.6.5. Stability constraints

The stability constraints based on experimental rules of stability are written as follows.

$$\left| \sum_{c=1}^C \sum_{x=1}^X \sum_{y=1}^{\lfloor Y/2 \rfloor} \sum_{z=1}^Z \delta_{c,t}^{x,y,z} \cdot W(c) - \sum_{c=1}^C \sum_{x=1}^X \sum_{y=\lceil Y/2 \rceil}^Y \sum_{z=1}^Z \delta_{c,t}^{x,y,z} \cdot W(c) \right| \leq LRB \quad \forall t \quad (3.8)$$

$$\left| \sum_{c=1}^C \sum_{x=1}^{\lfloor X/2 \rfloor} \sum_{y=1}^Y \sum_{z=1}^Z \delta_{c,t}^{x,y,z} \cdot W(c) - \sum_{c=1}^C \sum_{x=\lceil X/2 \rceil}^X \sum_{y=1}^Y \sum_{z=1}^Z \delta_{c,t}^{x,y,z} \cdot W(c) \right| \leq BSB \quad \forall t \quad (3.9)$$

$$\sum_{c=1}^C \sum_{x=1}^X \sum_{y=1}^Y \delta_{c,t}^{x,y,z} \cdot W(c) \leq \sum_{c=1}^C \sum_{x=1}^X \sum_{y=1}^Y \delta_{c,t}^{x,y,z-1} \cdot W(c) \quad \forall t, z \in [2..Z] \quad (3.10)$$

$$\sum_{c=1}^C \sum_{x=1}^X \sum_{y=1}^Y \sum_{z=1}^Z \delta_{c,t}^{x,y,z} \cdot W(c) \leq W_{Max}(t) \quad \forall t \quad (3.11)$$

$$\sum_{c=1}^C \sum_{x=1}^X \sum_{y=1}^Y \delta_{c,t}^{x,y,z} \cdot W(c) \leq W_{Column} \quad \forall z, t \quad (3.12)$$

The stability of the vessel must be maintained through the entire voyage. Constraints (3.8) and (3.9) are the horizontal and cross equilibrium stability showing that the weight difference between the right and the left and between bow side and stern side bays are within acceptable thresholds. Constraints (3.10) indicate that the weight of each tier must be equal to or lighter than the weight of the tier underneath. Constraints (3.11) and (3.12) limit the total weight of the containers on board for the vessel and for each column respectively.

To be more accurate (3.8) and (3.9) can be rewritten based on torque rather than weight as (3.13) and (3.14).

$$\left| \sum_{c=1}^C \sum_{x=1}^X \sum_{y=1}^{\lfloor Y/2 \rfloor} \sum_{z=1}^Z \delta_{c,t}^{x,y,z} \cdot W(c) \cdot (\lfloor Y/2 \rfloor - y) - \sum_{c=1}^C \sum_{x=1}^X \sum_{y=\lfloor Y/2 \rfloor}^Y \sum_{z=1}^Z \delta_{c,t}^{x,y,z} \cdot W(c) \cdot (y - \lfloor Y/2 \rfloor) \right| \leq LRB \quad \forall t \quad (3.13)$$

$$\left| \sum_{c=1}^C \sum_{x=1}^{\lfloor X/2 \rfloor} \sum_{y=1}^Y \sum_{z=1}^Z \delta_{c,t}^{x,y,z} \cdot W(c) \cdot (\lfloor X/2 \rfloor - x) - \sum_{c=1}^C \sum_{x=\lfloor X/2 \rfloor}^X \sum_{y=1}^Y \sum_{z=1}^Z \delta_{c,t}^{x,y,z} \cdot W(c) \cdot (x - \lfloor X/2 \rfloor) \right| \leq BSB \quad \forall t \quad (3.14)$$

The horizontal torque by each container is calculated in relation to the axis of symmetry going through the ship from the bow to the stern, while the cross torque is evaluated in relation to the mid line of the ship. The total left side and right side torque could differ only within the given threshold. The same argument is valid for the total bow side and stern side torques. The minor imbalance caused by the accepted threshold will be corrected using the ballast water.

3.6.6. Shift constraints

The shift constraints are written as follows.

$$U_{c,D(c)} = 1 \quad \forall c \quad (3.15)$$

$$\delta_{c,t}^{x,y,z} + \sum_{z'=z+1}^Z \delta_{i,t}^{x,y,z'} \leq 1 + I_{i,c,t} \quad \forall x, y, z, t \quad \forall c, i \neq c \in [1..C] \quad (3.16)$$

$$I_{i,c,t-1} + I_{c,i,t} \leq 1 \quad \forall t \quad \forall i, c \neq i \in [1..C] \quad (3.17)$$

$$U_{c,t} - U_{i,t} \leq 1 - I_{i,c,t-1} \quad \forall t \quad \forall i, c \neq i \in [1..C] \quad (3.18)$$

$$\delta_{c,t+1}^{x,y,z} - \delta_{c,t}^{x,y,z} \leq U_{c,t+1} \quad \forall x, y, z, c \quad \forall t \in [O(c)..D(c)] \quad (3.19)$$

$$\delta_{c,t}^{x,y,z} - \delta_{c,t+1}^{x,y,z} \leq U_{c,t+1} \quad \forall x, y, z, c \quad \forall t \in [O(c)..D(c)] \quad (3.20)$$

Constraints (3.15) force a container to be unloaded at its destination port. Constraints (3.16) determine whether a container is on top of another one at certain port. Constraints (3.17) enforce that a container cannot be positioned both under and above another container at the same time. Constraints (3.18) ensure a container to be unloaded if the container underneath has to be unloaded at a port. Constraints (3.19) and (3.20) imply that if the position of a container in the vessel changes from one port to another, the container must be rehandled in order to shift the position.

3.6.7. Different size containers constraints

The most common container sizes in business are 20 feet and 40 feet. In this formulation a container of size S TEU (20 feet equivalent unit) is treated as S individual 20' containers. Having $c = \{c_1, c_2, \dots, c_S\}$:

$$\sum_{s=1}^S \delta_{c_1,t}^{X-s+1,y,z} = 0 \quad \forall y, z, t, c \in C / TF \quad (3.21)$$

$$\delta_{c_i,t}^{x,y,z} = \delta_{c_{i+1},t}^{x+1,y,z} \quad \forall x, y, z, t, c \in C / TF, i \in [1..S-1] \quad (3.22)$$

$$U_{c_i,t} = U_{c_{i+1},t} \quad \forall x, y, z, t, c \in C / TF, i \in [1..S-1] \quad (3.23)$$

When assigning a multi-section container to the bay located at the end side of the vessel (3.21) makes sure that there is enough room available for all the sections. Constraints (3.22) force all the cells occupied by a multi-section container to stick together horizontally and (3.23) implies that all cells occupied by such a container must be unloaded should one of the sections be unloaded. This definition expands the flexibility of the formulation to address different stowing policies. Similar equations can be written for containers with irregular heights.

With the presence of multi-section containers, the objective function in equation (3.2) must be changed as follow.

$$\text{Min} \sum_{c=1}^C \sum_{t=1}^N U_{c,t} / T(c) \quad (3.24)$$

In (3.24) $T(c)$ is the TEU size of container c . Having this parameter as the denominator avoids double counting of the container moves for multi-section containers because all the sections are moved together as one piece.

3.6.8. Crane utilization constraints

The crane utilization constraints are as follows.

$$J_{c,k,O(c)} \geq \sum_{x=S(Q_{k,O(c)})}^{E(Q_{k,O(c)})} \sum_{y=1}^Y \sum_{z=1}^Z \delta_{c,O(c)}^{x,y,z}, \forall k \in [1..NQ_{O(c)}], \forall c \quad (3.25)$$

$$\sum_{k=1}^{NQ_{O(c)}} J_{c,k,O(c)} = 1 \quad \forall c \quad (3.26)$$

$$J_{c,k,D(c)} \geq \sum_{x=S(Q_{k,D(c)})}^{E(Q_{k,D(c)})} \sum_{y=1}^Y \sum_{z=1}^Z \delta_{c,D(c)-1}^{x,y,z}, \forall k \in [1..NQ_{D(c)}], \forall c \quad (3.27)$$

$$\sum_{k=1}^{NQ_{D(c)}} J_{c,k,D(c)} = 1 \quad \forall c \quad (3.28)$$

$$J_{i,k,t} + 2 \geq U_{c,t} + J_{c,k,t} + I_{i,c,t}, \forall c, i \neq c, \forall t \notin \{O(i), D(i)\}, \forall k \in [1..NQ_t] \quad (3.29)$$

$$\sum_{k=1}^{NQ_t} J_{c,k,t} = U_{c,t} \quad \forall c, \forall t \notin \{O(c), D(c)\} \quad (3.30)$$

$$\left| \frac{\sum_{c=1}^C \sum_{k=1}^{NQ_t} J_{c,k,t}}{NQ_t} - \sum_{c=1}^C J_{c,q,t} \right| \leq \frac{\sum_{c=1}^C \sum_{k=1}^{NQ_t} J_{c,k,t}}{CWL}, \forall t, \forall q \in [1..NQ_t] \quad (3.31)$$

Given the number of quay cranes at each port and the range of bays on which the cranes will operate, constraints (3.25) through (3.28) find the cranes that perform the load/unload for each container at its origin and destination port, and ensure that only one crane will perform the handling. Should a container be shifted at any port, constraints (3.29) and (3.30) find the crane that does the shifting at that port.

Constraints (3.31) balance the load among available cranes at each port. It is required that the difference between the workload of any crane and the average workload over all cranes at a port does not exceed a given threshold.

3.6.9. Operational constraints

The formulation is able to embrace other technical and operational considerations.

For example in case of having containers of different sizes the operator may forbid putting large size containers on top of smaller ones (e.g. 40ft containers are not allowed on top of 20ft containers). Equation (3.32) formulates this rule.

$$\delta_{c_i,t}^{x,y,z+1} \leq 1 - \delta_{h,t}^{x,y,z} \quad \begin{array}{l} \forall x,y,z \in [1..Z-1], t \in [O(h)..D(h)-1] \\ \forall h \in TF, c \in C/TF, i \in [1..S-1] \end{array} \quad (3.32)$$

In a reverse situation the following constrains can be used.

$$\delta_{h,t}^{x,y,z+1} \leq 1 - \delta_{c_i,t}^{x,y,z} \quad \begin{array}{l} \forall x,y,z \in [1..Z-1], t \in [O(h)..D(h)-1] \\ \forall h \in TF, c \in C/TF, i \in [1..S-1] \end{array} \quad (3.33)$$

It is important to note that based on the operational rules only one set of constraints (3.32), (3.33) or neither of them should be in effect.

As an example to specific design constraints consider a vessel that allows 40 ft containers only in specific bays while no such restriction is imposed on 20 ft containers. If a vessel can accommodate 40 ft containers only in bays with even indices the following constraint may be used.

$$\delta_{c_i,t}^{x,y,z} = 0 \quad \begin{array}{l} \forall \text{ odd } x,y,z,t \in [O(c_i)..D(c_i)] \\ \forall c \in C/TF, i \in [1..S-1] \end{array} \quad (3.34)$$

This basically forces all the sections of a multi-section container to avoid odd bays.

The regulations regarding special type containers can be formulated in a similar fashion. For example perishable commodities are loaded into refrigerated containers. These containers should be plugged into electricity outlets which are available only in some sections of the vessel. Equation (3.35) implies this regulation.

$$\delta_{c,t}^{x,y,z} = 0 \quad \begin{array}{l} \forall x \notin \{electrified\ bays\}, y, z \\ \forall t \in [O(c_i)..D(c_i)] \\ \forall c \in R \end{array} \quad (3.35)$$

When having hazmat containers mixed with other cargo, appropriate rules must be observed. For example if a special safety standard forbids storing a hazmat container adjacent to a refrigerated container the following constraints should be added to the model.

$$\delta_{c,t}^{x,y,z} + \delta_{h,t}^{x+1,y,z} \leq 1 \quad \begin{array}{l} \forall x \in [1..X-1], y, z, t \\ \forall (c, h) \in R \times H \end{array} \quad (3.36)$$

$$\delta_{c,t}^{x,y,z} + \delta_{h,t}^{x,y+1,z} \leq 1 \quad \begin{array}{l} \forall x, y \in [1..Y-1], z, t \\ \forall (c, h) \in R \times H \end{array} \quad (3.37)$$

$$\delta_{c,t}^{x,y,z} + \delta_{h,t}^{x,y,z+1} \leq 1 \quad \begin{array}{l} \forall x, y, z \in [1..Z-1], t \\ \forall (c, h) \in R \times H \end{array} \quad (3.38)$$

Constraints (3.36) and (3.37) avoid horizontal adjacency and (3.38) forbid vertical adjacency of each two hazmat and refrigerated containers.

3.7. Summary and conclusion

A binary integer programming model is proposed to solve the containership loading problem which is the problem of assigning containers to the cells of a containership that calls multiple ports. The objective function minimizes the total turnaround time

of the vessel at all ports which is different from the objective function of stowage planning. The containers have different types, sizes and weights. Stability considerations are addressed in the form of cross and horizontal equilibrium, tier equilibrium and single column constraints. These are experimental rules of stability; however more accurate forms of stability such as meta-centric height calculations can be modeled using the given notation as long as they are linear or can be approximated by linear functions. Operational rules regarding the placement of different size containers as well as special purpose containers (e.g. hazmat) are modeled as constraints. This optimization model tries to maximize the utilization of the quay cranes while minimizing the number of shifts in order to minimize the overall time that the vessel spends at all visiting ports. The model is flexible and can easily embrace new operational rules and constraints.

Chapter 4: Formulation validation

4.1. Generating sample problems

To validate the mathematical model in chapter 3, sample problems have been generated and solved using commercial solver CPLEX 12.0. Each problem consists of following elements:

1. Number of ports to be visited
2. Number of cranes at each port plus the operating range of each crane
3. Dimensions of the containership ($X \times Y \times Z$)
4. List of containers to be transported. Each container has an identification number, origin port, destination port, size, type and weight

The list of the containers is randomly generated for each example such that the basic feasibility requirement is met. To define basic feasibility a transportation matrix T is built based on the list of the containers:

$$T_{ij} : \text{Number of containers going from port } i \text{ to port } j$$
$$T_{ij} = 0, \forall j \geq i, \quad 1 \leq i, j \leq N$$

If L_p and U_p are the lists of containers to be loaded and unloaded at port p respectively, then:

$$|L_p| = \sum_{j=p+1}^N T_{pj} \quad , \quad |U_p| = \sum_{i=1}^{p-1} T_{ip}$$

Since the unloading is done before the loading starts, the problem is feasible only if at each port there are at least $|L_p|$ cells available in the vessel after all $|U_p|$ containers are removed. A program source code is developed to generate such problems.

4.2. Model verification

To verify the accuracy of the mathematical model, formulations are generated for several sample problems and solved using CPLEX solver. A computer program is developed for analyzing the output by calculating some performance measures and visualizing the results.

4.2.1. Sample problem from Avriel and Penn (1993)

As it was mentioned in the literature review Avriel and Penn (1993) developed an integer programming model to minimize number of shifts in stowage planning with single size containers. Stability constraints are not considered in this model. A sample problem is reported in their paper and solved to the optimality. To make sure that the model in chapter 3 is able to produce optimal solution for the same problem, a formulation is generated by relaxing crane utilization and stability constraints. The containership in this example calls five ports. The ship has one bay consisting of two rows and five columns. Table 4.1 shows the transportation matrix.

Table 4.1: Transportation matrix for Avriel and Penn (1993)

From/To	2	3	4	5
1	4	4	2	0
2	0	2	0	1
3	0	0	0	5
4	0	0	0	1

Although the total number of containers is 19, the total number of unload operations is reported to be 20. This means that at least one shift is necessary. The output from the new model confirms this. Figure 4.1 is a graphical representation of port by port view of the solution. Each rectangle represents a container painted in two colors. The narrow color bar shows the origin port of the container and the wide bar is color coded to show the port of destination. The container assignment in this figure shows the stowage planning upon leaving the port. Some containers may be marked with a black or a red dot on their top right corner. The black dot means that the container will be unloaded at the next port while the red dot means that the container will be shifted at the next port. The black frame surrounding the container means that the container has been shifted in that port. In this example container 13 must be shifted at port 4.

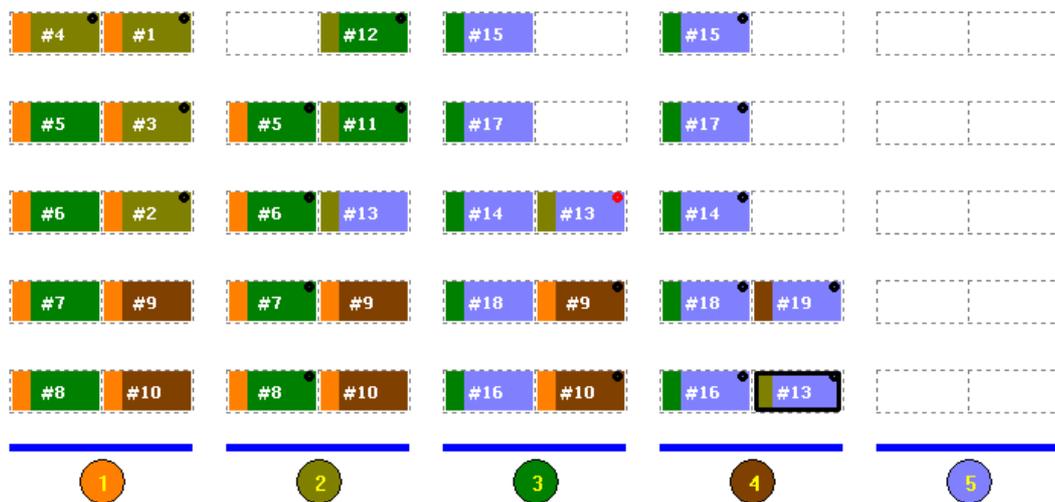


Figure 4.1: Solution to the original sample problem

4.2.2. Sample problem from Avriel and Penn (1993) with stability constraints

Assume that all containers in the previous example are of the same weight and each weigh 1 unit. It can be observed that the previous solution is not conforming with stability constraints since at ports 2, 3 and 4 total weight on the right side is not equal to the total weight on the left. If we allow 1 unit tolerance in the weight difference only ports 3 and 4 will violate the stability. We solve the problem again considering stability constraints with 1 unit threshold. The optimal solution can be seen in Figure 4.2.



Figure 4.2: Optimal solution with stability constraints

Number of shifts has increased to 2 in this case. This means that observing stability constraints may come at cost of extra shifts. Had we set the stability weight threshold to zero the problem would have been infeasible. This is because at ports 2 and 4 no arrangement of the containers will result in such balance. In the real operations imbalances are taken care of by using ballast water.

Consider the case that in the above example all containers with even numbers weigh twice as much as the ones with odd numbers. If we formulate and solve the problem based on these new assumptions and set the stability tolerance to 1 weight unit, the number of shifts in the optimal solution will be 3.

4.2.3. Effect of stack size on computational time

In this example, a containership will visit five ports. The transportation matrix is shown in Table 4.2, with a total of 38 containers of the same size and weight.

Table 4.2: Transportation matrix for the sample problem

From/To	2	3	4	5
1	8	8	4	0
2		4	0	2
3			0	5
4				2

Mathematical models are generated for five hypothetical containerships with approximately the same capacity (20-21 TEU) but different structures. To investigate the effect of stack size on computational time, the objective function minimizes the number of shifts at all ports while the crane and stability constraints are relaxed.

Optimal solutions are obtained for all hypothetical containerships using the CPLEX solver. The ships' structures and the corresponding computational times are summarized in Table 4.3.

Table 4.3: Ship configuration and running time for optimal solution

Ship	Bay	Row	Tier	Capacity (TEU)	Number of binary variables	Total number of constraints	Number of shift constraints	Running time (Second)
1	5	2	2	20	11020	86174	85674	521
2	4	1	5	20	11020	128384	127854	2011
3	3	1	7	21	11210	142595	142050	93465
4	2	1	10	20	11020	142454	141914	386142
5	1	1	20	20	11020	149489	148944	NA

The number of constraints in the formulation rises as the size of the stack increases.

Most of the constraints relate to shift operations. It can be observed that for this example the running time grows dramatically with the increase in the number of tiers.

For ship 5 the solver could not reach optimality in one week.

To investigate the pattern of the running time growth, four additional transportation matrices were generated and the solution was collected for ship structures 1 through 4 (optimal solution could not be obtained for containership 5). For each ship, average running time was calculated using the five recorded running times. The results are shown in Figure 4.3. The graph suggests that the running time rises exponentially as the height of the stack increases. This was expected from the literature since the problem is NP-Complete.

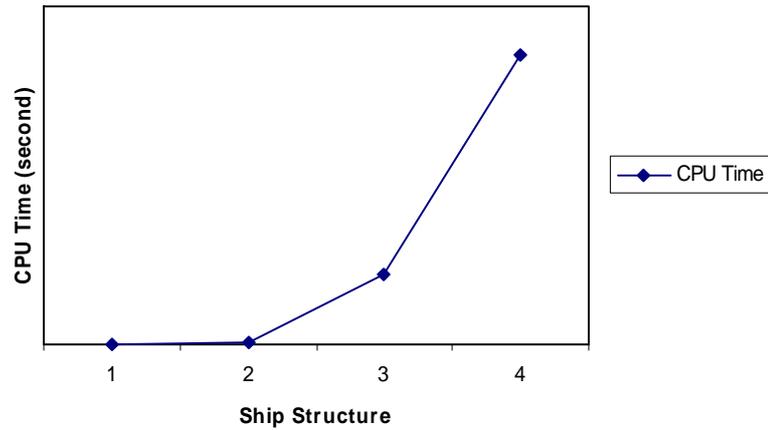


Figure 4.3: Average running time vs. ship structure

4.2.4. Sample problem for different size containers

This example aims to verify the situation of having a mix of 20' and 40' containers and the related operational policies. A containership with 5 bays, 1 row and 3 tiers is visiting three ports and is transporting 14 containers, 3 of which are 40' and the rest are 20'. The stability constraints are in place with threshold set as 1 weight unit. All containers are of the same weight. If 40' containers are not allowed on top of 20' units, the optimal solution will look like what is shown in Figure 4.4.

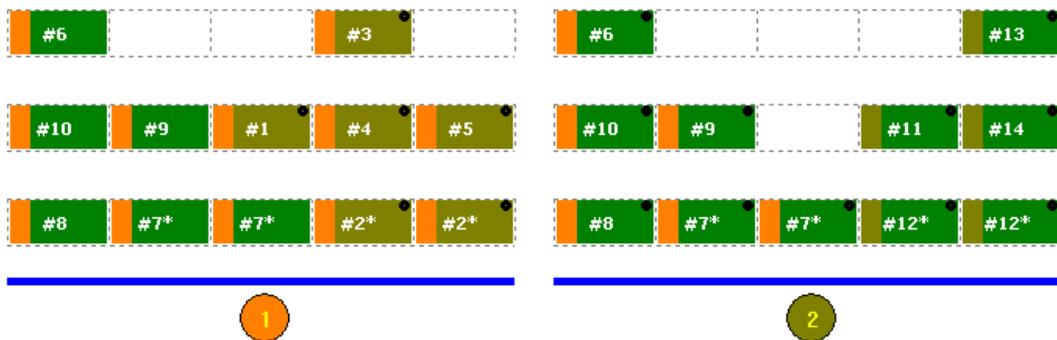


Figure 4.4: Results for no 40' container on top of 20' policy

Containers 2, 7 and 12 are 40' and are marked with asterisk. Since this figure shows the stowage planning upon leaving each port, there is no need to display the results for port 3 because the ship is empty then. No shift is necessary in this case. However if the regulation is changed such that 20' containers are not allowed on top of 40' containers, shifting of container 7 at port 2 will be inevitable. Figure 4.5 shows the optimal solution based on this regulation.

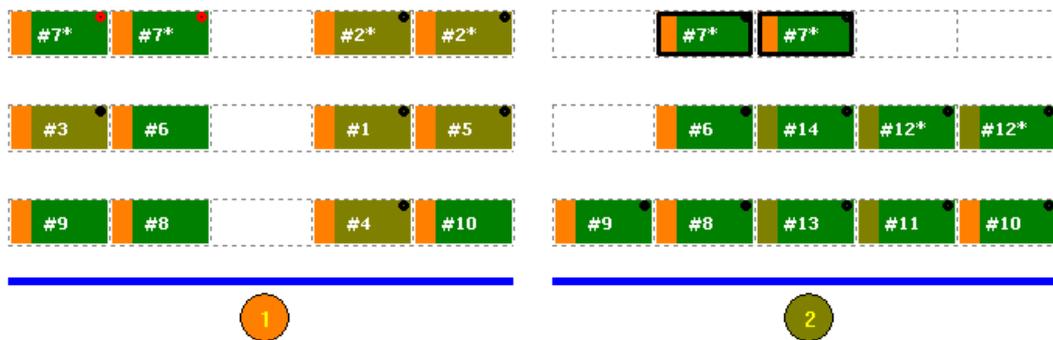


Figure 4.5: Results for no 20' container on top of 40' policy

4.3. Crane workload balancing

As it has been mentioned in the problem statement, the objective function of the stowage planning must be to minimize the total ship turnaround time at all ports. Part of this may be achieved by minimizing the shifts; however that is not the only factor. Knowing the assignment of quay cranes at each port, efficient use of this equipment must be considered in the stowage planning. The next two examples try to highlight the difference between using minimizing total time at ports as objective function and

the traditional stowage planning objective function which is the minimization of the shifts.

4.3.1. Crane workload balancing with single size containers

The containership in this example has 4 bays, 1 row and 5 tiers. There are five ports to be visited and 38 containers of the size 20' to be transported. The stability tolerance is set to a maximum of 1 weight unit. This example explores the effect of crane split on the solution. It is assumed that two cranes are available at each port, and each crane can handle one container per unit time. Handling includes loading a container at its origin, unloading at destination or shifting the position at an intermediate port. Four scenarios are compared in this example. In the first two scenarios all containers are assumed to have the same weight, while in scenarios 3 and 4, the containers departing from port 2 are four times heavier than the others. Scenarios 2 and 4 are the cases with the optimization of total turnaround time as the objective function while scenarios 1 and 3 are the classic stowage planning problems.

Figure 4.6 shows the stowage plan for the second scenario.

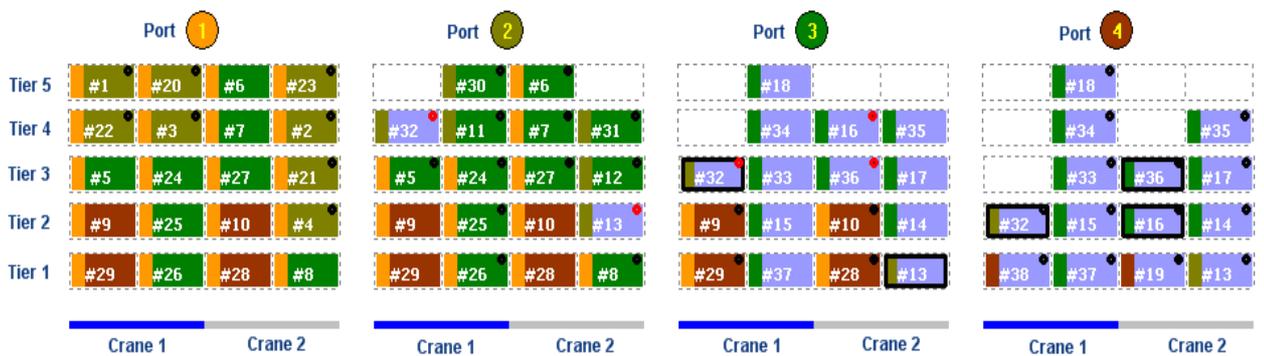


Figure 4.6: Stowage planning results for scenario 2

The operational range of each quay crane is shown in Figure 4.6. The last port is not displayed since the ship is empty after the operations are completed at that port. Total number of container handlings, total time spent at all ports, utilization of each crane and average crane utilization for each scenario are presented in Table 4.4. Utilization of each crane at each port is calculated by dividing the crane busy time over the total time that the vessel spends at the port. For scenarios 1 and 3 total time at all ports is a direct output of the model and the total number of handlings is calculated using the final value of the decision variables. The reverse happens in scenarios 2 and 4 in which the total number of handlings is obtained by the objective function and total time at all ports is calculated using the output variables.

Table 4.4: Summary of the results for four scenarios

	Port 1		Port 2		Port 3		Port 4		Port 5		Total number of container handlings	Total time at all ports	Average crane utilization %
	Crane utilization %		Crane utilization %		Crane utilization %		Crane utilization %		Crane utilization %				
	1	2	1	2	1	2	1	2	1	2			
Scenario 1	100	100	100	56	73	100	20	100	100	100	42	46	84.9
Scenario 2	100	100	100	100	100	85	100	80	100	100	43	40	96.5
Scenario 3	100	100	100	100	100	77	100	60	100	100	41	42	93.7
Scenario 4	100	100	88	100	92	100	100	100	100	100	42	41	98

The number of handlings in scenario 2 is slightly greater than scenario 1, however the average crane utilization is 14% higher than that of scenario 1. By distributing workload between cranes properly, 13% improvement in total berthing time is achieved in this example. Similar comparison between scenarios 3 and 4 shows 2.5% improvement in berthing time. Solutions details including the input and output for scenario 3 are provided in Appendix B.

4.3.2. Crane workload balancing with different size containers

This example illustrates a case with mixed size containers. A containership with six bays, two rows and three tiers will visit four ports. There are 44 containers to be transported of which 16 are 40' and 28 are 20' containers. It is assumed that there are two cranes available at ports 1 and 4, and three cranes at ports 2 and 3.

Similar to previous example two scenarios are tested. The summary of the results is shown in Table 4.5. While total number of handlings is equal in both cases, optimizing the crane utilization has improved the total berthing time by 7% in this example.

Table 4.5: Summary of the results for two scenarios

	Port 1		Port 2			Port 3			Port 4		Total number of container handlings	Total time at all ports	Average crane utilization %
	Crane utilization %		Crane utilization %			Crane utilization %			Crane utilization %				
	1	2	1	2	3	1	2	3	1	2			
Scenario 1	100	93	40	40	100	80	80	100	100	100	61	57	83.3
Scenario 2	93	100	100	86	71	100	93	86	100	100	61	53	92.9

4.3. Summary

The examples in this chapter demonstrate the potential for saving in the total ship turnaround time if an appropriate objective function is used in stowage planning optimization. While minimizing shifts helps to reduce the turnaround time, it should not be used as the objective function. The results show that concurrent maximization of crane utilization and minimization of shifts improves the overall turnaround time at all ports. The model balances the tradeoff between the crane utilization and extra container movements.

The results also show that the model in its current form is capable of handling required operational and technical constraints. Unfortunately since the problem is NP-Complete even the small size problems can be very computationally expensive. Running time is highly correlated with the height of the stack and grows exponentially as the stack size increases. No analytical method exists for solving multi-column stacking problem with stability constraints according to the literature. Thus heuristics are needed to deal with the real size containership loading problem.

Chapter 5: An algorithm for containership load planning optimization

5.1. Introduction to optimization

According to the Merriam-Webster dictionary the optimization is defined as “an act, process, or methodology of making something (such as a design, system, or decision) as fully perfect, functional, or effective as possible”. Optimization techniques have been used in a broad range of engineering applications in order to find the best possible solution within the limits and constraints of a problem. Differentiation and gradient based optimization, hill climbing and linear programming are among the well known traditional mathematical approaches for solving engineering problems. However in many real optimization problems the corresponding mathematical function is not well-behaved, the solution space is discrete or the problem is multiple criteria. In such cases these conventional methods will either fail to cope with the complexity of the problem or simply need extensive computational resources. Solution techniques such as evolutionary algorithms will be helpful in this kind of situation.

5.1.1. Evolutionary algorithms

Conventional optimization techniques are often incapable of dealing with non-linear multi-criteria optimization problems. In such cases a random search in the solution space in hope of finding the optimal feasible point is an alternative method. However performing a random search in an unsystematic manner can be extremely inefficient. Many efforts have been made to add intelligence to the random search procedures in

the past decades. Evolutionary Algorithms as a class of intelligent search methods are results of such efforts.

Evolutionary Algorithms imitate the mechanisms inspired by biological evolution namely reproduction, mutation, recombination, natural selection and survival of the fittest. Individuals of the population are represented by candidate solutions to the optimization problem, and the fitness function determines the environment within which the solutions live. Evolution of the population is then simulated by applying the above operators iteratively. Genetic Algorithm is the most popular variant in this class.

Evolutionary Algorithms are not the only intelligent search methods inspired by ideas from the nature. Simulated Annealing, Tabu Search, Ant Colony and Harmony Search are examples of meta-heuristics which work based on the behavior of natural systems.

Simulated Annealing is based on the process of heating and controlled cooling of a material. It basically traverses the search space by replacing the current solution with a random nearby solution. The neighbor will be accepted if it is superior. For an inferior neighbor the acceptance probability depends on the difference between the corresponding function value and a global temperature parameter. Altering the temperature parameter during the process modifies the nature of the search.

Tabu Search is similar to the Simulated Annealing with the difference of generating more than one neighboring solution at each step. It moves to a better mutated solution by picking the neighbor with best fitness of those generated. Cycles are prevented by maintaining a tabu list of solutions which is being updated throughout the process.

Moving to the solutions that contains elements of the tabu list is prohibited. The idea came from observation of human behavior which appears to operate with a random element leading to inconsistent behavior given similar circumstances (Glover and Laguna 1997).

Ant Colony Algorithm is a probabilistic technique for optimization that hires a large number of artificial ants to incrementally build the final solution. It works by mimicking the movements of the ants in the real world. While searching for food or returning to their colony, ants lay down pheromone trails on their path which will be used by later ants to guide their search. As the time goes by, however, the pheromone trail starts to evaporate, lowering the attractiveness of the trail. This technique usually outperforms other meta-heuristics in routing problems such as traveling salesman problem when the graph changes dynamically (Dorigo Marco, Thomas Stützle 2004).

Harmony Search is another meta-heuristic which simulates the improvisation process by a musical band. While improvising each musician plays a note until finding the best harmony all together. Based on this idea decision variables in an optimization problem will accept different values and interact with each other to find the best solution vector all together.

5.1.2. Genetic Algorithms

Genetic Algorithm (GA) is an adaptive heuristic search method based on the evolutionary idea of natural selection which represents processes in natural system for evolution, specifically the principle of survival of the fittest by Charles Darwin. As such it performs an intelligent directed random search within a defined search space to optimize a problem. Genetic Algorithms use a vector of numbers to represent

decision variables. They pursue an iterative process in which several solution points are being explored simultaneously at each step. The only information required for search is a fitness assessment. An illustration of the general process is shown in Figure 5.1.

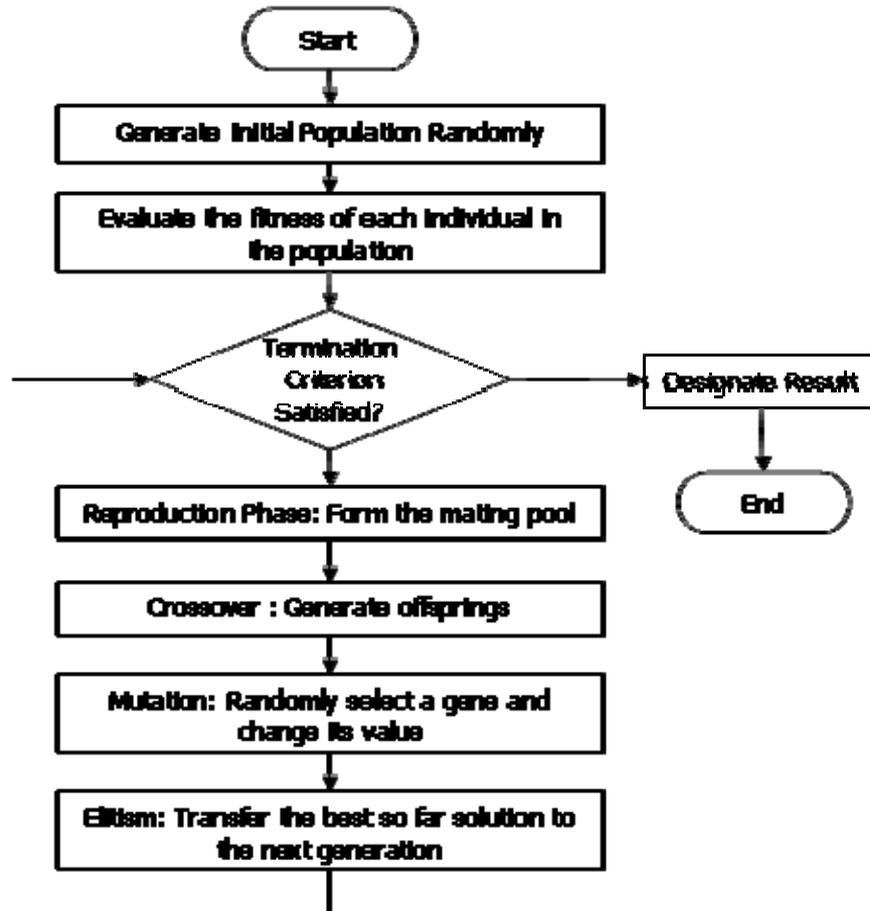


Figure 5.1: Flowchart of Genetic Algorithm

In summary genetic algorithms have been widely used to solve optimization problems where the analytical and other evolutionary methods fail. Some advantages and features of the genetic algorithms are as follow:

- They run simultaneous search over multiple regions of the search space rather than a unique point since a population is investigated at each step. This makes genetic algorithm suitable for parallel computing.
- They work with both continuous and discrete parameters as well as combination of them.
- They can handle a large number of parameters.
- They do not need a profound knowledge about the mathematical structure of the solution space in order to solve the problem.
- They can optimize multi-objective optimization problems to provide a list of solutions instead of a single one.
- Genetic algorithms are stochastic, not deterministic.
- They can work with incomplete information and noisy data.
- Genetic algorithms are flexible in cooperating with other techniques and can be part of hybrid methods.
- They have been successfully applied to a large number of complex problems in different fields of engineering.
- Genetic algorithms perform a very large number of objective function evaluations. Hence if such evaluations are computationally expensive, then the convergence might take a long time.

The following definitions are often used in genetic algorithm literature:

- **Chromosome:** The data structure that holds a potential solution.

- **Gene:** Fraction of a chromosome that represents a parameter in a potential solution.
- **Individual:** Collection of a chromosome and its fitness value.
- **Alleles:** The set of values that a gene can accept.
- **Locus:** The position of the gene on the chromosome.
- **Genotype:** In Biology a genotype is the total genetic information of an organism or phenotype and it can consist of one or more chromosomes. In most genetic algorithm applications however, a unique chromosome contains the total genetic information of the organism (solution), so this unique chromosome also represents the genotype of the organism. Because of that the terms genotype and chromosome are often used interchangeably in genetic algorithms context.
- **Phenotype:** The solution or organism built based on a genotype. For example if a chromosome represents the location of the containers in a containership stowage plan, the encoded locations will represent the genotype of the stowage plan while the actual vessel loaded based on that stowage plan makes the respective phenotype.

The complete terminology of the genetic algorithms can be found in Rawlins (1991).

5.2. Genetic Algorithm for containership load planning

As it was mentioned in the literature review in Chapter 2, containership stowage planning with uniform size containers is NP-Complete. Introducing multiple-size containers and crane assignment to the stowage planning adds to the complexity of the problem and because of that the mathematical model described in chapter 3 is

incapable of solving the real size problems. To overcome the large number of variables and constraints, the model can be reformulated to assign groups of containers to the bays of the vessel rather than individual ones. Grouping can be done based on a given property such as size, type or destinations and this will reduce the problem size significantly and such model can be solved using branch and bound methods. The assignment of individual containers into the cells in each bay is done in another step. However the drawback of the simplification by decomposition is the inflexibility in dealing with constraints specially while trying to optimize crane utilization. This method accompanied by a tabu search was developed by Wilson and Roach (1999), (2000) to solve stowage planning. One of the most challenging issues in combinatorial optimization is to deal with the combinatorial explosion effectively, such that the algorithm can generate solutions to the real world size problems in a timely manner. Genetic Algorithms have been successfully applied to the containership stowage planning problem before by Todd and Sen (1997) and Debrowsky et al. (2002). They solved instances of the containership where all the containers are of the same size. The former researchers used transverse as well as vertical center of gravity to address the stability while the latter group only used the horizontal equilibrium.

5.2.1. Genetic encoding

In a genetic algorithm each potential solution is represented by a string with a fixed bit-length known as chromosome that encodes the decision variables. This representation is a key part of the genetic algorithm because the genetic operators directly manipulate the chromosomes as representatives of the solutions. “The

complexity of a problem largely depends on the interactions between variables of a solution. A stochastic search process like evolution will perform well on a complex problem only when the search distribution is adapted to these interactions, i.e., when the search distribution obeys these dependencies between variables (Toussaint 2005)". To have a successful and efficient use of the genetic algorithm, it is crucial to find a proper representation of the problem, also known as genetic encoding and develop appropriate operators that conform to the characteristics of the problem. In other words the efficiency of the natural evolution process to perform an intelligent or learned exhaustive search for optimal or near optimal solution within a complex structure in which the fitness is measured by the interaction among variables, highly depends on a genetic representation that is both expressive and evolvable. In most genetic algorithms the individuals are represented by fixed-length binary strings that consist of genes with values of 0 or 1. The genetic encoding does not have to be binary, other types of encoding such as real-number encoding, integer or literal permutation encoding, and general data structure encoding can be used for different optimization problems. According to Collins and Eaton (1997) there does not exist a single encoding strategy that performs well on all optimization problems.

Infeasibility and Illegality are two common issues while developing the genetic encoding. There are two categories of spaces in each genetic algorithm: genotype space and phenotype space. Genetic operators work on genotype space where they manipulate different parameters of the problem. Evolution and selection on the other hand are done in phenotype space where the chromosomes are being evaluated. The mapping from genotype to phenotype space is a major contributing factor in the

performance of the genetic algorithm. Infeasibility happens when a solution decoded from a chromosome falls outside of the feasible region of the problem. Illegality refers to the case that a chromosome does not correspond to any solution of given problem at all. Infeasibility originates from violation of constraints and by penalizing the unsatisfied constraints the algorithm will direct the search toward the feasible region. Illegality however is a result of genetic operators where a generated offspring does not represent a valid solution to the problem. A good genetic encoding and proper design of genetic operators decreases the illegality. “Because an illegal chromosome cannot be decoded to a solution, the penalty techniques are inapplicable to this situation. Repair techniques are usually adopted to convert an illegal chromosome to a legal one (Cheng and Gen 2000)”. Figure 5.2 shows the phenotype and genotype space for a typical problem.

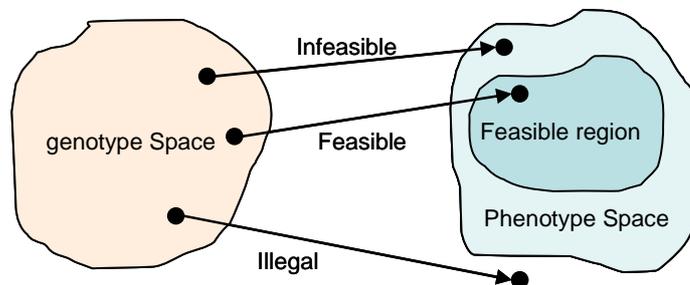


Figure 5.2: Infeasibility and Illegality

A new genetic encoding for containership loading problem is designed in this dissertation. Before going through the details of the new encoding, existing genetic representations including complete and compact encoding for containership stowage

planning problem are reviewed. The terms complete and compact encoding in stowage planning was first introduced by Debrovsky et al.(2002).

Complete encoding by Todd and Sen (1997)

In a complete encoding the whole layout of the vessel at each port is encoded into the chromosomes. In other words each gene represents a cell and alleles are the set of all the container numbers to be transported. So for an X -TEU containership visiting N ports the genotype consists of a string of integers with a length equal to $N \times X$. This encoding is trivial and easy to implement but it has some shortcomings. Evaluating the fitness of the chromosomes requires the processing of the complete layout for four criteria: unloading, proximity, transverse center of gravity and vertical center of gravity. This is very time consuming especially when the population size goes up. But the main drawback is the illegality of the resulting offspring by the crossover operator. The crossover operator is designed to restrict an individual to mate only with the individuals who are located in its close surroundings in the criteria space. Omission and duplication of containers in the resulting strings can occur as a result of such restriction. To fix the inconsistency in the results, a repair procedure is used which manipulates the offsprings after the crossover is done. This repair routine is not only time consuming, but also will partially destroy some of the inherited information that are accumulated during previous iterations.

Compact encoding by Debrovsky et. al. (2002)

To overcome the disadvantages of the complete encoding, the compact encoding introduces a new representation which stores only the changes in the layout that result from the loading and unloading along the route instead of the complete layout. It reduces the processing time for evaluating the chromosomes, preserves the consistency of the layout, insures the legitimacy of the crossover operator and allows convergence to good solutions within a reasonable time by decreasing the search space and storage resource consumption. For a containership visiting N ports, the genotype is divided into N sections. Each section consists of four lists: (1) list of columns for loading the containers originated at the corresponding port, (2) list of columns for loading the containers that were unloaded due to necessary shift, (3) list of columns for loading the containers that were unloaded due to voluntary shift, (4) list of columns from which the containers should be unloaded because of voluntary shifts. To simulate the ship unloading and loading operations two auxiliary vectors are hired for each port. One of these vectors contains the destinations of the loading containers which can initially be acquired from the transportation matrix. The other vector which is two dimensional is a column waiting list which keeps the column information for the containers to be loaded at the port and is obtained from decoding the corresponding solution chromosome. The total number of shifts will be known only after running the solution decoding procedure.

Although this encoding has reported to be more efficient than the complete encoding, it does not account for multiple-size containers. Both complete and compact encodings presented above must undergo significant changes to be able to handle mix of 20 and 40 ft containers. The reported real size problem solved using this encoding

had single size and uniform weight containers. Handling the stability was demonstrated by keeping the horizontal tilt within a threshold. However to enforce the vertical stability constraints which are a major source of mandatory shifts would be challenging for this method because of the genotype structure.

Assignment policy based encoding

As it was mentioned before the containers differ in weight, size and type. Export containers arrive to the container yard before the containership arrives, although some of them might arrive while the loading of the vessel has already started. Due to the shortage of space the terminal managers usually stack the containers in the terminal. It is a common practice to group the containers based on properties such as weigh, size or destination and then allocate the groups to the yard stacks .If the configuration of the stacks conforms to the stowage plan of the containership the unnecessary reshufflings of the containers at the yard can be minimized.

For loading the containers into the vessel on the other hand different strategies exist. The quay crane drivers may load the containers into the cells at one row and then move to the adjacent row, or they may fill up one column and then move to the next column in the row. Figure 5.3 illustrates these strategies.

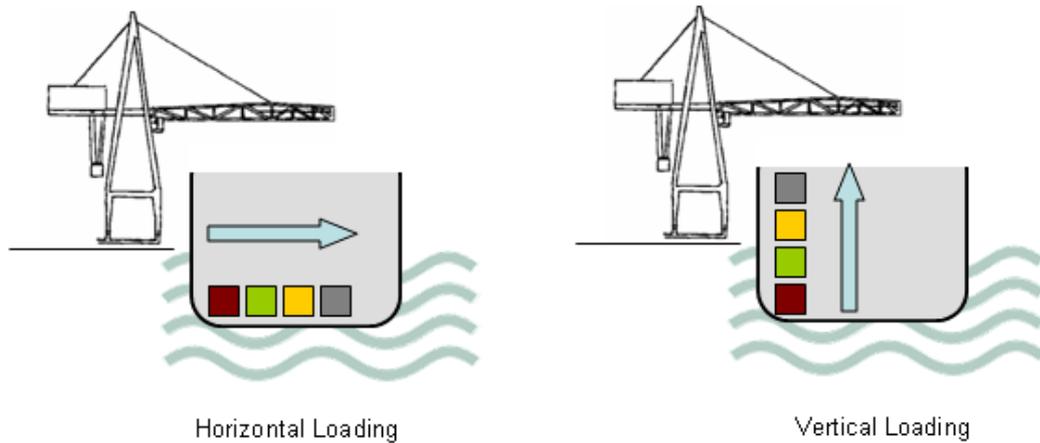


Figure 5.3: Horizontal and vertical loading strategies

The key idea for assignment policy based genetic representation comes from the combination of above grouping and loading strategies in the container terminal. In fact instead of searching for the favorite container to cell assignment pattern the search can be done to find the best combination of sorting, grouping and loading strategy at each port. Each chromosome string consists of several sections each of which corresponding to a visiting port. Each section then is divided into two subsections to represent sorting method and assignment strategy respectively. These subsections are represented by binary strings.

Four basic properties of the containers are size, weight, destination and type. One can sort a list of containers based on each of these criteria or any combination of them. For example the list can be sorted by destination only or by destination first, then weight and then size. Furthermore each criterion can be applied ascending or descending. Total number of sorting possibilities can be calculated as follow:

$$\text{Total sorting combinations: } \sum_{r=1}^4 P_r^4 \times 2^r = 632$$

There might be cases that none of the above sorting methods will suit the problem. To address this situation another sort based on random key is added to the pool of sorting options, so that containers can be retrieved and allocated in a predetermined random order.

Containers in the sorted list then can be retrieved and assigned to the available cells in the vessel. Initially at the first port all the cells are available. After berthing at each forthcoming port, first the containers that have reached their destinations will be unloaded. Because the containers are only accessible from the top of the stack, all the containers that block the access to container that should be unloaded must be removed first. These are the containers that have not reached their final destination yet, but must be shifted in order to allow access to the container below them. These containers must be loaded back into the vessel, along with the containers that originate from the current port. They may be given a location that is different from their former location in the ship. The recently emptied cells will be included in the set of available cells in the vessel. The allocation of export containers can be done horizontally or vertically as illustrated in Figure 5.3. In vertical policy the cells of each column are assigned from bottom to the top due to the fact that excluding the most bottom cell, a container can be stored in a cell only if the cell under it is not empty. For horizontal policy cells can be picked row-wise or bay-wise. In other words the cells can be picked horizontally either from bow side to the stern side and then from shore side to the water side or vice versa. In addition to that there are plenty of other orders in which the bays and rows can be picked. For example in selecting

the bays one strategy can be picking one bay after another from bow to stern while an alternative strategy is to pick every other bay from the opposite direction.

Combination of vertical and horizontal assignment strategy and the orders in which cells can be picked in each strategy creates a pool of possibilities to choose from.

Stowage plan at each port can be constructed by allocating the sorted list of containers to the containership cells according to the encoded sorting method and assignment strategy for that port. Figure 5.4 is a visual representation of this concept.

The generated stowage plan then can be analyzed to evaluate the fitness of the solution.

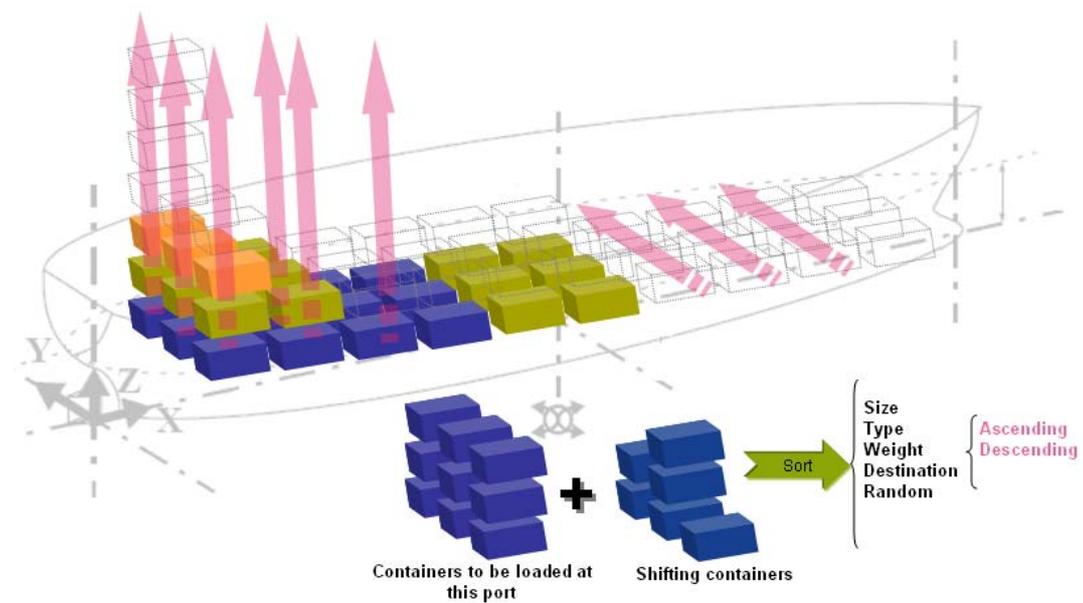


Figure 5.4: Different sorting and assignment policies for loading a containership

Usually a major part of the stowage pattern remains intact between two consecutive ports. Its implication for the new encoding is that the stowage plan for the next port will be built based on the remaining stowage pattern at the current port after

unloading is complete. However based on the structure of the program and the characteristics of the containers no feasible or competitive solution might be generated if the existing stowage plan is fixed. To address that issue and to make sure that the genetic algorithm can exploit the solution space effectively an extra bit is added to the genotype which determines whether the existing stowage plan at the current port should be relaxed. In other words if the aforementioned gene has the value of 1, all the containers already loaded in the vessel will be subject to cell allocation along with the export and shift containers. Although a large number of these containers might end up staying in the same positions, it is important to keep the options open for the algorithm to look for optimal allocation. Figure 5.5 shows an illustration of assignment based genetic encoding.

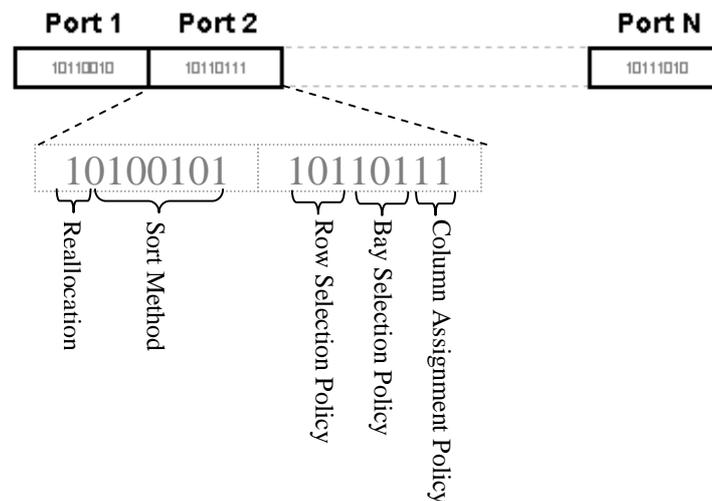


Figure 5.5: Illustration of assignment policy based genetic encoding

It can be observed that the length of the solution string is a function of the number of ports and is independent of the number of containers and the layout of the vessel. The

sort and assignment policy information for each port can be stored in 4 bytes, so the length of each chromosome is $4*N$ byte which is very compact and memory efficient.

5.2.2. Evaluation of solution

The selection mechanism of genetic algorithm looks at the fitness value of each chromosome to decide its fate. The better the value of the fitness is, the higher is the chance of advancing to the next generation. The objective function of the containership loading problem with quay crane assignment consideration is to minimize total turnaround time at all ports. This is an appropriate objective function if the value of time at all ports is equal. Otherwise by multiplying the turnaround time at each port by its cost parameter we can build an economical objective function to minimize total cost of the operations at all ports. However the objective function value is one of the components of the fitness function. With the presence of stability and operational constraints, more components must be added to the fitness evaluation function to penalize the violation of the corresponding constraints. Imposing penalty to the solutions that do not satisfy the constraints helps the genetic algorithm and its operators to move toward the feasible area of the solution space. Evaluation of a chromosome needs four steps: first is to decode the solution, second is to transform the decoded genotype to the corresponding phenotype, third is the analysis of the resulting phenotype and the final step is to calculate the final fitness value by summation of normalized objective function and the penalties.

Decoding a solution

Since all the information is in binary string format, bitwise operators are hired for decoding the solution. For every section of the chromosome, the locus (position of genes in the genotype) is known and fixed. By using binary shift operator, the desired section can be repositioned to the rightmost part of the chromosome string. In a unary right shift operation, all the bits in the binary string are shifted to their immediate right position, the first bit will be lost and a 0 will fill the empty position of the leftmost bit. A binary mask is needed which has the same length as the chromosome. Every bit in the mask equals 0 except for the k rightmost bits where k is the length of the section to be decoded. The shifted chromosome and the mask serve as the operands to a binary “AND” operator which extracts the binary value of the section. This binary number then is converted to decimal to represent the gene value. The example below shows how to extract the vertical assignment policy from the given chromosome. We already know that this policy is stored at the two rightmost bits of the string so no binary shift is necessary in this case:

Solution:	1001010110110111101001 10
Mask:	000000000000000000000000 11

Result (Binary):	000000000000000000000000 10
Decimal value:	2

Assuming bits are numbered from right to left starting from 0; if the bay selection policy is stored in bits 2 to 5 then the following example shows how to decode that information:

Solution:	100101011011011110100110
Binary shifted solution:	001001010110110111101001
Mask:	0000000000000000000000001111

Result (Binary):	0000000000000000000000001001
Decimal value:	9

After all sections of the chromosome are decoded the corresponding stowage pattern can be constructed.

Creating the stowage pattern

As it was shown in Figure 3.2, the general layout of a containership can be looked at as a three dimensional matrix. This however is not true in the real world since the hull shape of the vessels and the location of the engine and accommodation rooms are different at each vessel. To keep the generality and without losing flexibility, a four dimensional data structure is designed to save the produced stowage pattern by a decoded solution. This data structure is referred to as the allocation matrix. The fourth dimension in the allocation matrix corresponds to the ports of visit and the three dimensions correspond to the cellular structure of the vessel. Each element in this data structure holds an integer value which shows the container number to which the cell is allocated to. In order to account for the containership design an extra three dimensional matrix of integers called layout mask matrix is introduced. The layout mask matrix has the same dimensions as the allocation matrix and is constructed based on the specific design of the vessel. Prior to allocating a container to a cell, the counterpart element in the layout mask matrix is checked, if it holds a value of zero it shows that the cell does not physically exist and thus cannot be allocated. Figure 5.6

demonstrates a sample bay from the cross section of a sample vessel and the construction of the vessel layout mask matrix.

The layout mask matrix is an input to the algorithm. If the layout design of the vessel is available in electronically interchangeable format (e.g. XML³), the mask matrix can be automatically created based on that.

The allocation matrix is empty at the beginning of the evaluation and will be filled up by the container numbers based on the decoded solution and the layout mask. Let $\Pi(p)$ be the stowage pattern at port p and N be the total number of visiting ports. Also let U_p , L_p and S_p be the set of containers that must be unloaded, loaded and shifted at port p respectively.

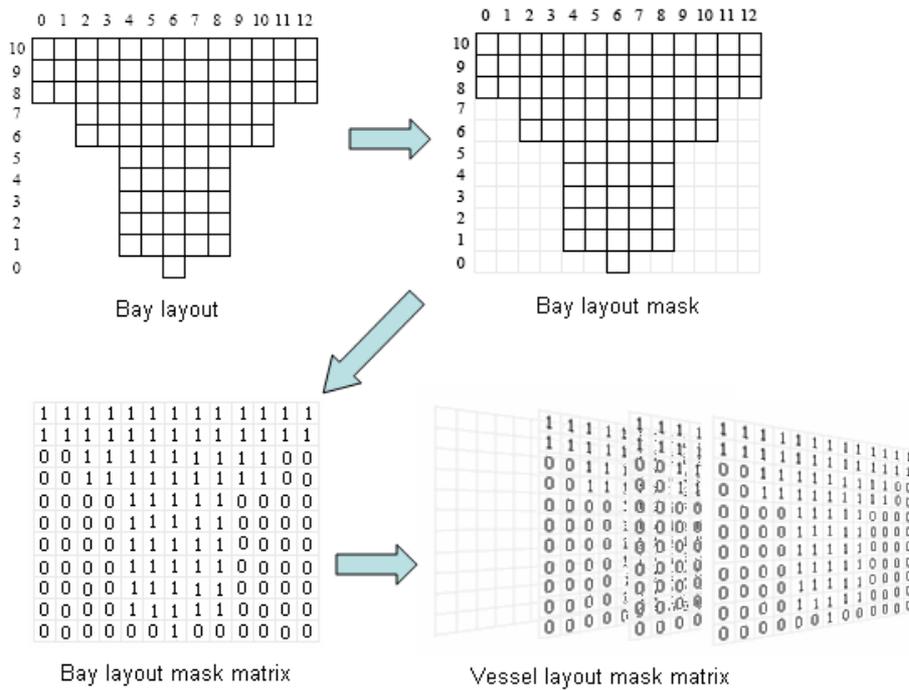


Figure 5.6: Construction of the vessel layout mask matrix

³ Extensible Markup Language

Figure 5.7 shows the vessel layout mask matrix designed for a 10500 TEU containership with 42 bays, 14 tiers and 22 rows. The layout can be further customized to account for the restricted areas of the vessel that may either be not be accessible temporarily or permanently.

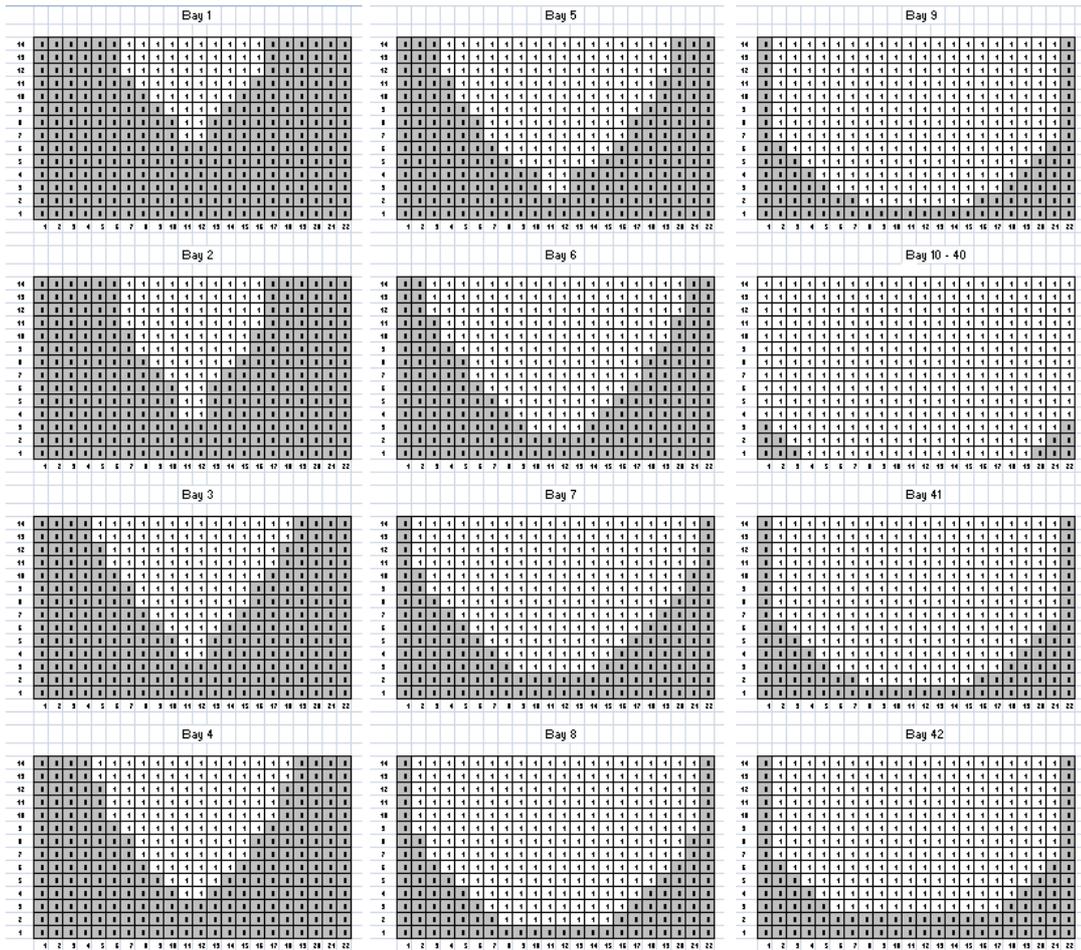


Figure 5.7: Sample of vessel layout mask matrix for a mega containership

The following procedure shows the main steps for creating the stowage pattern.

Procedure: Create Stowage Pattern

Initialization: $\Pi(p) \leftarrow \Phi$

For $P \leftarrow 1$ to N

{

Decode the gene values for port p.

Set: $\Pi(p) \leftarrow \Pi(p-1)$.

Un-assign all the containers in U_p from $\Pi(p)$ and calculate S_p

If reassignment bit is 0 then

$$T = \{L_p, S_p\}$$

Else

$$T = \{L_p, S_p, \text{all containers aboard}\}$$

$$\Pi(p) \leftarrow \Phi$$

Sort T according to the decoded sorting method

Allocate all the containers in T to $\Pi(p)$ with respect to the decoded assignment policy and the layout mask matrix

}

Calculating the crane operations

By now the stowage pattern for all ports from the solution has been generated and saved in the allocation matrix. This matrix must be analyzed to measure different contributing factors in the fitness function. A simple procedure is developed to count the number of container loading, unloading and shifting at each port and for each crane. Since the loading starts only after all the unload containers are processed, this procedure starts with the containers that are to be unloaded. Those containers are the containers that either have reached their final destination, or must be unloaded temporarily in order to allow access to the containers under them. If containers of

different size are mixed, the procedure accounts for the proper number of crane operations to retrieve a container. Figure 5.8 depicts an example.

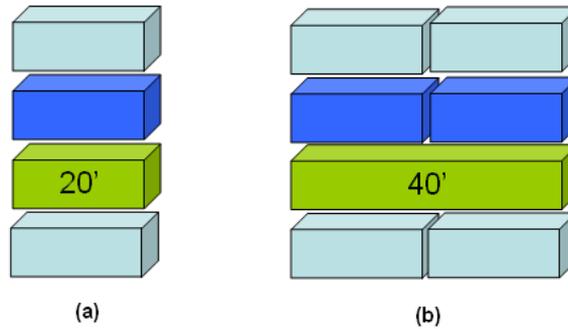


Figure 5.8: Stowage of different size containers

In figure 5.6 the two designated containers have reached their destinations while the other containers are to be transported to the forthcoming ports. In case (a), the two containers on the top must be also unloaded before then the 20' container can be retrieved and then must be put back to the vessel which accounts for a total of 5 crane operations. The total number of crane operations for unloading the 40' container in (b) will be 9 since all four containers on top must be shifted. This is based on the assumption that quay cranes can handle only one container per move regardless of the size of the container. This assumption however is not restricting since the procedure can be modified to support different crane characteristics such as double lifting. Total number of bays on the vessel is denoted by B . Consider $C : N \times B$ an array of integers for storing the total number of required crane operations per each bay. The create stowage pattern procedure must be called and $\Pi(p)$ should be populated before the

number of crane operations can be counted. The crane operations counting procedure is as follow.

Procedure: Count crane operations

Initialization: $C \leftarrow \Phi$

For $P \leftarrow 1$ to N

{

 For $b \leftarrow 1$ to B

 {

 For each container j in U_p that belongs to bay b in $\Pi(p)$

 If there is no container on top j then

$$C[p, b] = C[p, b] + 1$$

 Remove j from $\Pi(p)$

 Else

 For each container k blocking access to j

 Remove k from $\Pi(p)$

$$C[p, b] = C[p, b] + 1$$

 If P is the final destination of k then

 Remove k from U_p

 Else

 Add k to S_p

 For each container j in $L_p \cup S_p$ that belongs to bay b in $\Pi(p)$

$$C[p, b] = C[p, b] + 1$$

 }

}

Calculating turnaround time at each port

After creating the stowage pattern and counting total number of crane operations at each bay, the ship turnaround time can be calculated. Turnaround time of a vessel at a port also known as dwell time is the difference between the time that the vessel berths, and the time that she is released and may leave the port. Since the time at port is very valuable we assume that unloading the vessel starts right after berthing and the vessel leaves the port after last container is loaded and the crane operations do not suspend in the middle of operation. This requires careful coordination and planning at the container yard between the yard cranes and internal trucks, straddle carriers, AGV's or any other form of in yard equipment used for horizontal transportation of the containers. While unloading the vessel, movement of the import containers from the vessel to the yard should be planned properly such that quay cranes do not waste any time waiting for horizontal transportation. Also at the loading time a smooth flow of the export containers from the yard to the vessel will keep the quay cranes busy during the operations.

Quay cranes have different technical specification which determines their performance and capacity. Other factors such as weather conditions and visibility may also affect the performance of the cranes. Although the quay cranes at a specific port are usually homogenous, to generalize the solution algorithm we assume that not only the quay cranes at ports of call could be different, but also individual cranes at each port may be non-homogenous. We also assume that all the cranes that are assigned to a vessel work side by side and the vessel can be released only when the last remaining container is loaded onto the vessel by the respective crane. The

horizontal divide and the operational range of the cranes are determined by the technical constraints. Generally a crane may not interfere with a neighboring crane on a common bay, so the minimum unit of horizontal separation between two adjacent cranes is one bay. Utilization of a crane can be defined as the percentage of the time that the crane is busy and is calculated by the total crane busy time over the turnaround time at port. The crane busy time is composed of two components: horizontal movement time and container handling time. The horizontal movements do not occur very frequently and are required only when the crane has finished the job on a bay and needs to proceed to the next bay. So the major fraction of the crane busy time is the container handling time. Container handling is performed using the spreader arm and is composed of one horizontal and two vertical moves by the spreader arm as shown in Figure 5.9.

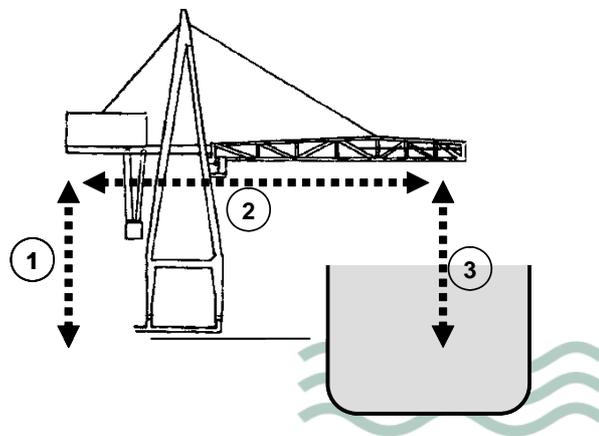


Figure 5.9: Three steps of spreader arm movement for handling a container

The time required for step 1 is the same for all the containers handled by the crane.

The completion time of steps 2 and 3 however depend on the position of the container in the vessel. The farther the container is from the berth line and the deeper the container is in the vessel, the higher is the time to handle the container.

The assignment of quay cranes to the vessel and the technical specifications of each crane at all ports is assumed to be known in this study. Given the stowage pattern and the set of available cranes, the solution to the crane split problem determines the ship turnaround time at port. As it was mentioned in section 2.5, crane split problem is in the class of scheduling problems and has been discussed as an independent problem or jointly with berth allocation problem in the container literature. To evaluate a candidate solution by the genetic algorithm we need to have the ship turnaround time at each port and for that matter we need to solve the crane split problem for each port. A large number of chromosomes are to be evaluated in each iteration of GA and to reach the convergence many iterations are required. Kim and Park (2004) report an average of 457 seconds CPU time for solving a problem with three homogenous cranes and 25 tasks. The computational burden of the crane split solution methods makes it impossible to use them in the evaluation procedure of our proposed genetic algorithm. To overcome that difficulty a heuristic procedure is proposed to approximate the crane split and total ship turnaround time. This procedure uses the output provided by the “Count Crane Operations” procedure in the former section as an input. Having B bays and Q_p quay cranes available at port p , the procedure begins with dividing the bays into Q_p subsets with $\left\lfloor \frac{B}{Q_p} \right\rfloor$ bays at each of sets. If B is not divisible by Q_p then the number of bays in the last subset will be equal to

$B - \left\lfloor \frac{B}{Q_p} \right\rfloor \cdot (Q_p - 1)$. Then starting from the first crane it considers each crane with the crane right after it. It looks for any potential improvement in the turnaround time that might be achieved by separating a bay from the operational range of one crane and appending it to the other one. As it was mentioned before the number of crane operations at each port are known at this time and given by matrix C . The following notation is used in the proposed procedure.

$R_{p,q}^f$: Index of the first bay in the operating range of crane q at port p

$R_{p,q}^l$: Index of the last bay in the operating range of crane q at port p

$BT_{p,q}$: Busy time of crane q at port p

$\alpha_{p,q}$: Required time to handle one container by crane q at port p

$\beta_{p,q}$: Required time for horizontal movement to adjacent bay for crane q at port p

TT_p : Turnaround time at port p

Procedure: Calculate crane split and turnaround time

Initialization: $BT_{p,q}, R_{p,q}^f, R_{p,q}^l = 0 \quad \forall p, q$

For $P \leftarrow 1$ to N

{

$i = 1$

For $q \leftarrow 1$ to $Q_p - 1$

{

$$R_{p,q}^f = i, R_{p,q}^l = R_{p,q}^f + \left\lfloor \frac{B}{Q_p} \right\rfloor$$

$$i = R_{p,q}^l + 1$$

}

$$R_{p,Q_p}^f = i, R_{p,Q_p}^l = R_{p,Q_p}^f + \left\lfloor \frac{B}{Q_p} \right\rfloor$$

For $q \leftarrow 1$ to Q_p

{

$$BT_{p,q} = \sum_{b \in [R_{p,q}^f, R_{p,q}^l]} C[p,b] \cdot \alpha_{p,q} + (R_{p,q}^l - R_{p,q}^f) \cdot \beta_{p,q}$$

}

For $q \leftarrow 1$ to $Q_p - 1$

{

Crane range adjustment for cranes q and $q + 1$:

If $BT_{p,q} > BT_{p,q+1}$ then

$$\gamma = BT_{p,q} - BT_{p,q+1}, R_{p,q}^l = R_{p,q}^l - 1, R_{p,q}^f = R_{p,q}^f - 1$$

Recalculate $BT_{p,q}, BT_{p,q+1}$

If $|BT_{p,q} - BT_{p,q+1}| \geq \gamma$ then $R_{p,q}^l = R_{p,q}^l + 1, R_{p,q}^f = R_{p,q}^f + 1$

Else

$$\gamma = BT_{p,q+1} - BT_{p,q}, R_{p,q}^l = R_{p,q}^l + 1, R_{p,q}^f = R_{p,q}^f + 1$$

Recalculate $BT_{p,q}, BT_{p,q+1}$

If $|BT_{p,q} - BT_{p,q+1}| \geq \gamma$ then $R_{p,q}^l = R_{p,q}^l - 1, R_{p,q}^f = R_{p,q}^f - 1$

}

$$TT_p = \text{Max}\{BT_{p,1}, BT_{p,2}, \dots, BT_{p,Q_p}\}$$

}

After calling this procedure crane utilization at each port and total turnaround time at all ports can be calculated as follow.

$$U_{p,q} = BT_{p,q} / TT_p$$

$$Total\ Turnaround\ Time = \sum_{p=1}^N TT_p$$

Figure 5.10 shows how the crane split approximation procedure works for a small example. The ship in this case has 6 bays and there are 3 cranes available. The number on each bay indicates the total number of crane operations required for the bay. Bays are numbered from stern to bow in increasing order.

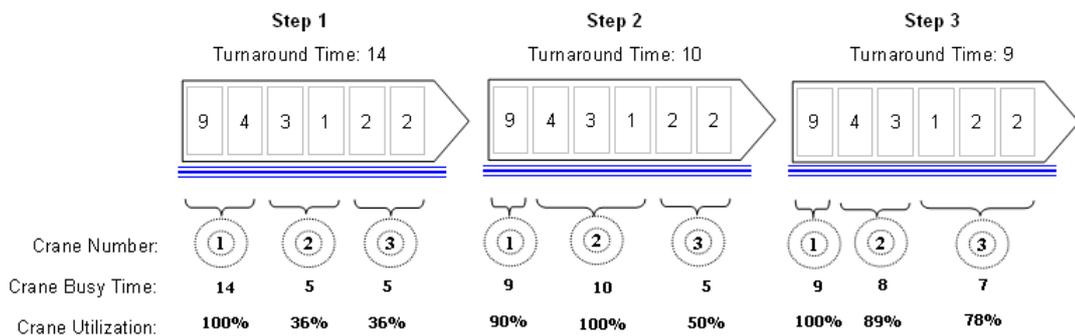


Figure 5.10: Illustration of crane split approximation procedure

At the first step two bays are assigned to each crane. It is assumed that each container can be handled in one time unit and also the crane can move horizontally to the adjacent bay in one time unit. Crane 1 for example must handle 13 containers in bays 1 and 2 and will need to do one horizontal displacement, which makes its total busy time equal to 14. The crane busy time for each crane as well as turnaround time and crane utilization for each step is shown in the figure. After the initial assignment the

procedure tries to reassign the bays to the cranes if doing so decreases the turnaround time. In step 2 by separating bay 2 from crane 1 and assigning it to the operational range of crane 2, turnaround time will decrease by 4 units and finally in the last step by assigning bay 4 to crane 3, turnaround time is improved by 1.

Objective function

As it was mentioned before, the conventional objective function of the containership stowage planning is to minimize the total number of container movements at all ports. However the solutions results in chapter 4 show that this objective function does not represent the true objective function of the problem which is the minimization of total turnaround time at all ports. By using the suggested procedures we can calculate the value of either of these objective functions for each solution. In next chapters we will use the conventional objective function for verification of the genetic algorithm and creating base case scenarios. Another advantage of these procedures is the capability of creating economical objective functions. If the monetary value for each unit of time per port is given we can easily apply the time value parameter to the total turnaround time equation in order to minimize the total cost of operations.

$$Total\ Operational\ Cost = \sum_{p=1}^N TT_p \times \delta_p$$

δ_p :Value of one time unit at port p

Similar cost minimization equation may be written for the situation that per TEU cost of handling the containers at each port is given and the cost parameter varies over ports or is different for different cranes.

5.2.3. Handling the constraints

The solution space for a constrained combinatorial problem can be divided into two regions: feasible and infeasible. Searching for optimal solution must be performed inside the feasible region. The assignment based genetic encoding for containership loading problem resolves the issue of illegality, however it may generate infeasible solutions. Infeasibility occurs as a result of violating the constraints. There are three ways to deal with infeasible chromosomes: reject, repair and penalty. Rejecting involves the elimination of infeasible chromosome from the generation. Repair methods try to find the genes that cause the infeasibility and modify their values to satisfy the feasibility criteria. Penalty methods identify the violated constraints and impose a penalty to the fitness value of the corresponding chromosome for each violation. The penalty can be fixed or be proportional to the deviation of the constraint from the acceptable range. The rejection method takes away any possibility of the chromosome for appearing in the next generations and may increase the convergence time dramatically. Choosing among the repair and penalty methods depends on the nature of the problem. A drawback of the repair method is that it interferes with the learning mechanism of the genetic algorithm by changing parts of the information. This might affect the convergence of the algorithm even more if repairing the infeasible chromosome asks for extensive modifications. The penalty method does not change the chromosomes; however it has the disadvantage of introducing the penalty term to the fitness function. Finding proper value for the penalty terms may be a complicated task especially if several constraints of different types are to be considered. In the proposed assignment policy based encoding it is

very difficult and time consuming to modify the genes in order to remove the infeasibility because the genes hold the policy and sorting codes instead of actual stowage of the vessel. So the penalty method is used in this research for enforcing the constraints.

Instability penalty

As it was discussed in 3.3.1, GM is a proper measure of stability for the containerships. The deviation of GM from the permitted threshold can be imposed as penalty to the fitness function. Measuring the GM however needs detailed information about the structural design of the specific vessel. To generalize the solution approach the experimental rules of stability are used in this research. After decoding the solution and generating the stowage pattern for each port, different stability measures may be easily computed according to the containers weight information and their position in the vessel. Cross equilibrium can be measured based on the axis of symmetry going from bow to the stern. The total weight or momentum of the containers at either side must be calculated and the difference must not exceed a given value. The penalty is calculated by multiplying the penalty parameter by the magnitude of the violation, so that the solutions that are farther from the feasible region receive higher penalties. Similarly, longitudinal and vertical equilibrium will be measured and the evaluation function will receive penalty for their violation. Theoretically speaking tightening the constraints will shrink the feasible region and will make it more difficult for the algorithm to converge to possible optimal or suboptimal solutions if any.

Violation of operational constraints

Similar to the stability constraints, the necessary information for checking the operational constraints is retrievable from the stowage pattern and the container information list. A very important constraint in the mathematical problem presented in chapter 3 is that the cell under a container cannot be empty. This constraint is naturally taken care of in the assignment policy based encoding because all the policies start assigning cells to containers from the first unassigned cell at the bottom of the column. Another operational constraint prohibits storing a heavy container on a lighter one. As it was shown in Table 1.1 average standard weight of an empty container ranges from 2.3 to 4 tons, while the maximum average weight of a full container to be stowed in a containership is 24 and 30 tons for 20' and 40' containers respectively. For implementing the container weight constraint a simple procedure goes through the stowage plan and compares the weight of each container with the container immediately on top. If the difference between the two weights cannot be tolerated it will be counted as one violation. The tolerance is a parameter that can be decided by the ship planner, i.e. 5% weight difference might be considered acceptable. Total number of container weight violations is then multiplied by its penalty parameter and will be applied to the fitness functions. Similar approach is used to account for other operational constraints such as regulations for stowing special containers or rules for mixing the containers of different sizes.

Similar cost minimization equation may be written for the situation that per TEU cost of handling the containers at each port is given and the cost parameter varies over ports or is different for different cranes.

5.2.4. Genetic operators and chromosome selection

Genetic algorithm is an iterative process which works on a generation of chromosomes. It starts with a population of randomly generated individuals. At each step of the algorithm genetic operators manipulate the current generation and then a selection procedure chooses the individuals that will advance to the next generation based on their fitness value. The two classical operators of the genetic algorithm are crossover and mutation. Crossover is a binary operator that performs the exchange of information between two individuals that are randomly selected for breeding to create new individuals. Mutation on the other hand is a unary operator which modifies a randomly selected individual. Both of these operators are important to the genetic algorithm. Crossover enables the algorithm to extract the best genes from different individuals and combine them to create potentially superior offsprings whereas mutation introduces diversity to the population and thereby decreases the possibility of converging into local optima. Without mutation it is very likely that the algorithm could only produce individuals whose genes are a subset of the combined genes in the initial population. The genetic operators and the mechanism for selecting the individuals are discussed in this section.

Crossover

Recombination in genetic algorithm is done by crossover operator. After randomly selecting two parents, there are several methods that crossover can be applied.

One-point crossover: the classical one point crossover splits each parent into two parts from a randomly selected crossover point and recombines the swapped sections

of the parent to create two new children. This operator is more likely to keep together the neighboring genes, but it can never keep together genes from opposite ends of the chromosome. Figure 5.11 (a) shows an example.

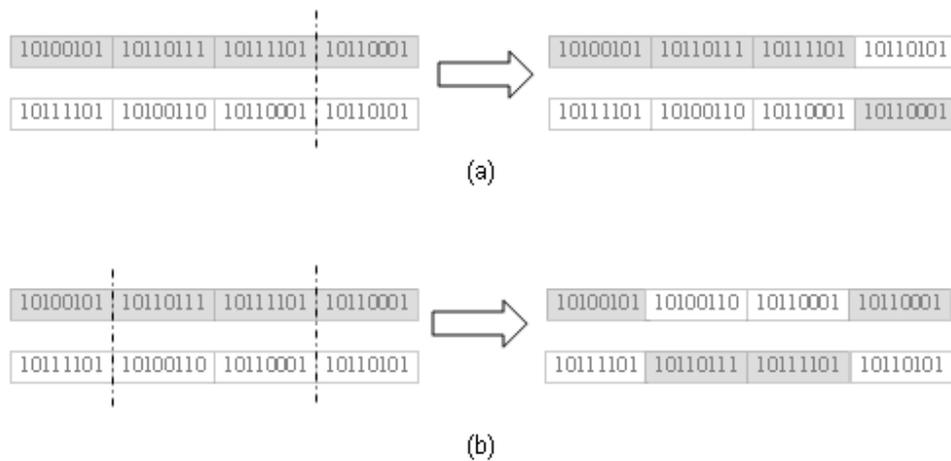


Figure 5.11: (a) one-point crossover (b) two-point crossover

Two-point crossover: this operator requires two random crossover points to be selected. Each parent then is split into three parts according to the crossover points and the children are created by recombining the sections of the parents as it is shown in Figure 5.11 (b). Unlike one-point crossover it is possible to keep the genes from both ends of the chromosome together while maintaining the block structure of the chromosomes.

k-point crossover: it is a generalization of the two-point crossover and applies the same idea to k randomly generated crossover points. De Jong (1975) and Goldberg (1989) conclude that the two-point gives an improvement, but adding further crossover points may reduce the performance of the algorithm.

In all above cases the crossover points will be located at the starting position of the gene values for a particular port. In other words the crossover points do not break the encoded sorting and assignment policy information for any particular port and because of that the integrality and legality of the generated children is guaranteed.

Uniform crossover: in this method for each bit position on the two children, corresponding bits in the parents are swapped with a fixed probability. The probability value determines the degree in which each parent contributes to each child and is typically 0.5. This method has the disadvantage of destroying the building blocks of the genes.

Cut and splice crossover: this method is a variant of the two-point cross over with the difference that crossover points on both parents are independent. This results in chromosomes with variable length. The proposed chromosome structure in this research is fixed length so this operator will not be a candidate.

The crossover operator has a probability P_c which determines the percentage of the chromosomes that undergo crossover. At the crossover step of the GA, a random number in the range of $[0, 1]$ is generated for each chromosome. If the number is below P_c then the individual will be selected for crossover. The type of the crossover operator and the value for P_c will be discussed in chapter 6.

Mutation

After applying the crossover and adding the new children to the generation the enlarged population undergoes mutation with probability P_m . Mutation is applied by randomly selecting a bit on the candidate chromosome and switching its value. In the

proposed genetic encoding for containership loading problem, mutation can be interpreted as modifying the sorting or assigning strategy at a port from one strategy to another. The value for the mutation parameter P_m will be analyzed in chapter 6.

Selection and migration

In the selection phase of the genetic algorithm a set of chromosomes from the current generation are chosen for breeding in the next generation. The selection process works in the favor of the individuals with better quality by giving them a higher chance for migration. The two well known classical methods for selection are roulette wheel and tournament methods.

Roulette wheel method: this is the most common method in which the selection chances are proportional to fitness. It starts with normalizing the evaluated fitness of all the chromosomes by multiplying the fitness value of each individual by a fixed number such that the sum of all fitness values over the population equals 1. Each individual then will be assigned a circular sector of the roulette wheel. The angle of the sector is equal to $2\pi f_i / \bar{f}$ where f_i is the fitness of chromosome i and \bar{f} is the fitness of the whole population (Holland 1975). Individuals can be chosen randomly one after another by spinning the wheel. To implement the wheel spinning process the population is sorted by descending normalized fitness values. A random number r is generated in the range of 0 to 1 and the first individual whose normalized fitness value is greater than r is chosen.

Tournament method: the simplest form of this method is binary tournament selection. Randomly picked pairs of individuals are selected from the population and the one

with higher fitness value is copied to the mating pool. The process continues until the population is full.

Elitism

The idea behind elitism is to ensure that the current generation is at least as fit as the previous generation. It is done by directly copying the fittest individual to the next generation. Elitism is believed to speed up the search, that is, to converge faster toward the optimal point. However, there are some arguments which criticize this strategy, since it can prematurely limit the search in local optima.

Termination criteria

The process of creating generations continues until the termination criterion is met. There are several criteria to stop the genetic algorithm and selecting the proper criteria usually depends on the application. The most common termination conditions are as follow.

- Maximum number of iterations has reached
- Maximum time for running the algorithm has reached
- The average fitness of the population has reached a steady state, that is, the absolute difference between the average fitness of the two most recent generations is below ε . Another variant of this criterion is when the percentage of the improvement in average fitness compared to that of previous generation is below a certain percentage value.

The termination condition can also be a combination of the above items.

5.3. Summary

In this chapter after a brief review on the evolutionary algorithms, a genetic algorithm for optimizing containership load planning considering crane split is proposed. A new genetic representation based on combination of sorting and assignment policy is proposed which is very compact and expressive. The idea behind the proposed encoding comes from the grouping and storing practices in the container yard in which the containers are sorted and grouped based on their common property such as weight, size, type or destination. A data structure called *vessel layout mask matrix* is designed to represent the cell availability of the containership. Required procedures for decoding a solution, generating stowage pattern based on the decoded solution and analyzing the generated stowage pattern for calculating the components of the evaluation function are discussed. It is shown that the algorithm is capable of dealing with different objective functions for the problem including the conventional objective function of the stowage planning, temporal objective function and economical objective function. The algorithm uses penalty method for handling the constraints. The designed crossover and mutation operators ensure the legality of the generated offsprings. The roulette wheel method is used for selecting the individuals to build the next generation. Different termination conditions are defined and will be implemented.

Chapter 6: Analysis of genetic algorithm parameters and lower bound

The proposed genetic algorithm in chapter 5 has been implemented using C++ language. To analyze the performance of the solution method and to find the appropriate set of parameters for the genetic algorithm a large set of sample problems have been generated and solved.

6.1. Generating sample problems

To estimate the value of the parameters and analyze the performance of the proposed genetic algorithm we need to run the algorithm on variety of sample problems with different sizes and structures. As it was mentioned in 4.1 the generated problems must be compatible with the capacity of the containership, that is, neglecting the stability and operational constraints the container to vessel assignment problem must be feasible. Besides that, it is important to generate scenarios to resemble the situations in which the containership operates under capacity or the emphasis is put on certain ports. The underlying structure of the transportation matrix plays a crucial role in the complexity of the containership loading problem. Figure 5.1 depicts an example. In this figure a 2000 TEU containership is considered to visit four ports under two scenarios. Each solid arc shows the flow of the containers between the corresponding ports and the demand can be seen in the transportation matrices. The numbers at the bottom show the percentage of the ship's capacity that is full while moving from one port to another. As it is shown in figure 6.1 (a) the vessel in this case is fully utilized to transport a total of 2000 containers. This number is the same for the case in figure

6.1 (b), however the vessel could have transported more containers as it is not full all the time. Even though both cases have equal number of ports and containers with the exact same containership, the complexity of their stowage planning problem is different. In the second case the issue of overstorage does not exist because the containers of different destinations are not present in the vessel simultaneously. The stowage planning at this case is reduced to a simple container to cell assignment with stability and operational constraints. This however is different for the first case as overstorage might be inevitable.

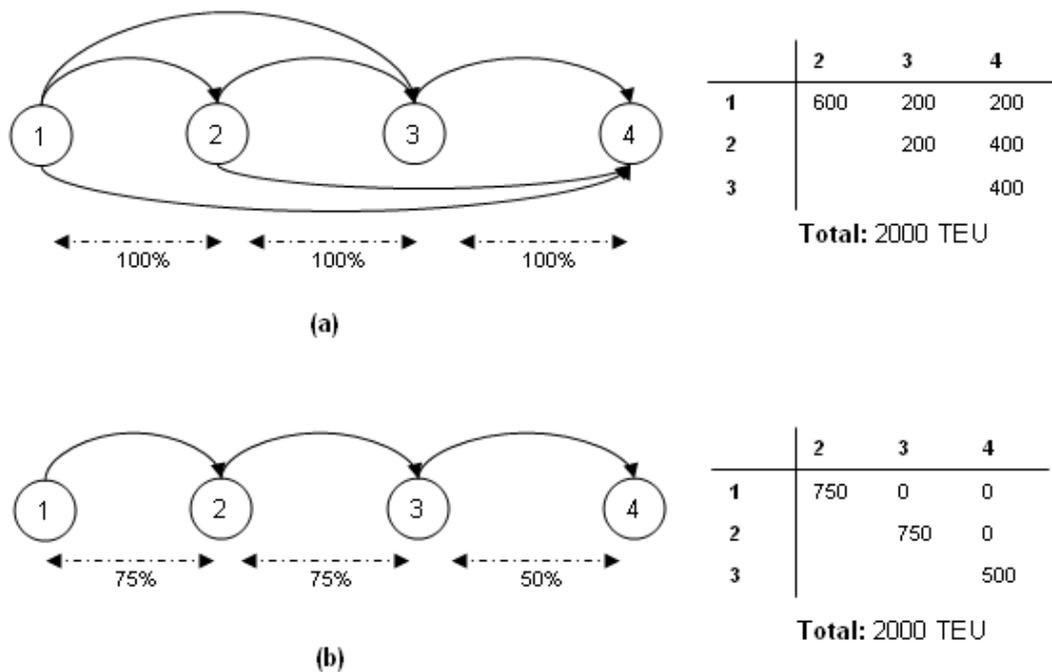


Figure 6.1: Transportation matrices for two different scenarios

Besides the structure of the demand, the property of the containers i.e. weight, size, and type may contribute to the level of complexity. Consider two set of containers for the case presented in figure 6.1 (b) where one set has 2000 containers of uniform

weights as opposed to the other set where weights vary across the containers. The case with different weights is more challenging since it has more binding operational constraints. The above example shows that the complexity of the containership loading problem is not governed only by the size of the problem, but also it depends on the structure of the demand matrix and the characteristics of the containers. The following pseudo-code is designed to generate random test problems of different sizes for the containership loading problem with respect to the ship capacity.

Procedure: Generate test problem

Input the capacity of the ship, number of ports, maximum load ratio, containers weight range, percentage of containers of different size and type.

For $P \leftarrow 1$ to N

{

Available capacity = Capacity * maximum load ratio - Sum of the containers that have been loaded at the ports preceding P + Sum of the containers that have been unloaded at port P and its preceding ports

Generate $(N - P)$ random demands, one for every port succeeding P , such that sum of the generated demand is less than or equal to the available capacity.

Apply the percentage of different size containers to the demand and adjust the numbers.

}

D = total generated demand (total number of containers)

```
For  $c \leftarrow 1$  to  $D$ 
{
    Generate random weight for container  $c$  within the specified weight range.
    Store the origin, destination, weight, size and type of the container  $c$  .
}
```

6.2. Genetic algorithm parameters

There are several parameters in each genetic algorithm that contribute to the accuracy and the performance of the algorithm. The population size, crossover and mutation ratio and termination criteria are the main parameters to be decided. Like other evolutionary algorithms, the value of the genetic algorithm parameters depends on the nature of the problem and has to be tuned for the specific problem representation. Alander (1992) studied the optimum population size of the genetic algorithms as function of problem complexity and concluded for problems coded as bit-strings, the length of the string in bits for sequential machines is a good approximation for the optimum population size. De Jong (1975) recommended population size, the mutation rate and the crossover rate to be 100, 0.001 and 0.6 respectively. We set the population size to 100 and analyze the value for crossover and mutation parameters based on this assumption.

The relative importance of crossover and mutation in genetic algorithm has been subject of discussion in the genetic algorithm literature. Although some researchers suggest that crossover operator alone is sufficient for evolving the solution, other

studies confirm that the power of mutation operator cannot be neglected (Schaffer et al. 1989) and crossover has no general advantage over mutation (Fogel and Atmar 1990). In other words crossover is explorative and discovers promising areas in the search space by gaining information on the problem while mutation is exploitative which uses the information to improve the optimization within a promising area. In fact cooperation and competition coexist between these two operators (Eiben and Smith 2003).

6.2.1. Crossover and mutation parameter

To capture the effect of different mutation and crossover values on the performance of the genetic algorithm and quality of the solution, a set of test problems have been generated using the procedure described in 6.1. Four containerships with the capacities of 500, 1000, 2000 and 3000 TEU are considered, each of which visiting five ports.

After running some pilot experiments we decided to analyze P_c , P_m in the ranges of [0.1..0.8] and [0.005...0.5] respectively. Starting from the lowest value we increase P_c by 0.1 at each step and increase P_m by 0.05. This creates 90 (P_c, P_m) combinations. The stability rules of cross and longitudinal equilibrium are enforced. Each of the generated test problems were solved for every (P_c, P_m) pair which makes 360 cases. To make the results comparable the termination criteria was set to 500 iterations of the genetic algorithm. For each case total number of container handling at all ports was chosen as an indicator of the solution quality. Figure 6.2 shows the results for the

1000 TEU containership. In this case $(P_c, P_m) = (0.6, 0.2)$ has generated better quality solutions in 500 iterations.

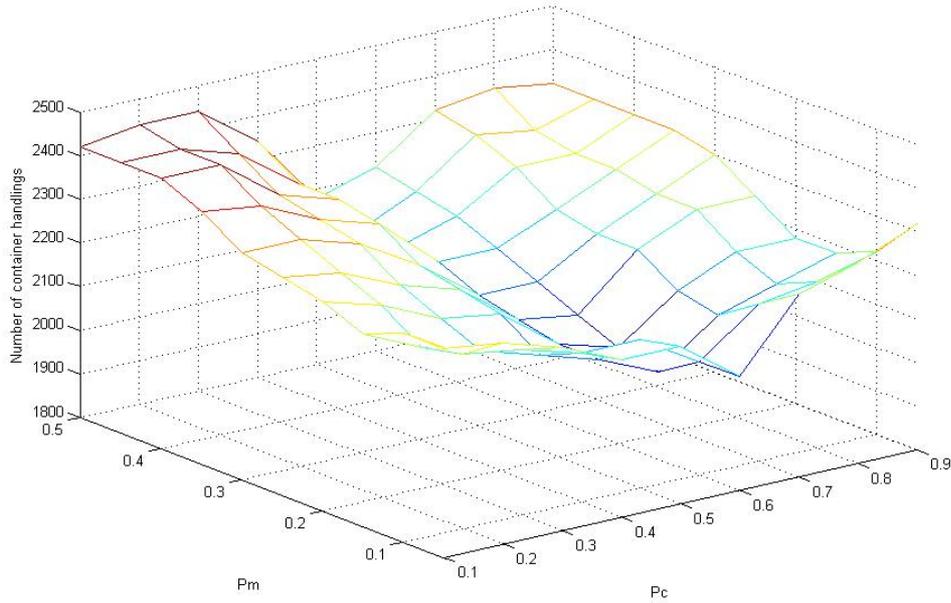


Figure 6.2: Crossover and mutation ratio analysis for 1000 TEU case

Since the containerships in the four considered cases are of different capacity, the result for each case has been converted to a scale of 1 to 100. The best solution among 90 combination of (P_c, P_m) has been given the score 100 and the other solutions have been given a score proportional to their deviation from the best solution. The average score of results over the four cases for each (P_c, P_m) is presented in figure 6.3 and table 6.1. The results show that by setting P_c, P_m equal to 0.6 and 0.15 respectively, better quality solutions are obtained within 500 iterations.

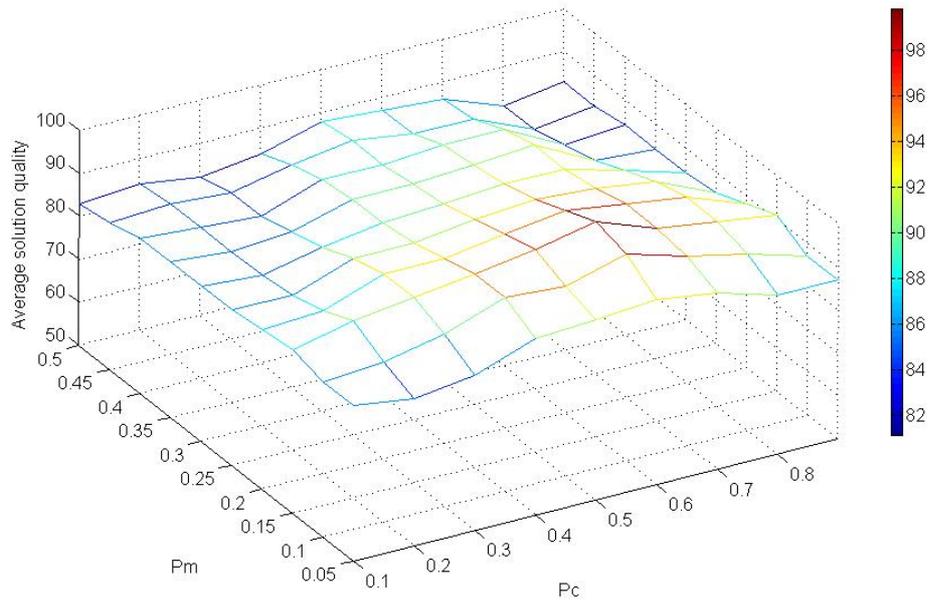


Figure 6.3: Overall crossover and mutation ratio analysis

Table 6.1: Normalized solution quality for overall crossover and mutation ratio analysis in four containership classes

		P_c								
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
P_m	0.05	36	56	79	73	87	86	82	71	60
	0.1	43	63	82	80	90	93	89	78	67
	0.15	50	70	85	87	97	100	96	80	70
	0.2	46	66	81	83	93	96	92	81	71
	0.25	42	62	77	79	89	92	88	77	66
	0.3	38	58	73	75	85	88	84	73	62
	0.35	35	55	70	72	82	85	81	70	59
	0.4	32	52	67	69	79	82	78	67	56
	0.45	31	47	62	64	74	77	73	62	51
0.5	30	42	57	59	69	72	68	57	46	

6.2.2. Population size

Genetic algorithm needs memory to store the population. The larger the population size, the more memory is required. Besides the memory requirement concerns, increasing the population size usually results in increase of running time at each step of the algorithm. This happens because more chromosomes will be subject to crossover, mutation and fitness evaluation in a larger population. But at the same time if the population size is not large enough, then the algorithm might converge to a suboptimal solution prematurely due to limiting the diversity of the solutions. Having fixed the parameters for crossover and mutation, we can analyze the effect of the population size on the solution quality. The 1000TEU containership case from the previous section is used. To investigate the effect of population size on the running time, the problem is solved for three cases. The objective function in all cases is the minimization of the total turnaround time, but the constraints are different. In case 1 only horizontal and cross equilibrium constraints are enforced. In case 2 the vertical equilibrium is added and finally in case 3 placing any heavy container on a lighter one is also prohibited. The average weight of the 1896 containers in this problem is 25.55 tons with the standard deviation equal to 14.03. The weight threshold for the equilibrium constraints is 10% (e.g. if the weight difference between two containers is less than 10% they are treated equally).

Figure 6.4 illustrates the increase of CPU time based on the population size for fixed crossover and mutation ratio parameters and fixed number of iterations in each case. Since the number of iterations is fixed the quality of solution for each population size is different from the others. Investigate the mutual impact of the population size and

the number of iterations on the solution quality, the convergence criteria is modified for figure 6.5. For this experiment the algorithm is set to stop when the average fitness value of the population does not improve by a margin of 0.001 compared to the prior iteration. The 1000 TEU containership described in section 6.2.1 is used and the vertical and horizontal equilibrium constraints are enforced. As figure 6.5 shows the results of this example, when the population size is small a higher number of iterations are needed to reach the targeted solution quality. Although the number of iterations is less as the population size grows, the CPU time goes up as a result of having a larger number of chromosomes. A population size of 100 in this case seems to be an acceptable tradeoff point between population size and number of required iterations.

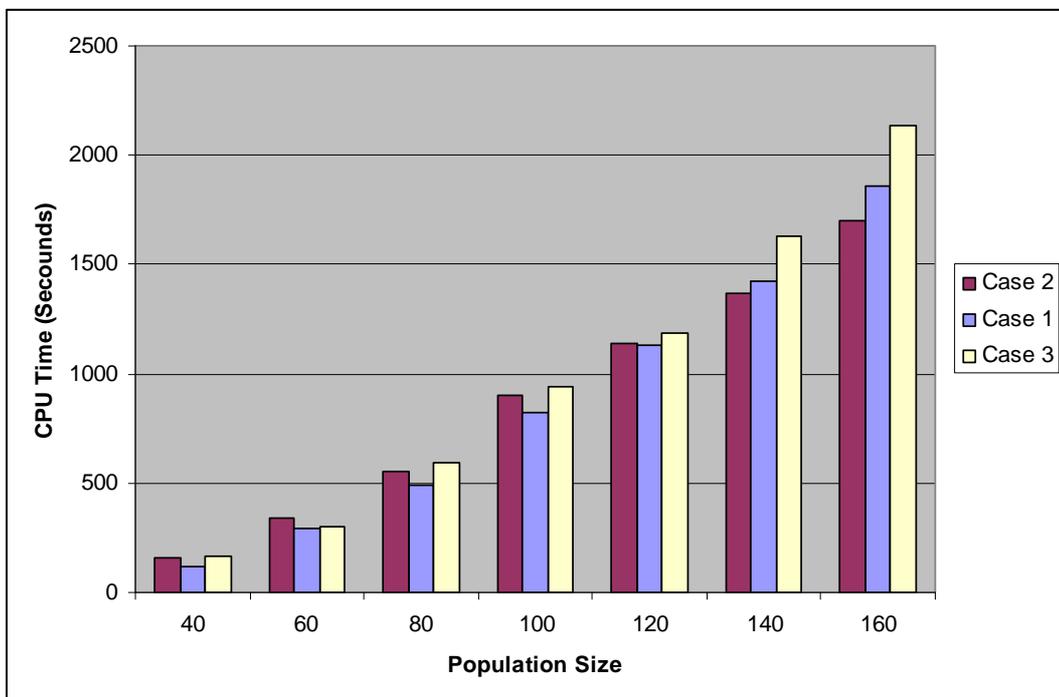


Figure 6.4: Effect on population size on CPU time

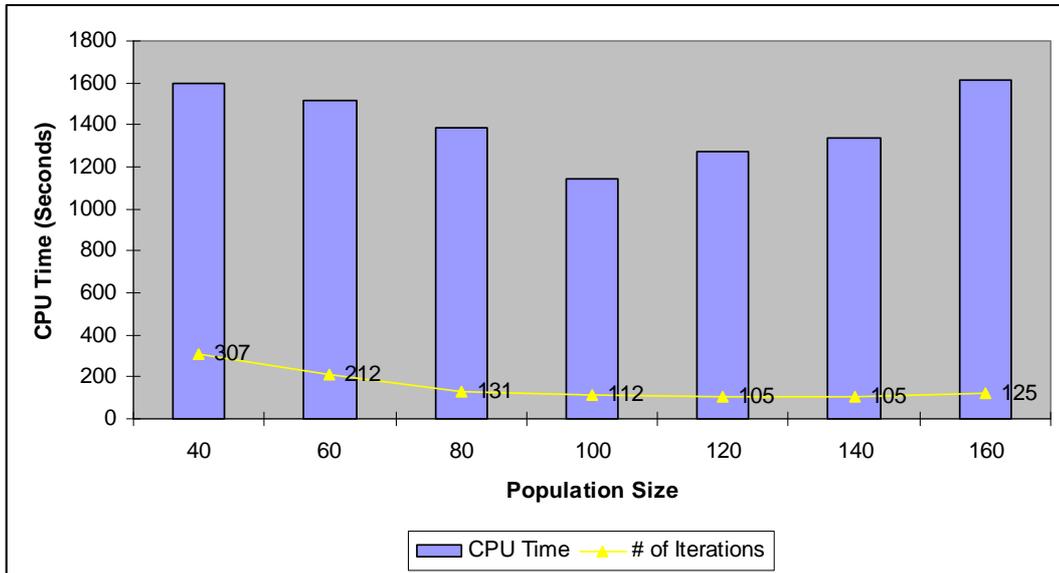


Figure 6.5: Effect on population size on CPU time and number of GA iterations

6.2.3. Two-point crossover vs. classic crossover

Classic and two-point crossover operators have been implemented. To evaluate their performance we applied the variation of the genetic algorithm using each operator to the same 1000 TEU containership problem having fixed the number of genetic iterations. If the number of iterations is large enough the results from test problems show that the quality of the solution by both methods are approximately the same, however the two-point crossover slightly speeds up the convergence. Figure 6.6 shows the comparison graph between the best fitness value of each generation versus the iteration number for the two operators.

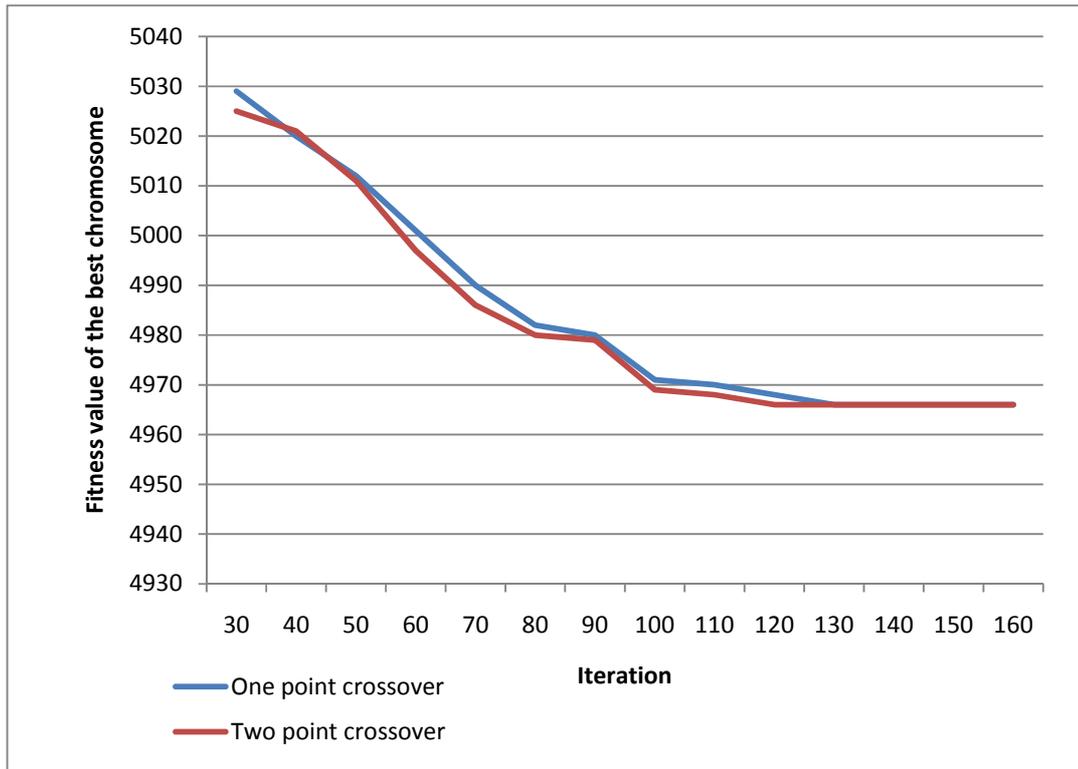


Figure 6.6: Comparison between one and two point cross over operators for a sample problem

6.2.4. Containership capacity and solution time

Although the capacity of containership and number of visiting ports are contributing factors to the problem complexity, the structure of the transportation matrix and the structural design are the vessel will define the complexity. In other words solving the containership load planning for a vehicle with larger capacity is not necessarily more challenging that solving the problem for a smaller vessel. In order to study the capability of the proposed solution approach for dealing with different classes of containership, and also the relationship between the solution time and size of the

vessel, 40 sample problems for eight class of containerships were generated. Ten ports are considered in these problems and for each class of vessels five origin-destination matrixes were generated. Stability constraints are enforced such that the maximum horizontal and vertical imbalance is limited to maximum 5%. The containers are of different weight generated based on a uniform random distribution of U(3,25). Table 6.2 shows the characteristics of the problems and the average CPU time for each class.

Table 6.3: Sample problems for different classes of containerships

Vessle Class	Number of generated problems	(Bay,Row,Tier)	Capacity (TEU)	Average number of containers	Average CPU time (Minute)
1	5	(10,10,10)	1000	2444	2
2	5	(20,10,10)	2000	5938	11
3	5	(30,10,10)	3000	9001	21
4	5	(40,10,10)	4000	10210	28
5	5	(50,10,10)	5000	12662	49
6	5	(60,10,10)	6000	16640	75
7	5	(70,10,10)	7000	18641	126
8	5	(80,10,10)	8000	22507	137

Figure 6.6 illustrates the increase in the average computational time with respect to the containership capacity. It can be observed that the solution to real size problems can be obtained in a relatively short time. The solution time for 8000 TEU containerships is less than 2.5 hour.

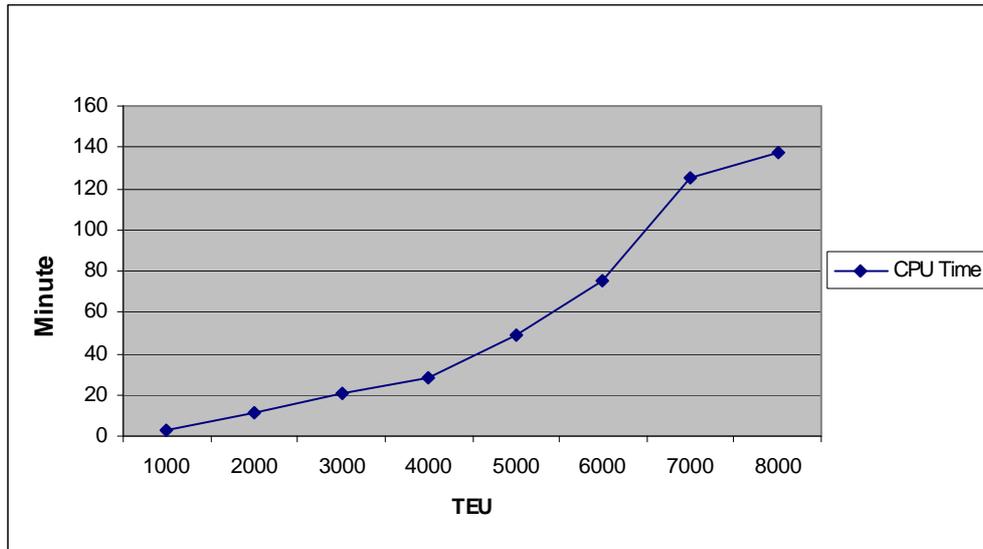


Figure 6.6: Average CPU time vs. containership class for 10 ports

6.2.5. Parallel processing

One of the methods to improve the efficiency of an algorithm is to take advantage of the parallel processing. As opposed to the sequential processing, parallel processing is simultaneous execution of the code or pieces of the code on several processors. On a multi-processor computer, parallelism can be done implicitly or explicitly. In implicit parallelism the operating system distributes the tasks over the available processors automatically whereas in the implicit method the programmer must design the algorithm in a way that different tasks or threads are assigned to the processors. Many parameters and factors govern the performance of the parallel algorithms, however if the architecture of the algorithm is not parallel then the benefits of parallel processing will not be significant. Genetic algorithms are parallel in nature and that makes them good candidates for parallel processing. The parallel parts of the program however need to be synchronized using programming techniques. In the proposed genetic

algorithm for containership load planning, evaluation of the chromosomes makes a big fraction of the total CPU time. After crossover and mutation operators are applied to the current generation, there are several chromosomes to be evaluated before building the next generation. In the presence of multiple processors, the evaluation of the chromosomes can be done simultaneously and will reduce the total evaluation time of the generation. The implementation of the genetic algorithm in this research uses *threads* and the *synchronization* classes in C++ to distribute the chromosome evaluation tasks over the available processors.

If the speed of an algorithm is defined as its execution time, then the speedup can be defined as the speed of the serial algorithm (execution time on a single processor) over the parallel speed (execution time of the parallel algorithm on a multi-processor). Efficiency of the parallel processing is measured by the speedup divided by the number of processors (Lewis and El-Rewini 1992). Amdahl's law is a model for the relationship between the expected speedup of parallelized implementations of an algorithm relative to the serial algorithm. If F is the fraction of the algorithm that is sequential and N is the available number of processors, then according to

Amdahl's law the maximum expected speedup by parallelization is $\frac{1}{F + (1 - F)/N}$.

Having set the P_c, P_m and generation size to 0.6, 0.15 and 150 respectively, on average there will be 90 new offspring and 22 mutated chromosomes to be evaluated in each generation. So the fraction of the algorithm that is parallel can be approximated as follow:

$$1 - F = \frac{90 + 22}{150} = 0.75, F = 0.25$$

According to Amdahl's law the maximum expected speedup by parallelism on a two processor computer is:

$$\text{Max Speedup} = \frac{1}{0.25 + (1 - 0.25)/2} = 1.6$$

Figure 6.7 shows the comparison of the results for the sequential and parallel runs of the algorithm on a computer with two processors.

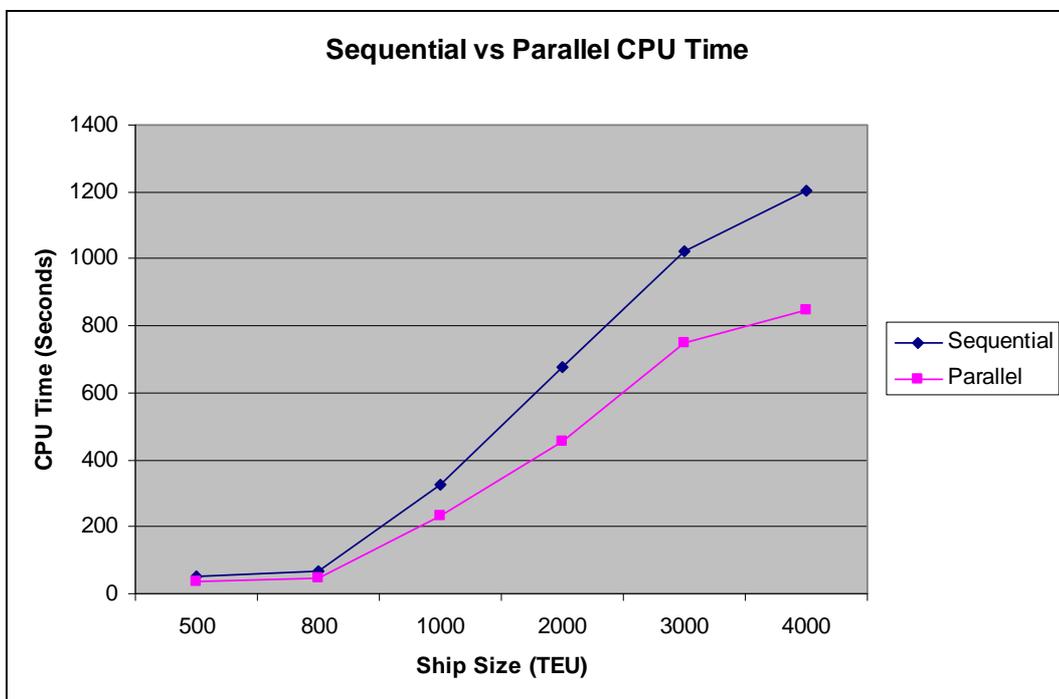


Figure 6.7: Sequential vs. parallel CPU time

Table 6.3 shows an average speedup of 1.44 for these cases. This is 0.16 less than the suggested value by the Amdahl's law. Debrowsky et al (2002) reported a speedup factor of 2.7 on a parallel computer with three processors.

Table 6.3: Summary of the results for sequential and parallel algorithms

Ship Size	CPU Time (Sec)		Speedup
	Sequential	Parallel	
500	54	36	1.50
800	67	46	1.46
1000	324	232	1.40
2000	677	455	1.49
3000	1021	749	1.36
4000	1204	847	1.42

Average Speedup = 1.44

Figure 6.8 illustrates a snapshot of the CPU usage history in two cases. In 6.8 (a) a the sequential algorithm is executed on a two processor machine and in 6.8 (b) the parallel algorithm has run on the same machine. The graphs are obtained from the task manager program in Microsoft Windows XP. It can be seen that in the second case some load is assigned to the additional CPU.

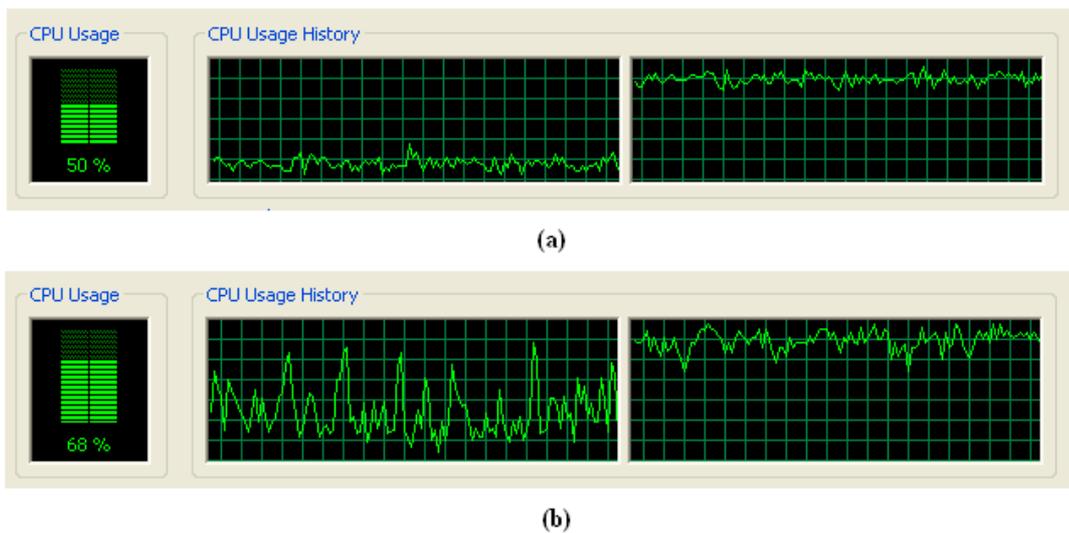


Figure 6.8: Snapshot of CPU usage history (a) sequential (b) parallel

6.3. Lower bound and algorithm performance

While developing heuristic algorithms to solve a minimization problem, having a lower bound helps to measure the deviation of the solution from that of the exact method.

There exist some traditional methods for developing lower bounds:

- Linear relaxation: the integrality constraints for some or all the integer variables are relaxed while the objective functions and other constraints remain intact.
- Lagrangian relaxation: some constraints especially the tight ones are moved to the objective function with a penalty term, where the value and sign of the penalty coefficient depend is determined by the nature of the optimization problem.
- Branch and bound: in the *branching* stage the solution space of the problem is systematically split into smaller sections whose union creates the original space and in the *bounding* stage upper and lower limits are assigned to the split node.

The complexity level of the containership stowage planning comes from the shift constraints to a great extent. The linear relaxation method is not applicable to the containership stowage planning problem since all the key variables in the mathematical model are binary and relaxing the integrality requirements is not an option. The Lagrangian relaxation method was not found to be useful for this problem either. This method requires moving the shift constraints as hard constraints (Eq. 3.15

to 3.20) to the objective function which creates two major issues. First because the shift constraints play a fundamental role in determining the value of the unloading variables as the building blocks of the objective function, their elimination oversimplifies the problem by transforming it to an assignment problem and generates a very loose bound. Second bringing these constraints to the objective function with a penalty term makes the objective function value of the lower bound problem non-comparable with that of the main problem. The branch and bound method cannot be applied because the large number of binary variables even for small problem instances results in an exponential number of branches. Since no contender method among the traditional methods exist, a lower bound formulation based on the specific structure of the containership stowage planning is developed.

NL-LB: A non-linear formulation

The idea of reducing unnecessary shifts in containership stowage planning can be looked at as minimizing *the change in the value of the container location variable* at two consecutive ports for all containers and over all the ports. It means that wherever the container is located in the vessel, it is most desirable to remain at the same location thorough the voyage. Therefore in an ideal situation each container will be loaded and unloaded exactly once. So the objective function can be built by summation of the changes in the location variables for each container between each two immediate port. Modeling this objective function calls for calculating the absolute value of the difference between the binary location variables of the

containers. Since the absolute value function is non-linear, the model will be a nonlinear programming model with quadratic objective function and linear constraints. The shift constraints can be removed from the formulation because the concept of shifts is taken care of in the proposed objective function. However the total number of unloading operations is not accurate and may be less than the actual number. Figure 6.9 depicts an example.

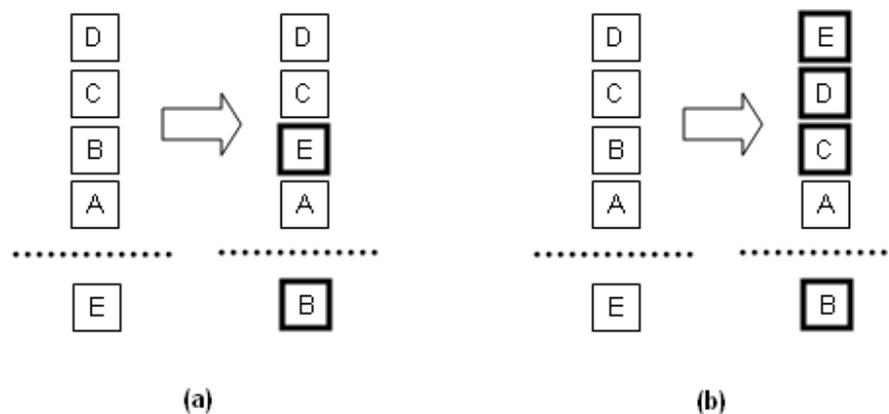


Figure 6.9: Number of unloading operations for the lower bound

Figure 6.8.a and 6.8.b show a single column of a containership in two different situations. Assume that container B has reached its destination, containers A, C and D must stay aboard and container B must be loaded at this port. To unload B, first containers D and C must be unloaded and then loaded back to the vessel. In fig 6.8.a stability and operational constraints have force the new container E to be loaded into the cell that belonged to B. Comparing the before and after snapshot shows that only two containers have changed position and hence the value of the lower bound objective function will be increased by two. On the other hand if like figure 6.8.b the new container is to be loaded at the top of the stack, the comparison of the two

snapshots shows change of the position for four containers. So the total number of container position changes is an estimate of the actual number of unloadings which gives a lower bound to the main problem. In an ideal scenario containers are loaded at the origin port, travel to their destination and get unloaded. So the total number of unloading operations is equal to total number of containers. In this situation the change of the position of each container happens only once at the unloading port and the gap between the lower bound and the optimal problem is nonexistent.

This lower bound model is as follow:

$$\text{Min} \sum_{c=1}^C \sum_{t=O(c)}^{N-1} \sum_{x=1}^X \sum_{y=1}^Y \sum_{z=1}^Z \left| \delta_{c,t}^{x,y,z} - \delta_{c,t'}^{x,y,z} \right| \quad (6.1)$$

Since the variables are binary and because mathematical solver does not recognize the absolute value, the eq. (6.1) can be written as follow:

$$\text{Min} \sum_{c=1}^C \sum_{t=O(c)}^{N-1} \sum_{x=1}^X \sum_{y=1}^Y \sum_{z=1}^Z \left(\delta_{c,t}^{x,y,z} - \delta_{c,t'}^{x,y,z} \right)^2 \quad (6.2)$$

If the objective function of the main problem is considered to minimize the total time at all ports, the value of the lower bound objective function cannot be directly compared with that, so a post processing routine is hired to generate total time at all ports based on the results obtained by solving the non-linear lower bound model.

The constraints for the lower bound model are as follow:

$$\sum_{x=1}^X \sum_{y=1}^Y \sum_{z=1}^Z \delta_{c,t}^{x,y,z} = 1 \quad \forall c, t \in [O(c)..D(c)-1] \quad (6.3)$$

$$\sum_{x=1}^X \sum_{y=1}^Y \sum_{z=1}^Z \sum_{t=D(c)}^N \delta_{c,t}^{x,y,z} = 0 \quad \forall c \quad (6.4)$$

$$\sum_{x=1}^X \sum_{y=1}^Y \sum_{z=1}^Z \sum_{t=1}^{O(c)-1} \delta_{c,t}^{x,y,z} = 0 \quad \forall c \quad (6.5)$$

$$\sum_{c=1}^C \delta_{c,t}^{x,y,z} \leq 1 \quad \forall x, y, z, t \quad (6.6)$$

$$\sum_{c=1}^C \delta_{c,t}^{x,y,z} - \sum_{c=1}^C \delta_{c,t}^{x,y,z+1} \geq 0 \quad \forall x, y, z \in [1..Z-1], t \quad (6.7)$$

$$\left| \sum_{c=1}^C \sum_{x=1}^X \sum_{y=1}^{\lfloor Y/2 \rfloor} \sum_{z=1}^Z \delta_{c,t}^{x,y,z} \cdot W(c) - \sum_{c=1}^C \sum_{x=1}^X \sum_{y=\lceil Y/2 \rceil}^Y \sum_{z=1}^Z \delta_{c,t}^{x,y,z} \cdot W(c) \right| \leq LRB \quad \forall t \quad (6.8)$$

$$\left| \sum_{c=1}^C \sum_{x=1}^{\lfloor X/2 \rfloor} \sum_{y=1}^Y \sum_{z=1}^Z \delta_{c,t}^{x,y,z} \cdot W(c) - \sum_{c=1}^C \sum_{x=\lceil X/2 \rceil}^X \sum_{y=1}^Y \sum_{z=1}^Z \delta_{c,t}^{x,y,z} \cdot W(c) \right| \leq BSB \quad \forall t \quad (6.9)$$

$$\sum_{c=1}^C \sum_{x=1}^X \sum_{y=1}^Y \delta_{c,t}^{x,y,z} \cdot W(c) \leq \sum_{c=1}^C \sum_{x=1}^X \sum_{y=1}^Y \delta_{c,t}^{x,y,z-1} \cdot W(c) \quad \forall t, z \in [2..Z] \quad (6.10)$$

$$\sum_{c=1}^C \sum_{x=1}^X \sum_{y=1}^Y \sum_{z=1}^Z \delta_{c,t}^{x,y,z} \cdot W(c) \leq W_{Max}(t) \quad \forall t \quad (6.11)$$

$$\sum_{c=1}^C \sum_{x=1}^X \sum_{y=1}^Y \delta_{c,t}^{x,y,z} \cdot W(c) \leq W_{Column} \quad \forall z, t \quad (6.12)$$

The solver CPLEX is capable of solving non-linear optimization models if the objective function is quadratic and the constraints are linear. The generated lower bound model was solved by CPLEX and experiments show that although this method

creates very promising lower bounds for small size problems, it is not useful to find lower bound to larger problems because the solver is not capable of reaching a solution in a timely manner for such problems. Table 6.3 shows the optimal value of the objective function, the gap compared to the lower bound generated by linear relaxation and the gap measured from the lower bound generated by nonlinear formulation for selected problems. Examples 4.2.1 and 4.2.2 and 4.2.4 that were discussed earlier in chapter four are used.

Table 6.3: Comparison between lower bound and optimal objective function value for sample problems

Problem	Objective function	Lower bound by linear relaxation	Lower bound by NL-LB formulation
4.2.1	20	19 (5% gap)	20 (0% gap)
4.2.2	21	19 (10% gap)	21 (5% gap)
4.2.4 case 1	42	38 (9.5% gap)	39 (7.1 % gap)
4.2.4 case 3	41	38 (7.3 %gap)	39 (4.8% gap)

Chapter 7: Sample containership load planning problems

During the course of this research many attempts were made to obtain real containership stowage planning and origin destination data from the shipping lines. Unfortunately the industry refused to share data and thus measuring the actual benefit of applying the proposed algorithm to the real world practice cannot be made at this point. However the algorithm can be applied to simulated data of realistic size and the results can be compared with base case scenarios to demonstrate the potential benefits of using the solution approach. This chapter provides several examples all of which generated using the procedure discussed in 6.1.

7.1. Indented berth terminal operations

There are two fundamental approaches to deal with the challenge of handling large container vessels. The first approach is to increase the capacity of quay cranes which can be done through methods such as double cycling or double lifting or both. The second approach is to increase the capacity of the quay side interface. This requires implementation of indented berth or use of floating cranes which both allow handling containers from either side of the vessel. A floating crane is a quay crane mounted on a pontoon that can be self propelled. A number of barges or feeders are needed to support the floating cranes in moving the containers from/to the vessel. Therefore structural change in the berth system is not necessary in the case of floating cranes. The indented berth on the other hand has twice as much quay wall as compared to a traditional berth and can deploy up to twice as many cranes on a vessel. Figure 7.1

shows the layout of an indented berth. Since the vessel is handled from both sides the chance of quay side congestion decreases significantly. The system is designed to accommodate large vessels, so if small vessels are served, the infrastructure will be underutilized.

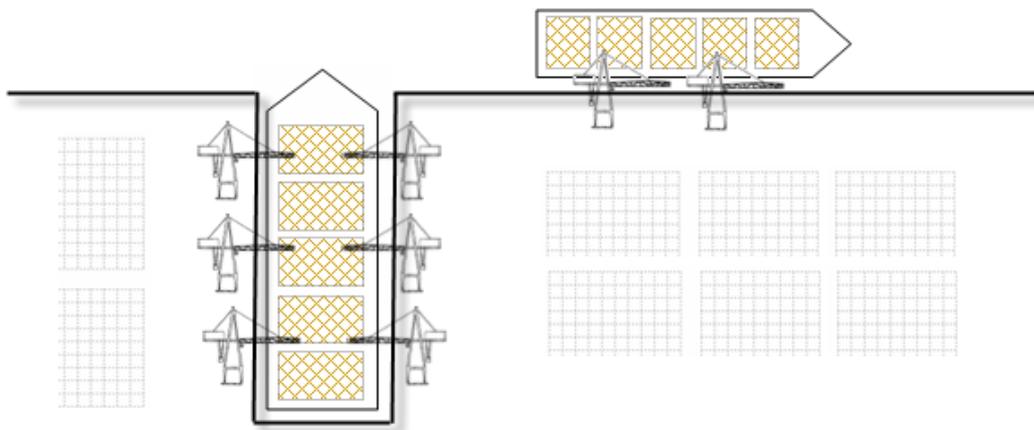


Figure 7.1: Indented berth vs. traditional berth

Figure 7.2 shows a containership at the Ceres Paragon container terminal at the port of Amsterdam. To increase the efficiency of the port system, besides optimal berth allocation decisions that must be made prior to the arrival, it is important to arrange the containers in the vessel in accordance with the configuration of the allocated cranes. Previous stowage planning algorithms do not account for the configuration of the cranes and thus they do not treat the indented berth terminal planning differently. An example is used to demonstrate the advantages of using the proposed solution approach in an indented berth operation.



Figure 7.2: A vessel entering the Ceres Paragon terminal at port of Amsterdam (photo courtesy <http://www.portofamsterdam.nl>)

To show the effect of considering crane split into stowage planning a 2000 TEU container ship is used as an example. This ship visits five ports to transport 3385 containers. The third port is equipped with an indented berth system. Configuration of the cranes and the transportation matrix are presented in figure 7.3 and table 7.1 respectively. The weights of the containers are generated randomly in the range of 1-20 tone. Trim, tilt and vertical stability constraints with a maximum 1% tolerance are observed. “The technical performance of the cranes is in the range of 50-60 box/hr, while in operation the performance is in the range of 22-30 box/h” (Steenkan et al. 2004). For simplicity and without lack of generality it is assumed that all cranes are identical and each can handle 25 containers per hour.

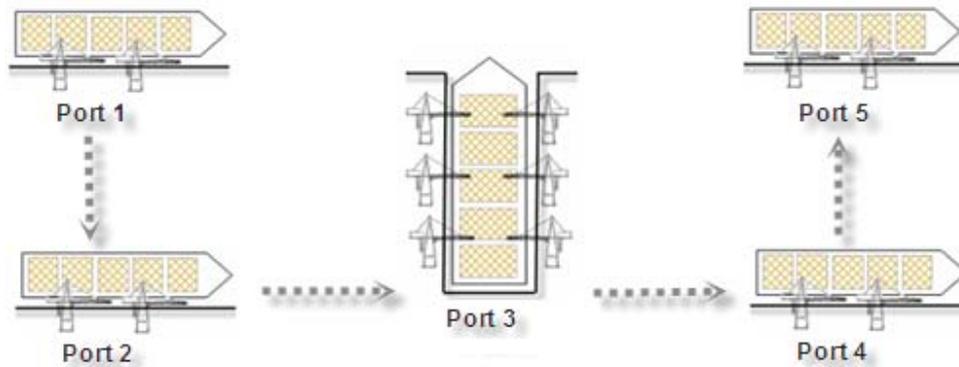


Figure 7.3: The shipping route and configuration of cranes at marginal and indented berth terminals

Table 7.1: Transportation matrix for indented berth operations problem

		Destination			
		2	3	4	5
Origin	1	463	141	308	685
	2		217	155	319
	3			270	155
	4				672

This example is solved for two scenarios. The objective function of scenario I and II are minimization of total berthing time and minimization of total shifts respectively. Table 7.2 shows the results for each scenario. According to this table, because of the proper horizontal distribution of the containers in scenario I, the utilization of individual cranes - which is the crane busy time over total time at port - and also average utilization of the cranes at each port is improved in 4 out of 5 ports. In scenario I, the vessel spend more time for rearranging the containers in the indented berth at port 3 compared to scenario II, however significant savings in berthing time

at port 4 will be achieved. These improvements may come at cost of more container movements.

Table 7.2: Solution results for indented berth operations problem

Scenario	Port														
	1		2		3						4		5		
	Crane		Crane		Crane						Crane		Crane		
	1	2	1	2	1	2	3	4	5	6	1	2	1	2	
I	# Containers	597	1000	651	641	415	391	359	375	366	343	723	743	918	913
	Utilization (%)	60	100	100	98	100	94	87	90	88	83	97	100	100	99
	Port Time (hr)	40		26.04		16.6						29.72		36.72	
	Avg. utilization	80.0%		99.0%		90.3%						98.5%		99.5%	
II	# Containers	1000	597	631	661	175	144	265	107	256	214	808	1048	927	904
	Utilization (%)	100	60	95	100	66	54	100	40	97	81	77	100	100	98
	Port Time (hr)	40		26.44		10.6						41.92		37.08	
	Avg. utilization	80.0%		97.5%		73.0%						88.5%		99.0%	

Table 7.3: Summary of the results for two indented berth operations scenarios

	Total Container Handling	Total Berthing Time (hr)	Overall Crane Utilization
I	5050	149.08	93.5%
II	4352	156.04	83.4%

Although total number of container handlings has gone up by 16% in scenario I compared to II, 4% reduction in total berthing time is gained which is the result of 12% improvement in overall crane utilization.

7.2. Technical and economical considerations in container load operations

In all the examples discussed so far, it was assumed that all cranes have similar performance. All approaches in the literature have either made the same assumption or have not accounted for the impact of crane operations on the stowage planning at

all. However in the real world operations this is not the case meaning that technical specifications of the quay cranes differ over container terminals. Although it is not very common but practically the performance of the quay cranes on a given terminal may also be different. Our proposed formulation and solution algorithm is capable of accounting for the performance of quay cranes. Consider a containership that visits five ports and two cranes are available at each port. If all cranes have the same performance, the objective function of the problem will minimize the total turnaround time at all ports by optimizing the arrangement of the containers into the vessel with respect to the crane utilization and other operation constraints as discussed earlier. Now let us assume that the second port upgrades its cranes with the latest technology that makes each crane twice as fast. This means that handling time of each container will be cut into half at this port. The solution algorithm can take advantage of this feature by rearranging more containers at the second port to reduce the time needed for the rearrangement at the forthcoming ports if this contributes to overall improvement of total turnaround time. Similarly if in any of the given terminals, some of the cranes have a higher performance compared to the other ones there may be possibility of reducing total turnaround time by assigning more work to the higher performance cranes.

Based on the same argument, by converting time into money one can change the objective function of the problem to a function of economic value. So if the time unit spent at a given port is more expensive than others the ship planners may save money by spending time to rearrange containers in cheaper ports in order to spend less time and money in expensive ports. So although the total time spent at all ports and the

total number of container handlings may be higher than the original solution, however the total cost of all operations could be lower. The following examples investigate these scenarios.

The 2000 TEU containership introduced in section 7.1 is used in this example. The vessel visits five ports, each of which make two quay cranes available. The transportation matrix is based on table 7.1. Stability constraints including horizontal and longitudinal equilibrium with 5% threshold are enforced. Also, weight of each tier must not exceed the weight of its underlying tier with an acceptable 1% tolerance. First, we set the objective function to minimize total turnaround time. We assume that cranes at all ports are of the same type and it takes four time units to move a container by each crane. Table 7.4 shows the summary of results including number of container shifts mandated by overstorage and turnaround time. As the table shows containers will only be shifted at the intermediate ports, because at the first and last port only loading and unloading happens respectively.

Table 7.4: Summary results for universal crane characteristics

	Port 1		Port 2		Port 3		Port 4		Port 5		Total
Crane	1	2	1	2	1	2	1	2	1	2	
No of containers	797	800	648	667	454	431	721	742	916	915	
Time unit	3188	3200	2592	2668	1816	1724	2884	2968	3664	3660	
Container shifts	0		161		102		58		0		321
Turnaround time	3200		2668		1816		2968		3664		14316

Now we assume that the two cranes at the third port are upgraded, such that each crane can handle a container in two time units. In other words cranes at port three are

twice as fast as the rest of the cranes. Table 7.5 shows the summary of results for this case. As shown in the table, the number of container moves by the cranes at port 3 has increased drastically by 174%, however the total turnaround time is reduced by 3.4%.

Table 7.5: Summary results for different crane types at port 3

	Port 1		Port 2		Port 3		Port 4		Port 5		Total
Crane	1	2	1	2	1	2	1	2	1	2	
No of containers	800	797	593	626	776	790	721	715	914	917	
Time unit	3200	3188	2372	2504	1552	1580	2884	2860	3656	3668	
Container shifts	0		65		783		31		0		
Turnaround time	3200		2504		1580		2884		3668		13836

If we change the cranes at port three again, and make them four times as fast as the rest of the cranes, each container handling will take one time unit by those cranes. With all other assumptions remaining intact, the results for this case are reported in table 7.6.

Table 7.6: Summary results for deployment of improved cranes at port 3

	Port 1		Port 2		Port 3		Port 4		Port 5		Total
Crane	1	2	1	2	1	2	1	2	1	2	
No of containers	800	797	589	605	827	814	719	702	916	915	
Time unit	3200	3188	2356	2420	827	814	2876	2808	3664	3660	
Container shifts	0		40		858		16		0		
Turnaround time	3200		2240		827		2876		3664		12987

Comparison with the case that all cranes are uniform shows 9% improvement in total turnaround time that comes with 187% in container shifts. As it is shown in tables 7.4 through 7.6, the algorithm tries to reshuffle the containers at the port with faster cranes, in exchange of saving container shifts at the second and the fourth port. From the economical perspective if the shipping line is charged by time, having extra container moves at port three in the cases that upgraded cranes are available is advised. Otherwise if the ports charge per container handling basis, solution for minimizing total container moves should be used. In any case, the algorithm is flexible to create appropriate stowage and loading plan with respect to technical and economical considerations.

7.3. Container load planning for mega containerships

Like many other industries, transportation companies benefit from economies of scale in maritime shipping. Since the cost per TEU reduces with the increase of the capacity, there is a powerful trend to build larger vessels. The growth in capacity comes with increasing challenges to cope with large amount of containers to be transshipped in short periods of time, as the port time is an expensive resource. According to the Journal of Commerce, 42 ultra large container carriers (with a capacity of more than 10,000 TEU) are in operation in the world's seas by August 2010⁴. One of the day to day problems to be solved is stowage planning for mega containerships. To show the capability of the proposed algorithm for dealing with real-size instances of stowage planning for mega containerships, a sample problem for a 12,000 TEU containership in a five port voyage is generated. There are 21,191

⁴ 100th mega containership in Rotterdam, The Journal of Commerce Online, Aug 2010, <http://www.joc.com/press-release/100th-mega-container-ship-rotterdam> last visited: 3/27/2011

containers in total with different weights to be transported in this example. The vessel has 40 bays, 20 rows and each stack can hold 15 containers. There are four quay cranes assigned at the first and second port, six quay cranes at the third and fourth port and five cranes will empty the ship at the last port. Real life operational constraints are imposed in this example. Horizontal and longitudinal stability must be met and total weight of each tier must not exceed the weight of the immediate tier underneath. A threshold of 5% is applied for both horizontal and longitudinal imbalance. Finally to make the problem challenging, in each column the weight of the top containers must be less than or equal to the weight of the bottom containers with a 5% acceptable weight difference. It is assumed that handling a container by each crane takes 1.5 minutes. Table 7.7 shows the summary of the transportation matrix. Table 7.8 shows a portion of the origin, destination and weight data for the containers. Since the complete data is more than 100 pages, complete data file is made available online for download⁵.

Table 7.7: Transportation matrix for a 12,000 TEU containership

		Destination			
		2	3	4	5
Origin	1	2041	3212	1188	3156
	2		645	750	3048
	3			1355	1731
	4				4065

In total 48,329 crane moves are done in this example which involves 5,974 container moves mandated by overstorage. Overall utilization rate for cranes at all ports is

⁵ http://www.eng.umd.edu/~masoud/dissertation_data

Table 7.8: Part of container data for a mega containership example⁶

No	O	D	W	No	O	D	W	No	O	D	W	No	O	D	W	No	O	D	W
1	1	2	27	2042	1	3	45	5254	1	4	78	9168	1	5	19	9964	2	3	39
2	1	2	15	2043	1	3	90	5255	1	4	94	9169	1	5	25	9965	2	3	95
3	1	2	11	2044	1	3	41	5256	1	4	63	9170	1	5	21	9966	2	3	92
4	1	2	73	2045	1	3	46	5257	1	4	89	9171	1	5	35	9967	2	3	55
5	1	2	32	2046	1	3	71	5258	1	4	37	9172	1	5	18	9968	2	3	27
6	1	2	95	2047	1	3	47	5259	1	4	42	9173	1	5	59	9969	2	3	18
7	1	2	47	2048	1	3	56	5260	1	4	60	9174	1	5	38	9970	2	3	35
8	1	2	53	2049	1	3	82	5261	1	4	72	9175	1	5	20	9971	2	3	86
9	1	2	26	2050	1	3	41	5262	1	4	94	9176	1	5	37	9972	2	3	53
10	1	2	99	2051	1	3	27	5263	1	4	66	9177	1	5	48	9973	2	3	3
11	1	2	60	2052	1	3	63	5264	1	4	74	9178	1	5	91	9974	2	3	62
12	1	2	27	2053	1	3	50	5265	1	4	24	9179	1	5	52	9975	2	3	97
13	1	2	56	2054	1	3	5	5266	1	4	84	9180	1	5	37	9976	2	3	27
14	1	2	16	2055	1	3	34	5267	1	4	50	9181	1	5	30	9977	2	3	39
15	1	2	15	2056	1	3	79	5268	1	4	5	9182	1	5	23	9978	2	3	68
16	1	2	51	2057	1	3	15	5269	1	4	14	9183	1	5	36	9979	2	3	48
17	1	2	41	2058	1	3	15	5270	1	4	55	9184	1	5	21	9980	2	3	42
18	1	2	93	2059	1	3	74	5271	1	4	11	9185	1	5	85	9981	2	3	10
19	1	2	86	2060	1	3	94	5272	1	4	47	9186	1	5	98	9982	2	3	71
20	1	2	82	2061	1	3	18	5273	1	4	83	9187	1	5	99	9983	2	3	20
21	1	2	62	2062	1	3	81	5274	1	4	26	9188	1	5	19	9984	2	3	2
22	1	2	12	2063	1	3	45	5275	1	4	50	9189	1	5	44	9985	2	3	54
23	1	2	13	2064	1	3	58	5276	1	4	12	9190	1	5	52	9986	2	3	15
24	1	2	95	2065	1	3	8	5277	1	4	20	9191	1	5	60	9987	2	3	10
25	1	2	22	2066	1	3	15	5278	1	4	4	9192	1	5	68	9988	2	3	21
26	1	2	61	2067	1	3	36	5279	1	4	71	9193	1	5	76	9989	2	3	12
27	1	2	43	2068	1	3	60	5280	1	4	50	9194	1	5	91	9990	2	3	8
28	1	2	52	2069	1	3	90	5281	1	4	87	9195	1	5	76	9991	2	3	65
29	1	2	94	2070	1	3	52	5282	1	4	68	9196	1	5	77	9992	2	3	69
30	1	2	23	2071	1	3	45	5283	1	4	10	9197	1	5	59	9993	2	3	95
31	1	2	78	2072	1	3	18	5284	1	4	78	9198	1	5	55	9994	2	3	1
32	1	2	39	2073	1	3	55	5285	1	4	47	9199	1	5	36	9995	2	3	71
33	1	2	35	2074	1	3	56	5286	1	4	41	9200	1	5	58	9996	2	3	65
34	1	2	31	2075	1	3	41	5287	1	4	96	9201	1	5	43	9997	2	3	44
35	1	2	85	2076	1	3	18	5288	1	4	34	9202	1	5	47	9998	2	3	90
38	1	2	8	2079	1	3	10	5291	1	4	23	9205	1	5	23	10001	2	3	46

⁶ No: container identification number, O: origin port, D: destination port, W: container weight

83%. Table 7.9 shows the details of crane split solution based on the operating range of each crane, the number of containers handled by each crane and the crane utilization rates. In total the vessel spends 291.7 hour at all ports. The solution for this case was obtained in 62957 seconds (17.5 hours) on a computer running Microsoft Windows XP 32 bit with two Core Duo 2.66 GHz CPUs and 2 GB of RAM. The parallel implementation of the algorithm was used.

Table 7.9: Crane split and utilization rates for 12,000 TEU containership

		Crane number					
Port		1	2	3	4	5	6
1	Operation bay range	1-11	12-20	21-29	30-40	N/A	N/A
	No. of containers handled	2100	2700	2700	2097		
	Utilization rate per crane	78%	100%	100%	78%		
	Average utilization rate	89%					
	Time at port (hours)	67.5					
2	Operation bay range	1-10	11-20	21-30	31-40	N/A	N/A
	No. of containers handled	1200	2305	1794	1199		
	Utilization rate per crane	52%	100%	78%	52%		
	Average utilization rate	70%					
	Time at port (hours)	57.6					
3	Operation bay range	1-6	7-13	14-18	19-24	25-30	31-40
	No. of containers handled	1043	904	1980	2058	2079	1161
	Utilization rate per crane	50%	43%	95%	99%	100%	56%
	Average utilization rate	74%					
	Time at port (hours)	52					
4	Operation bay range	1-6	7-13	14-18	19-24	25-29	30-40
	No. of containers handled	1281	1703	1883	2184	1877	2081
	Utilization rate per crane	59%	78%	86%	100%	86%	95%
	Average utilization rate	84%					
	Time at port (hours)	54.6					
5	Operation bay range	1-8	9-16	17-24	25-32	33-40	N/A
	No. of containers handled	2400	2400	2400	2400	2400	2400
	Utilization rate per crane	100%	100%	100%	100%	100%	100%
	Average utilization rate	100%					
	Time at port (hours)	60					

The program also generates the details for placement of individual containers as well as operations of each crane including loading, shifting and unloading a container. Table 7.10 shows a portion of the output for the above example. Since complete output is over 500 pages, the complete solution for interested reader is made available online⁷. In table 7.10, the first column provides container information including container identification number, origin and destination port of the container and the cell assignment information including bay, row and column. In the second column when one of the letters “L”, “U” or “S” are followed by a number it means that the container will be “Loaded”, “Unloaded” or “Shifted” by the crane number that appears after the indicating letter. The port in which crane operation happens is shown by letter “P” followed by the port number. So the first row in table 7 shows that container number 10864 which originated from port 2 and is destined to port 4, is assigned to the column located at bay 3, row 1 and the vertical position of the container in the column is 5 from bottom. This container is loaded to the assigned cell by crane 1 in port 2. Later on in port 4 the container is unloaded by crane 1. This container does not need to be shifted throughout the voyage. On the other hand container 10865 that goes from port 2 to port 4, is assigned to the column at bay 3 and row 7 which is the third container in the column. This container is loaded by crane 1 at port 2, and must be shifted by the crane 1 at port 3. As a result of the shift, this container will be relocated to bay 37, row 18. At the destination port the container will be unloaded by crane 6. In total 44824 instructions for container placement and handling are generated by the program. The results can be communicated electronically to the port authorities, ship planer and other parties involved in XML

⁷ http://www.eng.umd.edu/~masoud/dissertation_data

format. A graphical representation of the complete solution for the mega containership is provided in Appendix C.

Table 7.10: Partial solution details for 12,000 TEU containership load plan

Container information	Crane operations			
#10864 [2,4] (3,1,5)	L1	P2		
#10864 [2,4] (3,1,5)	U1	P4		
#10865 [2,4] (3,7,3)	L1	P2	S1	P3
#10865 [2,4] (37,18,2)	U6	P4		
#10866 [2,4] (4,3,12)	L1	P2	S1	P3
#10866 [2,4] (23,4,11)	U4	P4		
#10867 [2,4] (1,6,10)	L1	P2		
#10867 [2,4] (1,6,10)	U1	P4		
#10868 [2,4] (21,19,11)	L3	P2	S4	P3
#10868 [2,4] (13,11,10)	U2	P4		
#10869 [2,4] (22,17,9)	L3	P2	S4	P3
#10869 [2,4] (27,13,8)	U5	P4		
#10870 [2,4] (20,19,11)	L2	P2	S4	P3
#10870 [2,4] (27,14,10)	U5	P4		
#10871 [2,4] (40,6,1)	L4	P2		
#10871 [2,4] (40,6,1)	U6	P4		
#10872 [2,4] (40,13,14)	L4	P2	S6	P3
#10872 [2,4] (29,11,12)	U5	P4		
#10873 [2,4] (3,9,13)	L1	P2	S1	P3
#10873 [2,4] (13,17,11)	U2	P4		
#10874 [2,4] (21,12,5)	L3	P2		
#10874 [2,4] (21,12,5)	U4	P4		
#10875 [2,4] (3,16,7)	L1	P2	S1	P3
#10875 [2,4] (13,14,6)	U2	P4		
#10876 [2,4] (38,10,12)	L4	P2	S6	P3
#10876 [2,4] (27,13,10)	U5	P4		
#10877 [2,4] (21,12,3)	L3	P2		
#10877 [2,4] (21,12,3)	U4	P4		

7.4. Stability constraints and container load planning

In order to show the impact of enforcing stability constraints - specifically vertical stability - on the problem complexity, the example in section 7.3 is used. The

constraints concerning the weight of individual containers and the weight of tiers are relaxed in this case while the number of visiting ports, availability of the cranes and list of containers remain the same. Similar to the previous case, the horizontal and longitudinal imbalance threshold is set to 5%. In total 42,387 crane moves are involved in this example which calls for only five container moves mandated by over stowage. Overall utilization rate for cranes at all ports is 89%. Table 7.11 shows the details of crane split and utilization rate. Total turnaround time at all ports is 243.2 hours. The problem was solved on the same computer as described in previous section and the solution was obtained in 13776 seconds (3.8 hours).

A comparison between these two examples shows that relaxing the vertical stability constraints has reduced the solution time from 17.5 hours to 3.8 hours (78% reduction). The total ship turnaround time is also reduced from 291.7 hours to 243.2 hours (17% reduction). This is a result of a sharp decline in number of container shifts from 5974 to 5, however in 16285 occasions heavy containers are sitting on top of lighter containers in the latter example. Increasing the height of stack and tightening the vertical stability constraints dramatically impacts the complexity, running time and structure of the solution. A comparison between tables 7.10 and 7.11 shows how the arrangements of the quay cranes are adjusted according to the problem characteristics.

Table 7.11: Crane split and utilization rates for 12,000 TEU containership without vertical stability constraints

		Crane number					
Port		1	2	3	4	5	6
1	Operation bay range	1-10	11-20	21-30	31-40	N/A	N/A
	No. of containers handled	2400	2400	2397	2400		
	Utilization rate per crane	100%	100%	100%	100%		
	Average utilization rate	100%					
	Time at port (hours)	60					
2	Operation bay range	1-10	11-21	22-30	31-40	N/A	N/A
	No. of containers handled	1500	1676	1620	1688		
	Utilization rate per crane	89%	99%	96%	100%		
	Average utilization rate	96%					
	Time at port (hours)	42.2					
3	Operation bay range	1-6	7-12	13-18	19-24	25-31	32-40
	No. of containers handled	907	1062	1170	1140	1154	1514
	Utilization rate per crane	60%	70%	77%	75%	76%	100%
	Average utilization rate	76%					
	Time at port (hours)	37.9					
4	Operation bay range	1-6	7-12	13-18	19-25	26-31	32-40
	No. of containers handled	907	1038	1092	1245	1350	1727
	Utilization rate per crane	53%	60%	63%	72%	78%	100%
	Average utilization rate	71%					
	Time at port (hours)	43.2					
5	Operation bay range	1-8	9-16	17-24	25-32	33-40	N/A
	No. of containers handled	2400	2400	2400	2400	2400	2400
	Utilization rate per crane	100%	100%	100%	100%	100%	100%
	Average utilization rate	100%					
	Time at port (hours)	60					

To study the impact of partial vertical stability enforcement, we keep the horizontal and latitudinal constraints and only enforce the tier weight imbalance constraints. That is total weight of the containers in each tier must be less than or equal to the total weight of the containers in the tier immediately under it. The results for this case are reported in table 7.12.

Table 7.12: Crane split and utilization rates for 12,000 TEU containership with partial vertical stability constraints

		Crane number					
Port		1	2	3	4	5	6
1	Operation bay range	1-10	11-20	21-30	31-40	N/A	N/A
	No. of containers handled	2400	2400	2400	2397		
	Utilization rate per crane	100%	100%	100%	100%		
	Average utilization rate	100%					
	Time at port (hours)	60					
2	Operation bay range	1-9	10-20	21-30	32-40	N/A	N/A
	No. of containers handled	1590	1580	1627	1717		
	Utilization rate per crane	93%	92%	95%	100%		
	Average utilization rate	95%					
	Time at port (hours)	42.9					
3	Operation bay range	1-6	7-12	13-18	19-24	25-31	32-40
	No. of containers handled	974	1089	1144	1163	1303	1645
	Utilization rate per crane	59%	66%	70%	71%	79%	100%
	Average utilization rate	74%					
	Time at port (hours)	41.1					
4	Operation bay range	1-6	7-12	13-18	19-24	25-31	32-40
	No. of containers handled	981	1130	1264	1292	1871	1372
	Utilization rate per crane	52%	60%	68%	69%	100%	73%
	Average utilization rate	70%					
	Time at port (hours)	46.8					
5	Operation bay range	1-8	9-16	17-24	25-32	33-40	N/A
	No. of containers handled	2400	2400	2400	2400	2400	2400
	Utilization rate per crane	100%	100%	100%	100%	100%	100%
	Average utilization rate	100%					
	Time at port (hours)	60					

The running time for this case is 17765 seconds (4.9 hours). Total ship turnaround time is 250.8 hours and 957 container shifts are required. In 11,304 cells, individual heavy containers are placed on top of lighter containers in a column. Table 7.13 provides a summary of the results for the three cases discussed in this section.

Table 7.13: Comparison of stability constraint enforcement policies on 12,000 TEU
containership load planning

Constraints imposed	Imbalance threshold	Running time (hours)	Total turnaround time (hours)	Average crane utilization rate	Total container shifts	Total heavy-on- light cases
Horizontal stability	5%	17.5	291.7	83%	5974	0
Longitudinal stability	5%					
Tier weight stability	5%					
Container weight	5%					
Horizontal stability	5%	4.9	250.8	88%	957	11304
Longitudinal stability	5%					
Tier weight stability	5%					
Horizontal stability	5%	3.8	243.2	89%	5	16285
Longitudinal stability	5%					

7.5. Changes in the demand and container load planning

In all the examples solved so far, it was assumed that the transportation matrix is known and given prior to the ship's departure. We also started from an empty vessel at the first port. However due to the nature of real operations, the demand is subject to uncertainty and may change. The following example presents a case that involves change in the origin-destination matrix after the departure of the vessel. In order to address the issue, we solve the problem again for the forthcoming ports, by starting from an initial existing solution as opposed to having an empty vessel. Since the

solution approach is agile enough, by solving the problem iteratively throughout the operations, the stowage pattern can be adjusted based on the changes in the container list. However, we assume that demand fluctuation does not make the problem infeasible, such that the demand does not exceed the capacity of the vessel at any port.

Consider a 2000 TEU containership visiting five ports with the initial transportation matrix shown in Table 7.14. Stability constraints including horizontal and longitudinal equilibrium with 5% threshold are enforced for 4240 containers. Also, weight of each tier must not exceed the weight of its underlying tier with an acceptable 5% tolerance. Containers have different weight with a random distribution and each port has two cranes available. Table 7.15 shows a summary of the results.

Table 7.14: Initial transportation matrix

		Destination			
		2	3	4	5
Origin	1	567	51	594	387
	2		477	276	214
	3			285	138
	4				1251

Table 7.15: Summary results for all ports using original demand

	Port 1		Port 2		Port 3		Port 4		Port 5		Total
	1	2	1	2	1	2	1	2	1	2	
Crane	1	2	1	2	1	2	1	2	1	2	
No of containers	800	799	771	789	471	453	1252	1236	991	1009	
Container shifts	0		26		27		72		0		125
Turnaround time	800		789		471		1252		1009		4321

Now we assume that after leaving the first port, demand for shipping containers from port three to port five drops by 100 containers. The new transportation matrix is shown in Table 7.16.

Table 7.16: Modified transportation matrix

		Destination			
		2	3	4	5
Origin	1	567	51	594	387
	2		477	276	214
	3			285	38
	4				1251

Having fixed the stowage pattern for the first port, Table 7.16 shows the summary of results after solving the problem for ports two through five.

Table 7.17: Summary results for four ports using modified demand

	Port 1		Port 2		Port 3		Port 4		Port 5		Total
	1	2	1	2	1	2	1	2	1	2	
Crane	1	2	1	2	1	2	1	2	1	2	
No of containers	800	799	766	788	414	409	1250	1235	943	957	
Container shifts	0		20		26		69		0		115
Turnaround time	800		788		414		1250		957		4209

The containers that were removed from the demand were chosen randomly and comparison between tables shows that number of container shifts is decreased by 10 crane moves. Have we had the modified transportation matrix before the operation starts, we could have solved the problem for all ports based on the new demand.

Table 7.18 shows the summary of results based on this assumption.

Table 7.18: Summary results for all ports using modified demand

	Port 1		Port 2		Port 3		Port 4		Port 5		Total
Crane	1	2	1	2	1	2	1	2	1	2	
No of containers	800	799	770	784	413	410	1243	1230	946	954	
Container shifts	0		16		26		57		0		99
Turnaround time	800		784		413		1243		954		4194

As tables 7.17 and 7.18 show, both total turnaround time and number of container shifts are slightly higher when solution is adjusted amid the operation. In other words in this example the cost of not having perfect information from the beginning of the planning stage is 15 time units and 16 container moves.

Chapter 8: Summary and future research

Because of the tense competition among ports in recent years, improving the operational efficiency of ports has become an important issue in containership operations. One of the major performance measures is the berthing time at a port. Arrangement of containers both within the container terminal and on the containership play a vital role in determining the berthing time. The berthing time of a containership is mainly composed of the unloading and loading time of containers. Containers are loaded to and unloaded from the containership using quay cranes. The problem of allocating quay cranes to ship's sections is known as crane split. In some cases up to ten quay cranes might be allocated to a ship. Technical requirements determine the range in which each quay crane can operate. The ship's turnaround time is determined by the time that the last allocated crane finishes its job. Since the distribution of containers over the bays affects crane utilization and overall ship berthing time, crane split and stowage problem are interrelated. Given the configuration of cranes at each visiting port, stowage planning must take into account the utilization of quay cranes as well as the reduction of unnecessary shifts simultaneously to minimize the total time at ports over the voyage. Integration of the stowage plan and the crane split results in a more efficient working instruction which increases overall port utilization.

There are many operational regulations in the real world operation. Some of them apply to only certain type of containerships. The designed solution approach should adopt these operation requirements. Stability constraints are of the greatest importance. The trim of the vessel which is the difference in the height of waterline

between bow and stern must not exceed a given threshold. The containers on the bow side create a positive tilt while the containers at the stern side create a negative one. Total longitudinal tilt is the summation of these two tilts, the closer it gets to zero the better the trim is. Same calculations are valid for horizontal stability which is the difference between the tilt created by the containers of the left and the ones on the right side of the ship. Although the imbalance between left and right, bow and stern can be adjusted using ballast water to some extent, it will affect both the draft and the performance of the ship and may result in more fuel consumption. Vertical stability rules require that the weight on each tier must be greater or equal than the weight on the tier immediately over it. There also might be some limitations on the total weight of a single column, such as heavy containers must not be put on top of lighter ones. This is the reason that all empty containers are loaded above deck. Finally the total weight of the cargo must comply with the maximum allowed draft which is the depth of vessel below water, therefore at some ports the ship may not be loaded at full capacity.

This dissertation presented an integer programming model and a genetic algorithm which focuses on the containership load planning problem during a voyage. A new compact and efficient encoding based on sorting and assignment policy is introduced. The evaluation procedure of the GA decodes and calculates the value of desired elements of objective function based on the encoded solution. Objective function of the problem is different from those of traditional stowage planning problems in the sense that it tries to minimize the total time spent at all ports by minimizing shifts and maximizing crane utilization simultaneously.

The solution approach is very flexible and can easily embrace real world constraints and parameters such as stability and operational constraints, consideration of various cost of time at ports and technical specifications of quay cranes. Solutions obtained by GA are compared with the ones from the exact solvers for small size problems and in all cases the GA solutions are optimal. However this does not mean that the method guarantees optimality. A non linear lower bound model is presented. Results of other numerical experiments show that a feasible solution can be reached within a reasonable time for practical problems. The numerical experiments affirm that significant savings in overall ship turnaround time at ports can be achieved by considering stowage planning and crane utilization simultaneously. A parallel version of the genetic algorithm is developed and the effect of having multiple processors on running time is investigated.

Crane double cycling is a method of improving efficiency of the cranes at the container ports. In a typical container unloading operation, the crane is sent back to the vessel empty every time that it unloads a container to berth side. In an attempt to reduce the idle cycling time, double cycling solution was introduced in which the crane will load a new container every time it has unloaded a container as such the total berthing time will improve. Goodchild and Daganzo (2007) studied the impacts of crane double cycling on containership turnaround time and results indicate that the practice can reduce the ship dwell time on a single port. Schedule planning for double cycling is proven to be very difficult for real-world cases. However one can argue that in addition to the appropriate crane schedule programming, the stowage planning of the vessel is an important factor for an efficient double cycling operation.

Especially in the presence of multiple cranes, double cycling can be applied in its full potential only if the arrangement and distribution of the containers allows for simultaneous loading and unloading operations. Therefore if the ship planners are informed in advance that double cycling is practiced in the forthcoming ports, they must adjust the storage of the containers to utilize the full potential of the cranes. Due to the flexibility in evaluation procedure, the containership load planning solution proposed in this dissertation can be extended to account for crane double cycling. Incorporating crane double cycling into stowage planning, investigating the impacts of double cycling on the ship turnaround time over her journey as opposed to a single port and studying the solution time for the combined approach is subject of future research.

In order to increase productivity, ports have been pressuring crane manufacturers to increase acceleration, speed and handling capabilities of the cranes. As a result some container ports are equipped with cranes that are capable of lifting multiple containers at the time (mostly double lifting). Similar to the argument made for the double cycling case, it is of special importance to account for such operations at the containership stowage planning stage. Again the proposed solution approach can be modified to take advantage of potential time savings offered by multi-container lifting feature, while designing the stowage planning scheme. Combination of double cycling and multi-crane lifting and the impact on containership stowage planning is another subject for future research.

In this research it was assumed that the information is perfect meaning that list of containers to be transported is known and is made available in advance. However,

similar to any other real transportation system, the containership operations are subject to uncertainty. The proposed solution approach addresses the unexpected changes in demand by solving the problem iteratively using the updated transportation matrix. The algorithm is agile enough to update the stowage pattern caused by last minute changes prior to arriving to any future port. Introducing stochasticity of the demand to the model and investigating the benefits of such approach is an area of future research. One can compare the results of stochastic optimization with the results produced by iterative solution of the deterministic model under various scenarios. It was also assumed that the containership has enough capacity to accommodate all the containers throughout the operations. In case that the number of containers exceeds the capacity of the vessel, the algorithm should be able to optimally pick and choose the containers to be transported. Enhancing both the mathematical model and the algorithm to perform container selection is an interesting subject for future studies.

Numerical experiments show that the complexity of this class of problems goes hand in hand with the height of the stack and the enforcement of vertical stability constraints. This makes the containership load planning problem a good candidate for benchmarking commercial solvers. The sample problems in this dissertation were solved using ILOG CPLEX Version 11. A side by side comparison between performance of CPLEX and other solvers (e.g. XPRESS, GAMS and LINDO) based on generating problems with different degrees of complexity from the proposed mathematical model is a subject of future investigation.

Finally as it was discussed the containership planning process follows a multi-tier hierarchical decision making model which consists of ship routing, berth planning, quay crane scheduling and unload/load sequencing. The decision made at a higher tier imposes constraints to the solution at lower tier. Potential benefits may be introduced to the containership planning process by integrating the decisions at different tiers. Joint optimization of operations between the yard operations and stowage planning is an example. The integration of load/unload planning with containership ship routing problem, and combining berth allocation with containership load planning are promising topics for future research.

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Appendix A: Algorithm Implementation Interface

To implement the solution discussed in this dissertation a computer program is written in C++ which has the following features:

- Generating random test problems in accordance with the procedure described in 6.1.
- Generating input file for CPLEX solver based on the mathematical model described in 3.6.
- Solving the problem based on the proposed algorithm in 5.2.
- Visualizing the solution provided by the mathematical solver and the genetic algorithm.
- Generating detailed unloading, shifting and loading plan at each port based on the solution.

Figure A.1 shows the main interface of the program where assumptions and parameters for the objective function and constraints can be set by the user. In this figure an expanded form of the mathematical formulation for a sample problem is produced which can be sent to the CPLEX optimization engine. Statistics for the number of constraints and variables are provided. Figure A.2 shows the user interface for generating random test cases for containership load planning. Sample problems are produced based on the specified parameters and layout of the vessel. The number of visiting ports and different characteristics of the containers including weight, size and type can be adjusted. Figure A.3 shows the interface for the genetic algorithm solver where different parameters for solving the problem can be set. After solving the problem summary of the solution attributes is reported and the details of unload,

shift and loading plan for containers as well as crane operations at each port is reported in a file. The program produces a convergence diagram for the algorithm which shows the average, best and worst fitness value of each iteration as shown in figure A.4. Even small containership load problems involve a large number of variables. This makes keeping track of location of individual containers in the vessel at different ports very difficult for the user. A visualization tool is developed that automatically displays the stowage plan of the vessel at different bays and columns of the ship is a color coded fashion. The colors show the origin and destination port of the container. This tool also provides a graphic indicator for the shifting and unloading containers. Figures A.5 and A.6 show a snapshot of this tool.

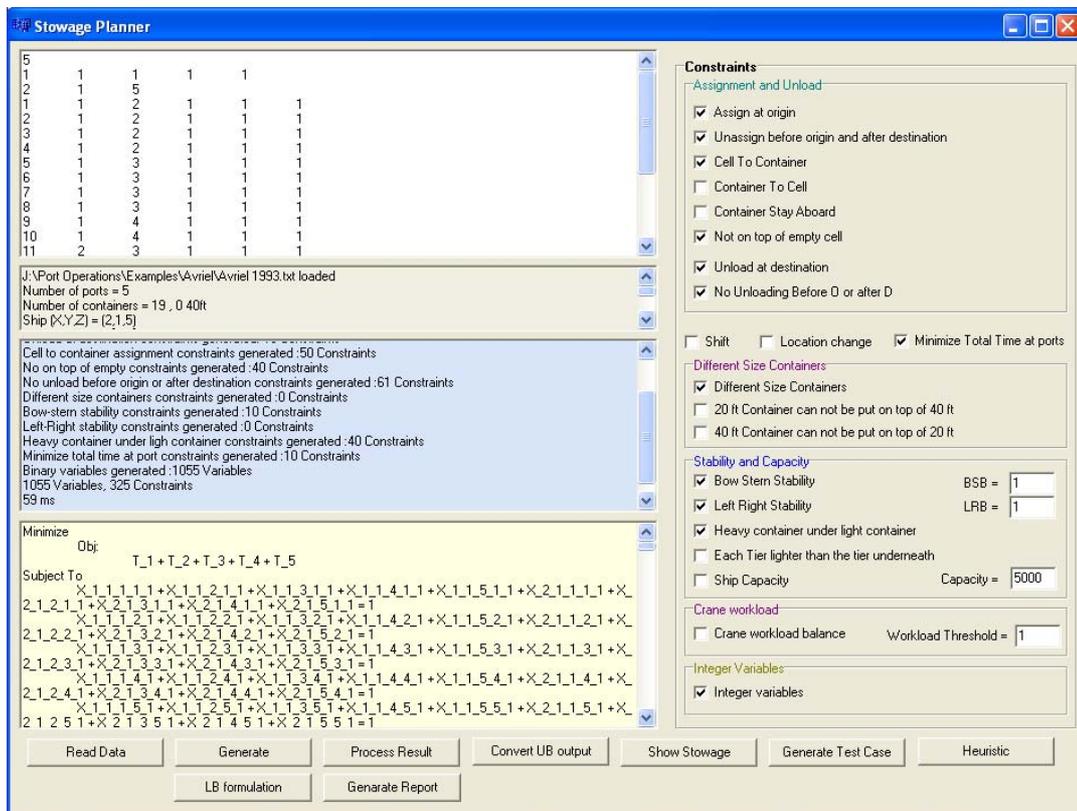


Figure A.1. The user interface and formulation output for a sample problem

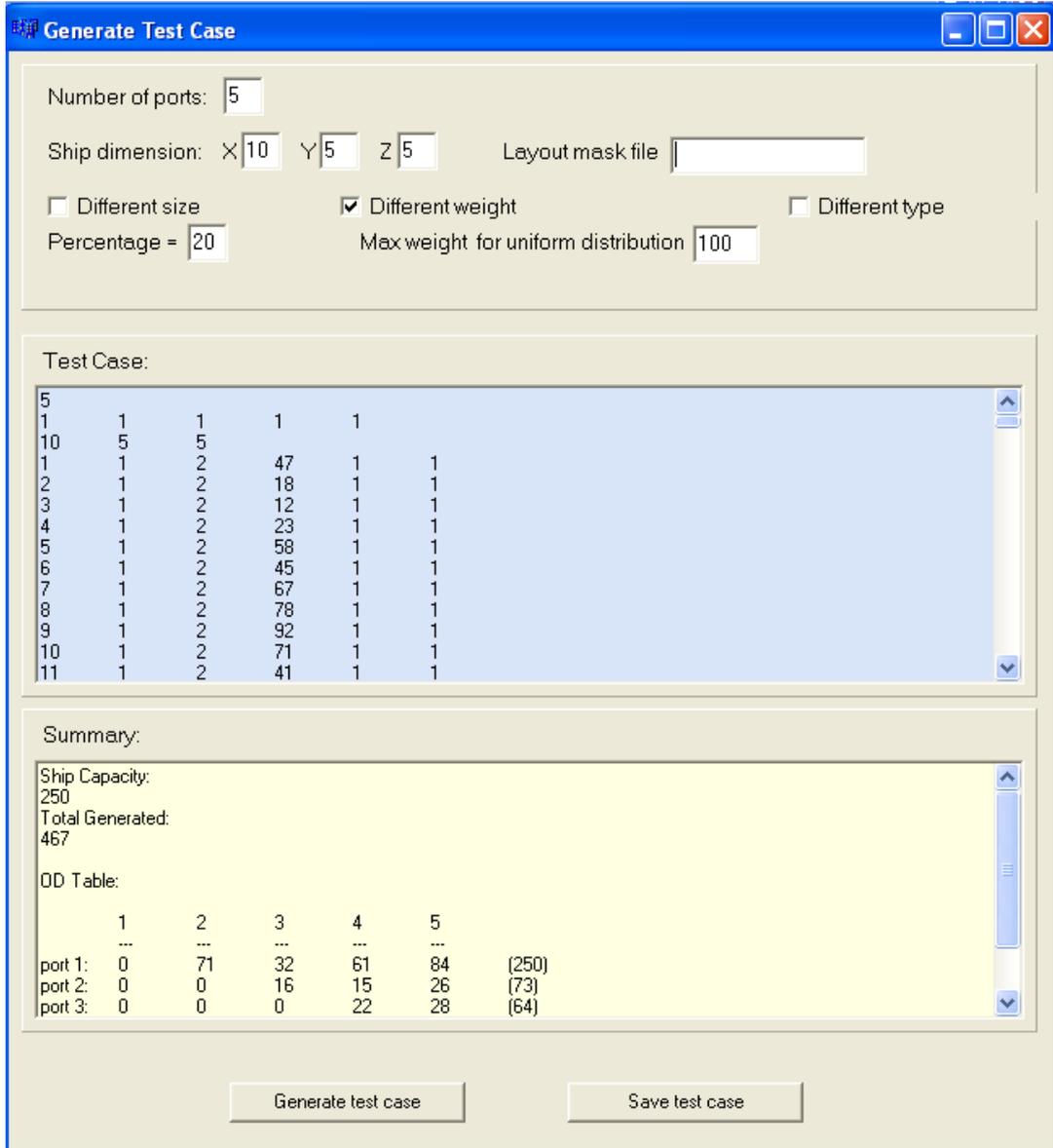


Figure A.2. Generating a test case

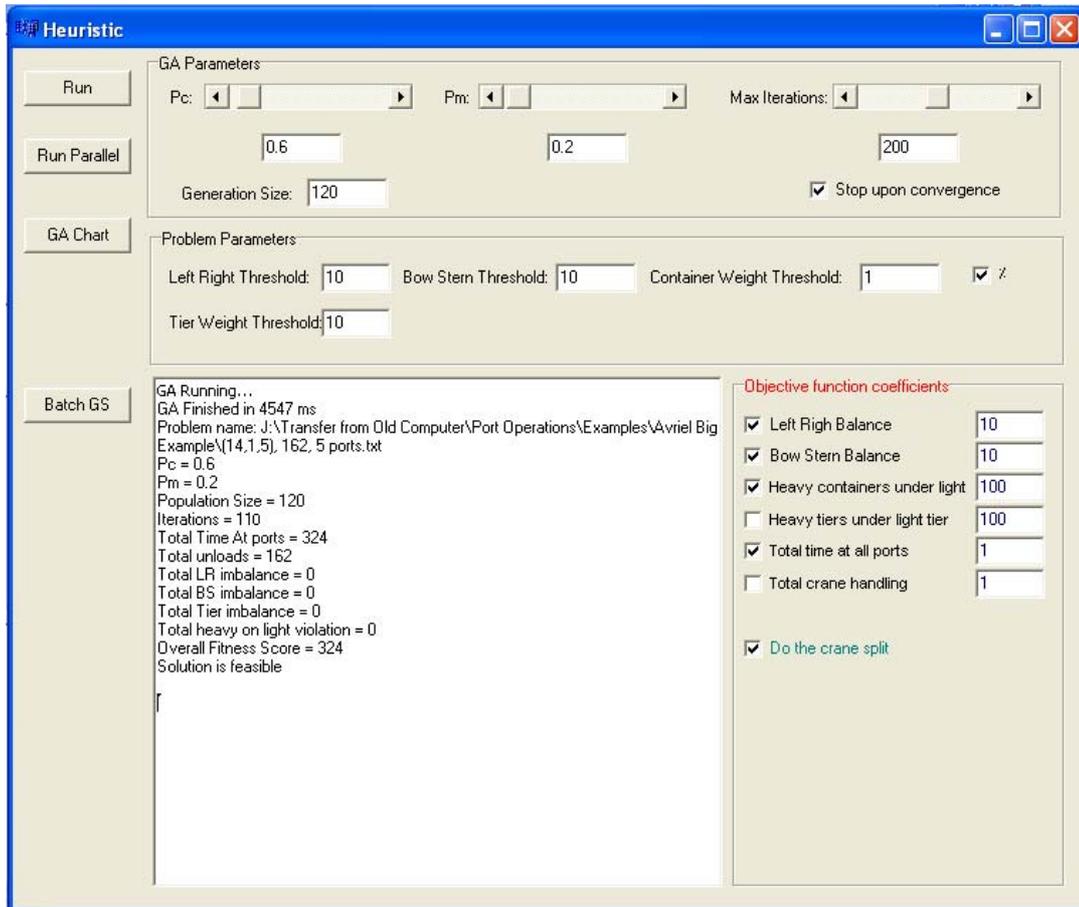


Figure A.3. Solver interface

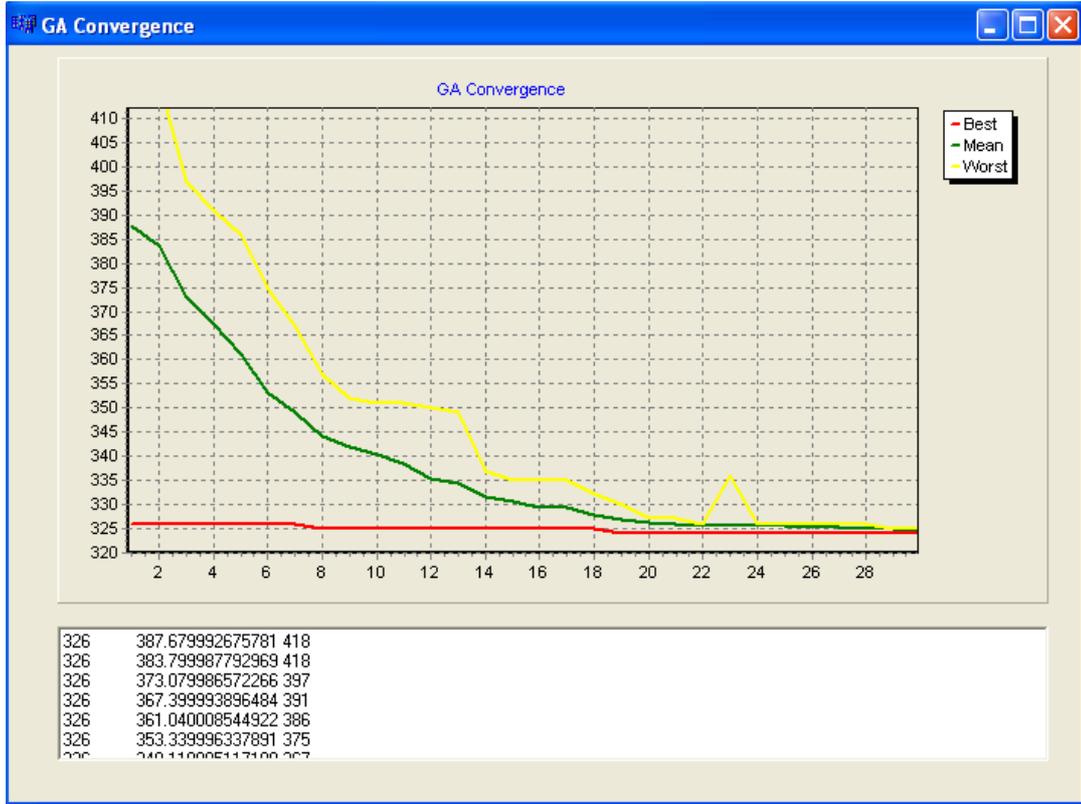


Figure A.4. Convergence diagram for a sample problem

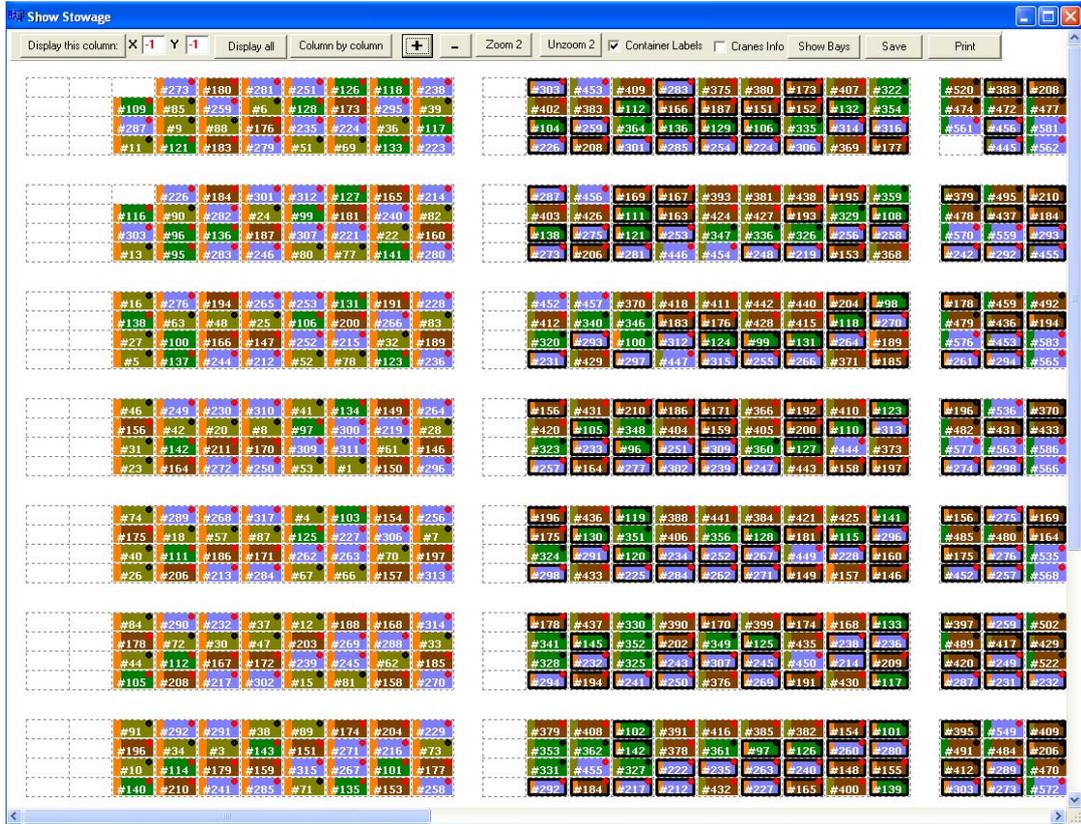


Figure A.5. Visual tier by tier presentation of the solution for a sample problem

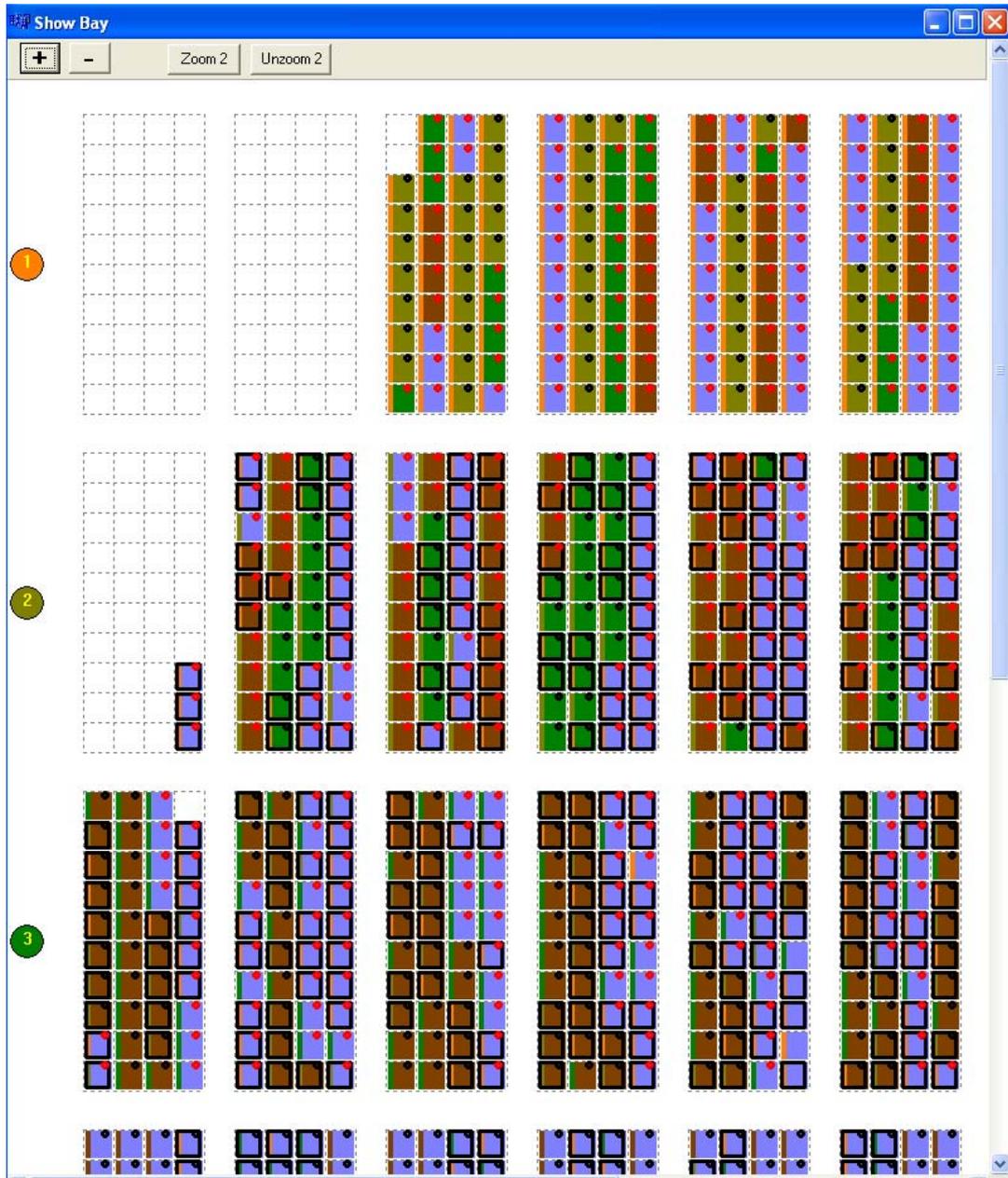


Figure A.6. Visual bay by bay presentation of the solution for a sample problem

Appendix B: Solution details for a sample problem

The input and output details of the scenario 3 of the sample problem solved in section 4.3.1 are as following:

Program input:

Container number	Origin port	Destination port	Weight	Size (number TEU)	Type
1	1	2	1	1	1
2	1	2	1	1	1
3	1	2	1	1	1
4	1	2	1	1	1
5	1	3	1	1	1
6	1	3	1	1	1
7	1	3	1	1	1
8	1	3	1	1	1
9	1	4	1	1	1
10	1	4	1	1	1
11	2	3	4	1	1
12	2	3	4	1	1
13	2	5	4	1	1
14	3	5	1	1	1
15	3	5	1	1	1
16	3	5	1	1	1
17	3	5	1	1	1
18	3	5	1	1	1
19	4	5	1	1	1
20	1	2	1	1	1
21	1	2	1	1	1
22	1	2	1	1	1
23	1	2	1	1	1
24	1	3	1	1	1
25	1	3	1	1	1
26	1	3	1	1	1
27	1	3	1	1	1
28	1	4	1	1	1
29	1	4	1	1	1
30	2	3	4	1	1
31	2	3	4	1	1
32	2	5	4	1	1
33	3	5	1	1	1
34	3	5	1	1	1
35	3	5	1	1	1
36	3	5	1	1	1
37	3	5	1	1	1
38	4	5	1	1	1

Program output:

- Each row starts with the container identification number followed by #
- [origin port, destination port]
- L=Load, U=Unload, S=Shift, number after L,U,S indicates the crane number
- P=Port, followed by the port number

```
#1 [1,2] (4,1,4)  L2    P1    U2    P2
#2 [1,2] (2,1,4)  L1    P1    U1    P2
#3 [1,2] (2,1,2)  L1    P1    U1    P2
#4 [1,2] (3,1,5)  L2    P1    U2    P2
#5 [1,3] (3,1,3)  L2    P1
#5 [1,3] (3,1,3)  U2    P3
#6 [1,3] (1,1,3)  L1    P1
#6 [1,3] (1,1,3)  U1    P3
#7 [1,3] (1,1,5)  L1    P1
#7 [1,3] (1,1,5)  U1    P3
#8 [1,3] (3,1,2)  L2    P1
#8 [1,3] (3,1,2)  U2    P3
#9 [1,4] (2,1,1)  L1    P1
#9 [1,4] (2,1,1)
#9 [1,4] (2,1,1)  U1    P4
#10 [1,4] (3,1,1) L2    P1
#10 [1,4] (3,1,1) S1    P3
#10 [1,4] (2,1,3) U1    P4
#11 [2,3] (3,1,5) L2    P2    U2    P3
#12 [2,3] (2,1,3) L1    P2    U1    P3
```

#13 [2,5] (2,1,2)	L1	P2		
#13 [2,5] (2,1,2)	S1	P4		
#13 [2,5] (4,1,2)	U2	P5		
#14 [3,5] (3,1,3)	L2	P3		
#14 [3,5] (3,1,3)	U2	P5		
#15 [3,5] (3,1,4)	L2	P3		
#15 [3,5] (3,1,4)	U2	P5		
#16 [3,5] (3,1,1)	L2	P3		
#16 [3,5] (3,1,1)	U2	P5		
#17 [3,5] (3,1,2)	L2	P3		
#17 [3,5] (3,1,2)	U2	P5		
#18 [3,5] (1,1,5)	L1	P3		
#18 [3,5] (1,1,5)	U1	P5		
#19 [4,5] (2,1,2)	L1	P4	U1	P5
#20 [1,2] (4,1,5)	L2	P1	U2	P2
#21 [1,2] (4,1,3)	L2	P1	U2	P2
#22 [1,2] (2,1,3)	L1	P1	U1	P2
#23 [1,2] (2,1,5)	L1	P1	U1	P2
#24 [1,3] (1,1,2)	L1	P1		
#24 [1,3] (1,1,2)	U1	P3		
#25 [1,3] (1,1,4)	L1	P1		
#25 [1,3] (1,1,4)	U1	P3		
#26 [1,3] (3,1,4)	L2	P1		
#26 [1,3] (3,1,4)	U2	P3		
#27 [1,3] (1,1,1)	L1	P1		
#27 [1,3] (1,1,1)	U1	P3		
#28 [1,4] (4,1,1)	L2	P1		

#28 [1,4] (4,1,1)				
#28 [1,4] (4,1,1)	U2	P4		
#29 [1,4] (4,1,2)	L2	P1		
#29 [1,4] (4,1,2)				
#29 [1,4] (4,1,2)	U2	P4		
#30 [2,3] (4,1,4)	L2	P2	U2	P3
#31 [2,3] (2,1,4)	L1	P2	U1	P3
#32 [2,5] (4,1,3)	L2	P2		
#32 [2,5] (4,1,3)	S1	P4		
#32 [2,5] (2,1,1)	U1	P5		
#33 [3,5] (1,1,4)	L1	P3		
#33 [3,5] (1,1,4)	U1	P5		
#34 [3,5] (1,1,2)	L1	P3		
#34 [3,5] (1,1,2)	U1	P5		
#35 [3,5] (1,1,3)	L1	P3		
#35 [3,5] (1,1,3)	U1	P5		
#36 [3,5] (1,1,1)	L1	P3		
#36 [3,5] (1,1,1)	U1	P5		
#37 [3,5] (3,1,5)	L2	P3		
#37 [3,5] (3,1,5)	U2	P5		
#38 [4,5] (4,1,1)	L2	P4	U2	P5

Appendix C: Visual solution details for a mega containership

This section provides a visual representation of the container stowage planning and crane split solved for the mega containership example in section 7.3. A tier-by-tier view of the vessel's layout is used to show the results. Horizontal members from 1-40 and vertical numbers from 1-20 show the bays and row indexes respectively. Each box represents a container which consists of a narrow strip to the left and a wider strip to the right. The narrow strip has the color of the origin port and the wide strip matches the color of the destination port. The container identification number appears on the box. The colors assigned to each port are displayed in the legend section. Results are only displayed for ports one to four since the containership is empty at the last port. The crane split results in terms of the range of bays that each crane operates on is shown at the bottom of each layout. Table C.1 is a guide for interpretation of the graphic layout display.

Table C.1: Description of graphic symbols for stowage and crane split display

Symbol	Meaning	Sample
White box	The cell is empty	
Colored box without frame and with no dots	The container stays at the corresponding cell through next port	
Black dot on the top right corner	The container will be unloaded at the next port	
Red dot on the top right corner	The container will be shifted at the next port	
Solid black frame around the box	The container is shifted at the current port	
Solid black frame around the box and a black dot at the top right corner	The container has been shifted at the current port and will be unloaded at the next port	
Solid black frame around the box and a red dot at the top right corner	The container has been shifted at the current port and will be undergo another shift at next port	

20				7023	8344	8596	8199	8335	8949	8063	8264	8598	8446	8587	8423	934	1136	882	1096	806	131	9	830	8281	8252	2214	8179	8001	8909	8271	8598	8754	8272	8136	8031
19				8412	8511	8697	8349	8869	8674	8612	8790	8978	2295	8504	8284	839	1112	1480	84	960	767	179	4426	848	8689	8878	2220	8172	8680	8303	8699	8008	8516	8257	8631
18				8322	8494	8551	8182	8717	8254	8552	8531	8637	8114	8750	8933	253	1225	1277	584	1908	154	156	8983	8398	8767	8868	8131	8249	8139	8054	8282	8103	8293	8504	8724
17				8616	8661	8525	8336	8062	8288	8294	8081	8250	8235	2141	8513	806	174	149	115	1870	1800	925	8502	8516	8574	8564	8021	8630	8378	8412	8588	8553	8885	8047	8746
16				8523	8406	8852	8416	8466	8243	8219	8576	8070	8931	8963	8510	299	463	185	914	224	711	101	8628	8164	8423	8142	8711	8657	8871	8300	8911	8790	8499	8460	8459
15				8117	8267	8597	8935	8916	8301	8444	8948	8981	8246	8665	8003	433	495	768	912	131	715	179	2344	8071	8819	8846	8090	8732	8276	8393	8553	8548	8480	8481	8862
14				8980	8151	8727	8654	8882	8297	8067	8190	8046	8698	8112	8945	888	148	903	1910	155	197	641	8507	8273	8054	8421	8218	8346	8495	8595	8164	8029	8453	8367	8867
13				8562	8721	8420	8940	8545	8859	8361	8311	8185	2149	8030	8500	158	133	126	401	132	143	144	8950	8229	8578	8813	8258	8752	8340	8445	8286	8068	8415	8798	8752
12				8864	8738	8154	8863	8774	8248	8145	8216	8570	8272	8771	8422	889	101	149	178	731	159	147	8594	8567	8944	8413	8934	8416	8981	8502	8674	8896	8823	8936	8997
11				8988	8521	8144	8611	8418	8918	8309	8707	8832	8604	8436	8543	136	732	79	669	164	239	175	8758	8152	8747	8270	8912	8780	8296	8248	8160	8481	8973	8827	8975
10				8213	8028	8286	8866	8777	8381	8591	8989	8761	8911	8419	8805	128	179	117	538	114	218	814	8990	8134	8632	8624	8637	8999	8350	8945	8170	8587	8374	8930	
9				8219	8006	8357	8563	8882	8447	8432	8791	8802	8124	8851	8198	81	899	561	167	890	567	419	8154	8059	8424	8817	8230	8485	8345	8288	8485	8441	8456	8124	8713
8				8088	8155	8507	8220	8819	8023	8061	8914	8977	8797	8690	8244	818	264	193	102	115	114	121	8408	8760	8710	8309	8184	8670	8393	8641	8835	8612	8417	8471	8316
7				8599	8013	8550	8314	8928	8610	8632	8187	8262	8735	8223	8987	935	957	254	174	151	742	59	8680	8924	8077	8125	8219	8928	8089	8916	8521	8667	8639	8395	8204
6				8176	8585	8737	8014	8171	8944	8583	8365	8558	8352	8800	8029	788	169	104	157	174	163	44	8683	8794	8921	8922	8212	8256	8068	8068	8265	8332	8334	8757	8638
5				8671	8646	8899	8782	8850	8667	8311	8870	8867	8896	8809	8016	137	821	873	203	670	160	305	8712	8324	8432	8580	8384	8088	8179	8911	8580	8744	8756	8730	8522
4				8943	8487	8368	8182	8473	8182	8083	8559	8907	8681	8536	8229	810	193	946	689	197	207	143	8792	8719	8415	8055	8209	8876	8805	8066	8645	8592	8976	8184	8701
3				8432	8736	8540	8787	8668	8466	8772	8527	8131	8904	8116	8736	8572	86	121	158	184	692	136	8884	8815	8399	8743	8079	8802	8160	8573	8193	8919	8820	8400	8071
2				8230	8520	8974	8487	8753	8092	8976	8682	8783	8534	8674	8601	8405	845	203	166	118	189	486	8545	8099	8089	8005	8606	8948	8682	8038	8376	8521	8884	8361	8758
1				8577	8007	8146	8157	8901	8276	8641	8532	8428	8017	8450	8110	8809	196	704	813	415	189	115	8827	8187	8703	8371	8647	8882	8356	8467	8384	8666	8455	8044	
20				8656	8980	8575	8173	8955	8952	8358	8031	8598	8447	8515	8761	130	130	894	995	112	107	1	8100	8146	8824	8283	8885	8013	8108	8371	8775	8539	8448	8274	8305
19				8526	8441	8240	8424	8711	8996	8807	8373	8841	8001	8142	8474	131	460	923	505	148	107	897	8887	8578	8953	8611	8707	8949	8291	8971	8700	8012	8552	8732	8900
18				8994	8269	8887	8689	8930	8718	8908	8102	8864	8125	8401	8523	103	155	149	200	202	154	150	8222	8292	8699	8357	8255	8560	8142	8708	8372	8110	8178	8978	8378
17				8587	8483	8932	8848	8311	8180	8537	8088	8723	8484	8551	8138	163	896	145	146	141	382	366	8062	8549	8018	8939	8100	8066	8417	8135	8117	8231	8936	8080	8141
16				8461	8661	8479	8363	8255	8530	8409	8031	8416	8597	8577	8258	124	530	635	871	659	778	338	8196	8145	8829	8339	8464	8281	8857	8316	8791	8857	8204	8600	8763
15				8237	8180	8974	8907	8069	8837	8096	8199	8738	8128	8185	8251	108	968	189	502	796	122	541	8321	8290	8626	8162	8835	8153	8153	8704	8967	8855	8709	8393	8915
14				8250	8199	8685	8619	8883	8265	8850	8131	8552	8909	8447	8580	142	169	138	181	700	175	270	8205	8305	8188	8261	8405	8321	8709	8343	8999	8226	8938	8093	8874
13				8778	8791	8501	8881	8743	8581	8298	8322	8934	8318	8564	8595	451	127	132	137	178	117	195	8173	8305	8901	8778	8221	8096	8363	8546	8362	8530	8806	8831	8906
12				8007	8733	8457	8746	8666	8275	8717	8240	8981	8052	8066	8136	128	181	189	201	818	127	877	8726	8129	8975	8147	8158	8427	8714	8634	8695	8685	8880	8108	8099
11				8840	8796	8190	8505	8212	8274	8336	8086	8838	8372	8123	8022	798	169	190	851	188	868	163	8230	8324	8025	8388	8365	8808	8275	8391	8858	8161	8275	8057	8993
10				8222	8359	8463	8902	8782	8035	8719	8061	8925	8863	8505	8923	157	123	698	106	183	175	166	8872	8296	8048	8965	8590	8173	8249	8947	8750	8002	8215	8527	8236
9				8166	8704	8739	8646	8622	8291	8347	8922	8804	8591	8283	8137	70	114	161	286	187	173	639	8270	8222	8734	8717	8618	8912	8331	8999	8448	8834	8066	8287	8581
8				8516	8156	8922	8314	8034	8816	8404	8497	8362	8748	8222	8161	186	103	949	40	690	516	121	8573	8254	8229	8671	8236	8262	8021	8590	8604	8940	8045	8661	8849
7				8718	8001	8947	8968	8402	8564	8326	8328	8784	8089	8670	8184	964	110	130	117	73	828	819	8977	8126	8798	8967	8156	8624	8386	8503	8128	8919	8900	8766	8339
6				8218	8541	8875	8163	8734	8222	8891	8533	8806	8133	8583	8860	793	481	109	624	179	147	71	8565	8209	8326	8669	8072	8208	8300	8832	8531	8294	8570	8307	8683
5				8593	8481	8912	8495	8584	8304	8282	8713	8709	8218	8664	8812	144	982	822	229	654	898	125	8218	8125	8078	8470	8087	8819	8862	8587	8653	8354	8077	8297	8703
4				8073	8334	8802	8713	8868	8194	8342	8705	8076	8465	8360	8522	842	165	190	217	819	412	831	8437	8355	8556	8472	8469	8363	8827	8480	8450	8891	8025	8037	8707
3				8921	8012	8675	8782	8957	8328	8288	8965	8312	8978	8107	8350	8640	199	151	126	439	165	50	8670	8211	8368	8854	8524	8649	8120	8564	8528	8232	8338	8029	8028
2				8955	8848	8432	8737	8998	8851	8171	8716	8655	8382	8295	8069	8083	172	160	642	195	156	678	8866	8013	8692	8138	8777	8442	8888	8714	8019	8519	8285	8323	8924
1				8523	8349	8684	8986	8114	8407	8933	8165	8148	8298	8796	8337	8141	116	37	164	187	125	621	8192	8426	8988	8867	8503	8899	8504	8123	8595	8018	8335	8828	
20				8839	8528	8488	8583	8974	8791	8962	8879	8278	8978	8851	8633	858	1950	201	148	894	171	33	8935												

20				6640	7856	7380	8966	8956	8470	8382	4290	4903	5239	8108	2993	6334	8079	8300	5991	7619	1005	8499	8839	4756	4055	4905	8643	4086	5737	6049	7871	8883	8843	8636	7821	
19				8539	8298	8460	8551	8794	8000	8720	8964	8770	8912	8383	8786	8488	7666	6899	6944	9633	1597	2844	8444	4391	8484	8252	5014	2833	5516	8027	8476	8473	8003	7406	8501	
18				7201	8114	8442	8108	8733	8364	8790	8107	8219	8564	8504	8722	8569	8238	4188	5668	2938	7929	6329	4297	8333	8386	4272	8720	8566	8203	8076	8008	8042	8084	8464	8346	
17				8461	8791	8567	8426	8741	8404	8620	8119	8106	8242	8333	8822	1669	2029	1829	1899	1829	6399	1769	4241	4466	8815	4750	2363	2310	8055	8143	8983	7436	8805	7567	8952	
16				7063	7927	7286	8369	7247	8390	8340	8243	8697	4422	2684	4631	1537	1088	2029	1644	9788	2029	1949	8110	4553	8352	4471	8974	2847	5577	5622	8459	8914	7464	7493	8339	
15				7696	8306	8242	8963	8529	8132	8712	8204	8456	8211	8040	4672	7959	5499	1879	6940	4069	1359	1329	2739	8799	2241	2928	8940	8202	5799	8731	8219	8855	8722	8119	8115	
14				8732	8250	8710	8090	8046	8295	8451	8074	4528	8311	8165	2605	1249	9659	1129	2269	1809	5189	1539	2060	2979	4882	8805	4389	4512	5370	8060	7904	8463	8309	8227	8610	
13				8024	8651	8706	8416	8293	8441	8599	8040	8938	8277	2797	4878	2029	6519	1269	4889	7449	1059	1259	5224	8641	8033	2207	5081	8184	5687	8786	8982	8531	8797	8487	8692	
12				8017	8171	8662	8784	8615	8283	8429	8675	8121	4226	4417	8962	1059	1879	6999	1329	1359	7919	1719	4739	4729	2138	8043	4295	4741	5767	8979	8395	8204	8171	8610	8419	
11				8744	8991	8287	8799	8844	8239	8629	8063	8245	8358	8105	8302	7509	2889	4889	1299	8159	1249	1949	8862	8883	8084	4674	8005	2994	8175	8635	8532	8678	8140	8712	8427	
10				8805	8273	8970	8445	8708	8969	8811	8079	8802	8262	8259	2115	8589	1139	1559	5509	6639	1289	3409	8428	8153	4285	8060	2495	8140	8267	7624	8218	8074	7980	8169	8978	
9				8546	8550	8854	8305	8704	8518	8864	8503	8264	4268	2266	4377	1569	1929	1629	7519	1459	1789	4699	2602	8678	8007	4933	8214	8604	8590	8268	8356	7690	8136	8654	8438	
8				8541	7167	8457	8275	8543	8101	8004	8038	8166	2042	4331	4955	9189	2339	1259	1009	1819	1399	1669	5120	2186	8796	2975	4088	8943	8225	8995	8666	7122	8648	8817	7061	
7				8848	8623	8670	8939	8990	8289	8306	8842	8129	4152	8873	4447	1139	1029	2219	8869	7389	8689	1699	4642	2077	8050	4751	8127	8569	8090	7835	8103	8570	7705	7229	7447	
6				7341	8569	7742	8353	7957	8697	8817	4132	8871	2547	4798	4018	9119	7349	9989	1129	7629	1539	1009	2489	2612	8960	4826	2889	8081	8792	8883	8116	8225	7907	8747	7263	
5				8413	8155	8075	8607	8996	8188	8758	8103	8479	8889	4836	4878	1579	8319	1989	1509	8569	7569	1369	8112	8315	8313	2097	4575	8820	8326	7600	7478	8109	8454	8829	8379	
4				8860	8406	8023	8613	8841	8036	8923	2181	8157	4499	8349	2215	4899	1559	1399	1609	1039	1529	6799	4301	2704	8636	4157	4953	8905	8217	7010	8930	7887	8622	8668	8825	
3				7108	7088	8793	8360	8185	8301	8147	4118	8240	2353	2111	8619	8899	1569	1829	1119	1049	1419	5269	2691	4951	4581	8544	8244	8100	8501	8165	8533	7888	8531	8132	8307	
2				7987	8582	8210	8152	8179	8269	8311	4732	8403	2183	4969	4628	4821	8339	2009	1569	6679	1089	1109	8402	4611	8472	4256	8831	8947	8047	8890	8628	7539	8186	8143	8826	
1				8585	8253	8429	8105	8833	8576	8984	8572	4418	4344	2575	4926	4231	8809	7719	1209	8079	7289	8058	4504	4113	8836	8236	8020	8003	8539	8709	8948	8000	8525	8517		
20				8677	8432	8214	8653	7109	8763	8405	2066	8395	2757	2586	8204	1679	4219	4309	9899	1852	1539	8359	8074	4360	8980	4679	8516	4108	8930	8162	8072	7279	8106	7345	8753	
19				8042	8319	8027	8873	7813	8258	8721	8036	2256	2948	4051	4489	1129	1529	1799	4559	9439	6539	8879	8430	8571	8885	8880	2434	8754	8274	8788	7740	7076	8212	8101	7874	
18				8961	8546	8984	8724	8533	8264	8392	2457	8644	2989	8345	8748	4379	1679	1349	1059	1659	1499	1209	8601	2269	4539	4029	8994	8578	5381	8724	8950	7994	7803	8580	8348	
17				7026	8276	8781	7363	8667	8761	8197	8131	8004	8188	4839	4028	1679	1569	1919	1689	1469	1669	9029	2431	8285	4356	4687	2700	8366	8421	8863	8627	8421	8104	7963	7291	
16				8040	7826	8688	8597	8788	8878	8406	4078	8117	8194	8517	8965	4509	6239	1999	1189	1599	5699	9799	8742	8539	8781	4081	4726	4774	8617	8764	7598	8573	8675	8764	8345	
15				8553	8915	8587	8451	7222	8359	8484	8547	2393	8506	4035	8031	1039	1289	6289	1849	1749	2039	1959	2637	4894	8554	8800	2737	8455	8706	8016	8505	7898	8439	7614	8486	
14				8074	7630	8119	8892	8804	8240	8348	4294	8360	2650	8144	4169	1769	5339	1489	2009	6799	4729	2599	8862	4158	8024	4374	8618	4518	8176	8865	7981	8515	8460	8904	8359	
13				8806	8567	8237	8468	8858	8374	8395	8224	8327	8720	4060	2775	1069	5579	1969	9919	6649	1619	6169	4282	4048	4400	2843	2751	8766	8743	8824	8810	8815	8546	8470	7427	
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9				8433	8372	8927	8325	8897	8315	8480	4224	8233	8833	4696	4378	4259	1349	2529	1679	1089	1789	1709	2890	8840	8327	8677	2767	8126	8872	8257	7659	7841	8002	8664	8456	
8				7948	8894	8634	8434	8472	8793	8584	8393	8104	2672	2373	4997	6689	8569	1269	1889	4799	1589	5109	4648	4027	2687	2544	4098	8327	8873	7880	8953	8534	8185	8926	8581	
7				8859	8271	7197	8824	8614	8104	8977	8217	4003	8606	8997	4867	5449	8189	2629	1119	1229	6629	1829	4008	4444	2974	4214	4405	4415	8762	8513	8306	8195	7601	8183	8469	
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4				7261	8218	7255	8914	8437	8755	8707	8251	8159	8272	8400	2062	4089	1869	8889	2789	1039	1479	6829	8389	2386	4141	8146	2565	8174	8385	8897	7522	8172	8506	7186	8892	
3				7589	8443	7995	8482	8954	8983	8493	8165	8926	2649	2961	2482	8082	5228	1739	1159	1789	8899	1599	2242	4169	4489	2086	8543	8342	8167	8780	8285	7865	7445	8188	8443	
2				8998	8126	8141	8638	8949	8746	8803	8689	2622	8436	2841	2497	2126	1339	1899	8999	8599	8539	7379	1179	8649	4192	8105	8080	8609	8879	8286	8541	8664	8740	8288	7241	8529
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17				7726	8090	8773	8315	8213	8883	8370	8845	2211	8151	2933	8660	1000	850	431	780	1960	1010	800	4958	4153	8707	8597	8557	8388	8639	8349	7319	8220	7433	8241	8496
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14				8488	8355	7344	7003	7136	8427	8227	4175	2203	8836	2674	2822	1010	231	860	29	1920	1700	1000	4460	4765	2744	2738	4292	4626	8877	8226	7644	7139	8033	7142	7771
13				8561	8402	8957	7137	8474	8102	8150	8122	2178	2731	4591	8308	743	821	115	92	1420	1400	1470	8183	2326	2701	2702	8035	2955	8125	8413	8435	7508	7356	8686	8069
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11				8085	7184	8147	7006	8216	8963	8323	8369	8007	8202	8849	2857	1290	222	745	585	443	1410	272	324	2179	2366	2270	8203	8692	8437	8278	8475	8272	7425	8565	8422
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9				8985	8021	8598	8159	7170	8436	8338	8240	2232	4593	8969	8216	684	712	111	1280	1400	215	1380	8554	4172	8522	2630	4269	8411	8911	7227	8597	7932	8503	8320	8589
8				7057	8398	8679	7315	7637	8487	8556	8106	8018	2623	8984	2619	124	626	884	1760	1510	1710	132	2659	4342	2499	4799	4012	8443	8660	8914	8475	7391	8716	8550	7541
7				7250	8231	8295	8150	7510	8329	8678	2465	8006	4973	4651	4584	1880	173	1400	1330	838	836	1820	8979	4752	8976	4468	8936	8337	8776	7514	8573	7052	8495	8442	8492
6				8301	8101	7497	8095	8886	8988	8146	4963	8201	2681	4338	4168	122	857	1730	4410	1330	753	1920	8894	8246	4120	4122	4352	8255	8771	7609	8908	8020	8263	8619	8870
5				8981	8072	8491	7653	8508	8596	8855	2697	4964	2383	8025	8091	1740	249	111	1160	8580	454	810	2636	2347	8724	2419	8687	8368	8026	7708	8524	7682	8399	7877	7695
4				8894	8821	7370	7840	8866	8896	8756	4487	4542	2793	8229	4213	867	636	1910	1920	448	786	370	8945	4609	2592	4056	4502	8636	8198	8445	8220	8866	8357	8768	8540
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20				8937	8527	8038	8036	8845	8253	8796	8020	8282	8168	8154	4653	199	462	892	1570	1600	279	144	4548	8060	8891	2155	8814	8279	8488	8408	7651	7260	8336	8486	8162
19				8405	8522	7111	8519	8625	8716	8247	2846	8825	2997	8764	8030	2030	984	1930	186	999	1200	1700	4541	8775	8047	2271	8087	8789	8166	8013	7486	8199	7657	7042	8322
18				8498	8465	8556	8164	8134	8437	8740	4354	2298	2342	2915	2177	812	1490	436	1840	1880	1920	172	182	8054	2361	4219	4796	8266	8295	8400	7033	7798	7642	8239	7969
17				7727	8988	7741	7810	8544	8926	8367	8864	2604	4155	2441	2205	942	1370	1990	45	876	661	1670	4244	8045	4738	2657	2551	8134	8677	8327	8786	7333	8451	8440	8502
16				7113	7878	7812	8401	8752	8305	8727	4779	8852	4597	4330	4720	896	985	809	787	1120	1990	80	2778	4343	2275	2606	8182	8937	8730	8411	7723	8412	7132	7120	7437
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14				8627	8436	8389	8873	8194	8606	8085	8382	8079	2148	4148	2490	146	821	1700	953	958	967	89	8998	8166	4437	4823	4420	8449	8379	8267	7455	7305	8223	8381	7658
13				8574	8126	7067	8472	8091	8935	8592	8129	8385	8756	8893	2286	243	148	1610	837	854	769	476	4445	4376	2629	8696	8739	2198	8768	8920	7364	8854	8154	8331	7081
12				8907	8508	7724	8595	8615	8475	8994	8883	2686	4695	8733	8041	1972	493	1970	1500	1900	202	1890	8116	2491	8755	2425	8046	8076	8951	8355	8605	8995	8325	8918	7195
11				7765	7151	7206	8474	8827	8903	8418	2927	8528	8089	2603	4065	1590	780	426	96	2130	186	1660	4202	8335	8622	2644	4015	8712	8396	8980	8742	8302	8785	8347	8735
10				8504	8145	8120	8993	8086	8111	8978	2551	8010	8972	2414	2528	176	1890	188	214	129	855	258	8432	4392	2382	2292	4892	8129	8280	7064	7992	8771	7417	8371	8536
9				7921	8455	7193	8960	8442	8695	8192	8923	2781	8132	4592	8533	200	1230	1470	1570	1350	1850	189	8698	2194	2587	8055	4492	8663	8361	8426	8770	8055	7309	8416	8226
8				8987	8249	7933	8704	8290	8889	8279	4766	2624	8591	8553	4668	810	730	781	162	1550	125	1230	4234	8253	4199	4520	8433	8281	8043	8297	8264	7654	8026	8380	8726
7				8935	8453	8197	7145	8238	8334	8118	2349	8011	2396	8410	4303	124	1730	111	1660	1820	1100	245	8406	8212	8902	8297	8765	8391	8597	8333	8954	7825	8554	8009	8312
6				7820	8078	7745	7246	7828	8376	8625	2259	4159	8749	8713	8751	122	660	1620	244	642	1380	865	2254	8091	4370	4945	4495	8127	8079	8249	7021	8903	7766	7401	8700
5				8309	8662	8095	8789	7295	8377	8051	8210	8429	8813	2090	2673	1850	891	972	643	904	1190	88	8907	2774	8902	8704	4412	8608	8207	8543	7101	8494	7330	8728	7702
4				8544	8113	8368	8543	7625	8619	8080	8151	4918	8225	4491	2553	8590	1870	150	457	1190	267	1380	8662	8103	8164	2864	2195	8801	8319	8613	7414	7648	8692	7928	8877
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20				8018	7510	8672	8271																												

20					3728	3591	3471	3316	3259	3532	3366	3216	3151	4727	4359	3658	1310	168	1741	206	1062	480	961	2557	3312	4069	4477	2081	4928	5966	5006	3137	3508	3673	3839	3670	
19					3202	3707	3025	3006	3533	3940	3031	3511	4119	3150	2615	3206	1660	369	367	610	197	168	171	151	2416	3207	2139	2322	5203	2119	3440	3095	3079	3736	3415	3052	3332
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17					3240	3162	3517	3433	3423	3308	3866	4070	3700	2423	4189	2899	864	986	691	801	118	28	161	2845	2717	2122	3347	2581	3861	3906	3161	3121	3597	3362	3320	3073	
16					3754	3952	3880	3534	3893	3672	3362	2291	4150	3918	3226	4557	74	1264	118	193	135	408	90	3293	3369	2213	3181	2577	4936	3373	3041	3330	3811	3158	3858	3452	
15					3690	3711	3076	3789	3887	3320	3373	4467	3809	3141	3009	2658	752	199	119	132	442	344	511	3002	4703	2253	2772	3529	4483	3205	3268	3798	3396	3056	3067	3730	
14					3494	3333	3339	3512	3659	3778	3394	4916	3384	3043	3338	2308	150	128	128	145	134	177	374	3211	4723	3844	2719	4763	3605	3296	3298	3157	3865	3039	3799	3030	
13					3902	3404	3911	3149	3783	3353	3280	3542	3685	3146	4104	4835	136	157	100	138	484	881	141	3250	2201	3258	3526	3572	3084	3833	3391	3684	3645	3114	3361	3511	
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11					3253	3072	3538	3802	3069	3699	3489	4419	2776	3409	4331	4097	162	191	315	144	525	185	300	2746	3036	4788	3316	5113	3847	3304	3435	3064	3078	3189	4970	3808	
10					3785	3967	3125	3517	3570	3502	3474	4130	2303	3691	4671	2787	324	846	123	794	195	130	266	2963	3694	4724	2154	3050	3870	3064	3367	3304	3211	3626	3316	3512	
9					3842	3777	3159	3989	3990	3986	3066	2598	4187	2728	4757	2227	309	112	176	122	504	593	210	3892	3015	3985	3113	4166	3314	3344	3951	3068	3264	3148	3588	3248	
8					3535	3346	3475	3573	3685	3329	3019	4249	3811	3592	3152	2866	100	192	130	535	590	512	474	3772	3110	4149	4615	2247	3115	3325	3186	3676	3884	3398	3468	3458	
7					3376	3994	3361	3125	3253	3375	3312	2532	4198	3051	2262	3039	190	367	116	116	658	346	438	4721	4508	2433	2667	4734	3505	3025	3523	3323	3112	3376	3091	3544	
6					3925	3478	3963	3846	3045	3345	3191	4195	4857	3075	2157	2279	124	509	370	105	119	143	570	4946	3147	2617	3163	2562	3323	3077	3758	3543	3802	3301	3205	3989	
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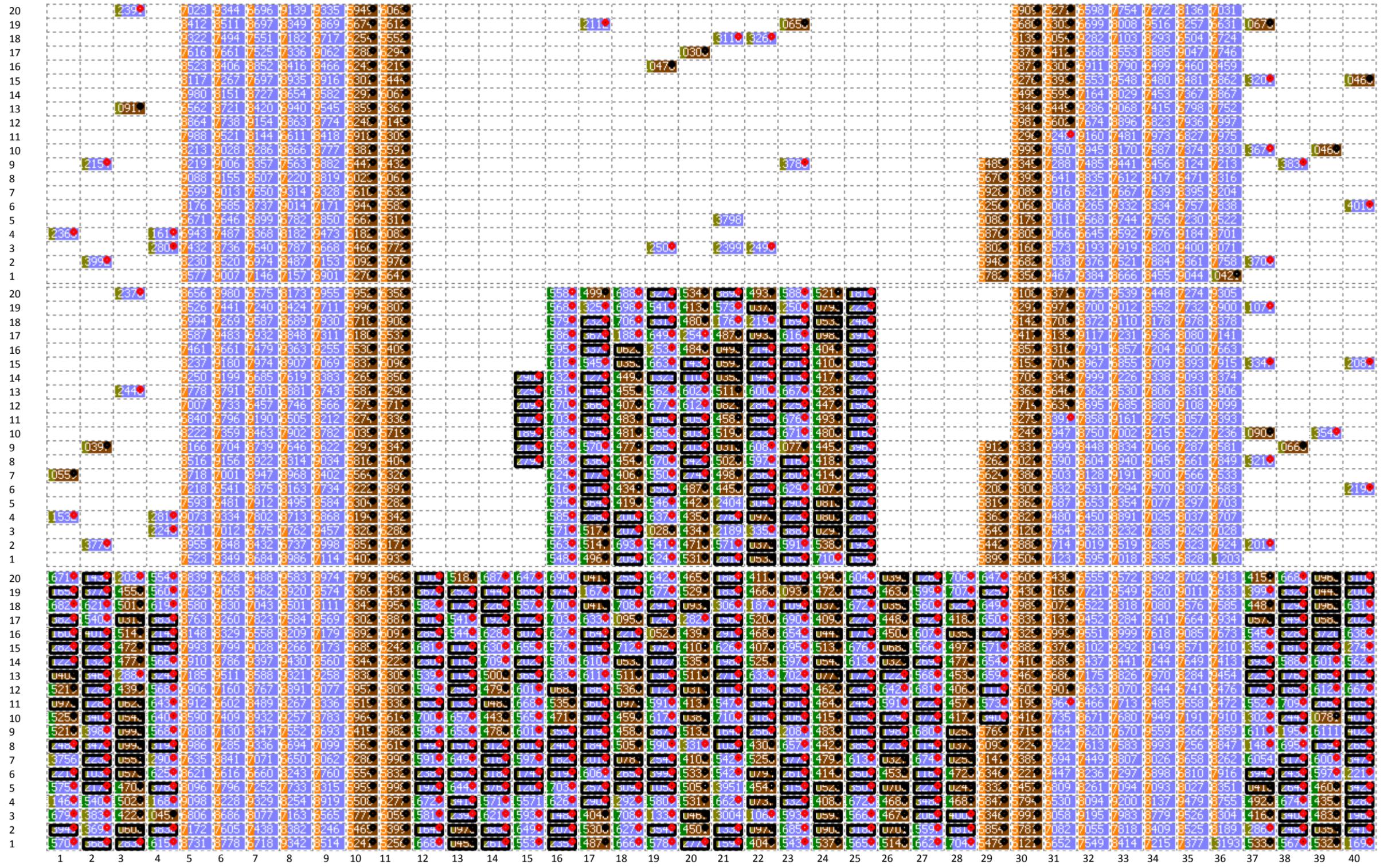
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18	9690	1116	1136	8480	7327	8992	8110	8625	8276	8491	8107	2440	2420	8830	2500	8560	0770	0130	8804	2991	1017	0786	8384	7140	2270	8780	8050	2110	8130	8844	8322	8852	7419	7235	7731	8008	8344	0750	1782	8390		
17	2000	2370	0480	8431	8572	8174	7337	8116	7169	8116	8048	2570	8630	2350	4600	4170	8990	8960	8620	2224	0562	0883	1799	8870	4270	4940	2950	8220	4960	8728	8022	7817	7990	8528	8641	8564	8100	2679	8810	1840		
16	1065	1216	8698	2702	8882	8365	7984	8496	8629	8902	8350	2910	2220	8380	8270	4640	8876	0150	0637	1306	1480	1912	4030	8830	2420	8130	4430	8010	8330	8290	8259	7822	7281	7776	8758	7127	8623	2910	8526	2549		
15	2459	2889	8472	0839	8904	7774	8270	8578	8549	8535	8074	2440	8180	4430	4780	4362	8600	0444	1784	0542	0090	1950	0482	2850	5020	4130	2090	8950	8622	8651	8354	8801	8576	8608	8745	8870	0838	1630	2458	2655		
14	1920	1788	8890	1010	8929	8856	8513	8729	8408	8961	8118	2110	2460	4560	8220	8870	1282	2704	2859	8770	8925	1937	0180	2560	2540	8220	8350	4230	2450	5582	8398	8097	8603	8480	8118	8849	0641	8100	0837	0543		
13	0040	2292	8359	0660	8899	8343	8451	7070	8868	8543	8293	8940	4410	2910	2350	8180	0948	2107	8780	0813	2853	8830	1210	2600	2640	2060	4640	4250	2560	8621	8269	7159	8953	8908	8396	7403	1640	1767	1560	2250		
12	0590	8032	8451	8617	7622	8417	7621	8388	8524	8322	5460	2680	4450	4500	8430	8480	8800	7225	1660	1786	1240	1900	0436	4780	3110	2810	8500	8200	4980	8356	8408	7939	8872	7757	8538	8859	8830	0896	0977	2050		
11	2155	1277	8708	8850	8079	7528	2223	8917	7836	8942	8845	8230	2150	8580	4510	8330	0790	1310	1405	2018	8890	1651	8750	8160	3110	8090	4450	2460	4360	5496	8548	7356	8401	8227	7293	7219	8588	1940	1874	0754		
10	2643	8700	9730	1647	7940	8640	8584	8708	7110	8383	8481	8570	8810	2250	8600	8900	8870	0000	0854	1100	8245	2092	1610	2100	2100	4030	8090	2760	2650	8846	8901	7647	7300	7394	7962	8975	2493	8680	1477	2010		
9	1665	2803	8279	8960	8050	8133	7199	8887	8440	8265	5681	4300	8910	2740	2090	4070	0890	0742	8272	10537	8221	8820	0468	4200	2920	2960	8340	4460	8163	8654	8054	7154	8239	7901	8370	8923	1715	8049	1568	8810		
8	2680	8397	2102	8960	8996	8642	8300	8113	8228	5473	2520	4050	4940	8530	8270	8718	8498	0150	1142	1428	0150	1082	8830	2703	0578	4320	4330	4160	8530	2440	8186	5655	8355	8146	8094	8967	8260	8707	8430	0800	8911	8868
7	2626	2854	0280	0649	7015	7275																																				



Crane split

Color legend



Port 3

20	665	288	567	3640	7856	7580	8966	8956	347C	5382	640	200	200	100	579	Ubb	100	584	200	200	486	602	557	490	200	Ubu	200	411	573	5045	7871	8883	8843	3636	7821	100	476	590	489		
19	667	647	637	8539	8298	8460	8551	8794	300C	572C	200	200	200	200	567	614	357	669	503	607	456	203	661	437	200	U43	543	440	551C	802	8476	8473	9003	7406	8501	055	U04	688	U11		
18	667	667	667	7201	8114	8442	8108	8733	336A	579C	674	634	600	714	200	517	527	546	U04	275	198	664	623	542	632	431	431	496	520	5076	7008	8042	9084	8464	693	346	693	507	614	424	
17	671	671	669	8461	8791	8567	8426	8741	340	562C	200	669	200	673	200	405	090	200	266	578	429	480	200	562	U27	400	U42	505C	814	8983	7436	8805	7567	8952	200	511	542	U95	U95		
16	668	628	200	7063	7927	7286	8369	7247	339C	534C	200	583	200	200	655	492	858	509	578	Ubb	705	510	200	633	531	200	484	557	5622	8459	8914	7464	7493	8339	630	U43	200	449	U95		
15	640	200	200	7696	8306	8242	8963	8529	313C	571C	200	200	200	684	472	674	587	234	568	487	200	U71	681	U04	U70	200	414	628	497	579C	573	8219	8855	8722	8119	8115	044	418	200	151	
14	678	482	625	8732	8250	8710	8090	8046	329	545	617	U95	579	446	200	6554	425	680	597	200	457	200	470	200	470	200	511	537C	806C	7904	8463	8309	9227	8610	200	420	200	522	U95		
13	499	225	200	8024	8551	8706	7416	8293	344	559C	200	U41	6879	481	856	200	034	608	426	954	200	589	436	200	589	435	200	463	568	578	8982	8531	8797	6487	8692	665	678	659	449	U95	
12	64	409	200	489	9017	8171	8662	8784	8615	328	542	200	424	200	515	200	589	Ubb	574	487	200	200	100	U45	200	200	419	576	597	8395	8204	8171	8610	8419	200	553	200	200	200		
11	612	406	655	Ubb	8744	8991	8287	8799	8844	323	562C	622	442	200	526	678	300	425	Ubb	Ubb	200	569	478	Ubb	Ubb	200	70	445	817C	853	8532	8678	7140	8712	8427	200	675	U95	631	U95	
10	200	U41	581	Ubu	8805	7273	870	8445	8708	396	581	100	464	461	658	100	637	523	644	690	653	430	200	200	200	200	U41	526	7524	8218	9074	7980	8169	8378	180	U71	095	200	200		
9	371	561	U94	7546	8550	8854	8305	7044	351	586A	200	U41	656	498	200	61	U94	522	Ubb	080	411	200	590	439	200	600	559C	8268	8356	7690	8136	8654	8378	U95	320	U95	200	200			
8	499	540	642	8541	7167	8457	8275	7543	310	500A	300	460	111	441	200	335	432	620	070	680	667	100	424	644	636	Ubu	7015	594	622C	8995	8666	7122	8548	8817	7061	280	U95	200	523	U95	
7	1205	Ubb	200	101	8848	8523	8570	8939	8990	328	330C	200	200	200	455	300	596	530	200	456	579	Ubb	200	Ubb	Ubb	643	635	498	200	356	609C	7835	8103	9570	7705	7229	7447	300	U01	621	408
6	711	032	283	7341	8569	7742	8353	7957	369	581	616	611	U71	712	582	635	493	200	416	707	Ubb	620	472	610	310	308	579C	8883	8116	9225	7907	8747	7263	300	527	594	301	U95			
5	581	200	675	8413	8155	8075	7607	7996	318	575C	200	200	200	711	550	421	528	200	U41	1360	458	544	U32	530	530	300	382C	826	7500	7478	9109	8454	8829	8379	660	478	200	200	U95		
4	276	709	575	041	8860	8406	8023	8613	8841	303C	592C	310	635	200	462	272	547	455	624	429	200	534	300	697	432	200	390	621	7010	8930	7387	8622	8668	8825	300	U24	542	459	U95		
3	604	318	200	317	7108	7088	8793	8360	8185	330	514	200	200	200	543	700	470	563	875	U42	1509	302	200	661	415	200	310C	550	8165	8533	7888	8531	9132	8307	690	448	200	518	U95		
2	289	330	200	7987	8582	8210	8152	8179	326	531	200	557	549	567	Ubb	516	300	691	516	200	455	200	467	693	479	200	394	604	8890	8628	7539	8186	9143	8326	159	U28	200	515	U95		
1	631	548	200	611	8585	8253	7429	7105	8333	357	598A	489	U95	200	454	687	200	200	485	200	200	588	Ubb	Ubb	560	508	655	302C	800C	8539	7709	8948	7000	525	817	581	535	200	200		

Tier 12

Tier 11

Tier 10

Crane split

Color legend



Port 3

20	540	490	232	534	705	728	9560	9458	8877	3692	5270	U72	200	636	618	157	450	443	440	548	632	704	529	570	712	5025	575	3555	8431	8112	8732	8989	453	437	180	Ubb							
19	521	338	188	188	596	8938	3566	8874	7268	3375	5207	425	U22	310	631	323	476	666	320	497	364	200	599	200	U24	Ubb	3305	537	3193	8066	8317	7817	8131	061	614	200	481						
18	U22	604	U72	188	7626	8843	8995	8757	9053	5522	5030	188	Ubb	300	701	U71	404	500	328	308	188	688	200	200	200	5585	6130	8924	7629	8273	7782	7177	593	200	650	475							
17	413	641	641	726	8090	7773	8315	8213	888	5370	623	200	Ubb	424	300	941	200	085	500	1061	696	200	200	200	200	5635	534	7319	9220	7433	8241	8496	473	U44	621	457							
16	242	494	200	200	549	951	759	7368	7982	8400	5170	542	200	581	414	419	3718	438	136	459	576	406	188	431	591	489	200	200	634	5330	6395	8530	7446	8994	8764	563	200	Ubb	5920	655			
15	185	U51	200	300	7117	7351	7196	8230	8014	9965	5810	200	616	472	U34	200	358	170	202	Ubb	200	629	661	600	200	468	550	5380	585	7480	8473	8463	8340	8542	172	504	130	097					
14	707	171	620	585	9488	8355	7344	7003	7136	8427	5227	200	U74	Ubb	316	1275	1746	541	200	U7b	415	661	200	200	546	516	5877	5220	7644	7139	8033	7142	7771	638	188	607	645						
13	708	659	357	711	8561	8402	8957	7137	8474	1102	5150	200	678	200	700	531	045	692	677	U34	428	674	Ubb	310	Ubb	512	541	8435	7508	7356	686	8069	443	200	535	200							
12	220	200	U72	200	9294	8090	8886	8594	8131	9432	5667	200	519	200	446	188	603	188	200	534	200	638	607	537	601	699	U91	5010	584	5897	7547	7686	7743	8345	8601	200	529	420	200				
11	248	675	185	200	8085	7184	8147	7006	8216	996	5320	626	408	415	210	310	508	6486	680	258	188	682	182	613	433	703	691	200	5437	827	8475	8272	7425	9565	8422	411	604	U51	180				
10	130	425	410	518	7710	8319	8179	8111	7282	840	5264	200	622	574	082	300	709	200	651	200	578	200	220	488	479	5430	7408	8537	7955	8251	8949	7058	084	578	609	631	200						
9	235	235	659	8985	8021	8598	8159	7170	8430	3330	685	696	200	407	586	200	689	590	651	080	537	200	491	Ubb	479	541	591	7227	8597	7932	8503	8320	5689	544	116	3103	681	200					
8	U51	502	Ubb	200	7057	8398	8779	8315	7637	8487	5550	466	602	Ubb	200	595	592	U94	551	874	504	188	525	536	408	505	651	7089	844	5660	8914	8475	7391	8716	8550	7541	184	Ubb	200	Ubb			
7	2270	Ubb	606	130	7250	8231	8295	8150	7510	3329	5670	519	200	686	U7b	563	090	220	200	444	445	431	524	578	200	200	458	333	5770	7514	7573	7052	8495	8442	8492	188	200	188	200				
6	494	36	211	301	8101	7497	8095	8886	8980	5140	590	200	424	659	616	294	230	Ubb	403	553	569	516	423	690	U72	469	478	525	577	7509	8908	8020	8263	8619	8870	497	699	300	026				
5	667	U48	300	1519	9981	7572	8491	7653	8508	8590	5850	519	452	200	490	521	230	200	U24	3853	176	200	409	528	675	U9b	409	200	5000	7708	8524	7682	8399	8877	7695	474	590	300	501				
4	067	Ubb	056	314	8894	8521	7370	7840	8866	8890	5750	447	604	Ubb	200	174	032	129	566	200	625	486	489	200	613	200	200	5630	8190	8445	8220	8866	8357	8768	8540	188	614	200	182				
3	297	649	065	7606	8527	7556	8045	8251	8297	5330	200	442	654	200	432	646	049	675	8047	277	200	200	200	480	586	334	5010	8429	8422	7952	8453	580	8400	636	200	200	Ubb	200					
2	545	100	145	385	8270	7852	8146	8997	8796	8040	5190	557	711	U34	Ubb	957	200	Ubb	430	548	534	622	672	648	200	3419	5492	7083	8410	7439	7993	8287	8636	074	200	Ubb	200	Ubb					
1	833	200	U48	300	8673	8465	8127	8043	8801	8745	5090	559	502	200	688	200	188	619	200	619	034	602	075	U7b	200	533	5019	5535	8471	8490	8699	8502	8909	8617	063	675	686	834	200				
20	590	190	662	9937	8527	8038	8036	7845	8250	5790	200	691	188	200	200	332	200	278	200	2378	200	188	572	560	200	473	628	548	8400	7651	7260	9336	8486	8162	188	200	Ubb	542	200				
19	441	Ubb	065	200	8405	8522	7111	8519	8625	5710	5247	485	U33	U2b	200	956	071	200	U94	200	158	036	644	637	688	200	617	8160	8010	7486	8199	7657	7042	8322	031	Ubb	566	561	200				
18	Ubb	165	200	8498	8465	7556	8164	8134	8437	5740	200	426	188	200	620	U74	200	419	200	139	281	704	188	628	449	188	474	5220	5290	5400	7033	7798	7642	8239	7969	200	U24	200	200				
17	565	U44	500	7227	8988	7741	7810	8544	8920	5367	656	706	671	200	451	600	213	642	2410	656	486	465	664	200	5895	639	188	666	5677	832	7886	7333	8451	8440	8502	Ubb	436	200	200				
16	246	547	711	501	7113	7878	7812	8401	8752	8305	5727	200	Ubb	679	471	2398	514	115	694	200	596	626	200	444	200	5730	8411	7723	8412	7132	7120	7437	188	200	188	6754	200	200					
15	307	200	638	157	7062	8461	8075	8452	8178	8231	3088	478	526	7018	404	454	811	164	310	200	992	200	605	515	674	424	U94	5700	8100	8067	7889	8632	8844	8151	134	5735	234	041	200				
14	682	229	Ubb	200	8627	8436	8389	8373	8194	8600	8080	U2b	188	200	567	843	1334	8946	600	200	200	200	200	619	624	200	U74	U94	5375	8267	7455	7305	8223	8381	7658	625	514	200	440	200			
13	449	482	340	200	8574	8126	7067	8472	8091	8935	5590	645	200	444	464	200	242	375	660	U74	562	200	200	200	424	483	5760	8920	7364	8854	8154	8331	7081	466	534	200	200	200					
12	607	200	526	200	8907	8508	7724	8595	8615	8475	5994	200	412	200	200	5955	695	200	586	638	648	200	648	200	490	200	595	835	8605	8995	8925	8918	7195	569	052	188	200	200	200				
11	38	041	155	476	7765	7151	7206	8474	8827	8900	8410	200	200	200	200	8602	624	163	200	200	200	200	200	200	200	200	3990	838	8742	8302	8785	8347	8735	485	188	200	635	200					
10	071	501	200	U2b	8504	8145	8120	8993	8086	8114	5970	537	188	634	200	644	115	200	300	200	692	200	U94	390	U94	601	520	188	607	5280	7064	7992	8771	7417	8371	8536	201	188	096	300	200		
9	257	200	200	300	8921	8455	7193	8960	8442	8695	8190	506	586	439	188	188	635	585	554	619	487	652	290	518	695	200	366	536	8426	7770	9055	7009	8416	8226	188	222	3980	623	200				
8	5658	162	200	200	8987	8249	7333	8704	8290	888	5270	696	605	200	604	422	310	484	292	606	Ubb	615	188	684	555	Ubb	328	5040	8297	8264	7654	8026	8380	8726	078	696	055	623	200				
7	3832	1256	673	402	8935	8453	8197	7145	8238	8330	8110	599	648	533	188	170	350	499	200	616	200	200	200	200	200	200	598	545	675	8097	513	339	5500	8100	8954	7825	8554	8009	8312	188	695	188	477
6	487	200	041	314	7820	8078	7745	7246	7828	8370	5620	470	461	551	188	660	171	134	434	189	200	486	466	U24	200	699	432	512	5075	8249	7021	8903	7766	7401	8700	U94	405	641	163	200			
5	421	473	200	1154	8309	8662	8095	8789	7295	8377	8051	200	411	585	409	826	200	572	420	200	2431	237	200	558	200	632	3608	5207	8543	7101	8494	7530	8728	7702	465	200	545	200	200				
4	325	424	1265	167	8544	8113	8368	8543	7625	8619	8080	566	U51	482	5915	595	0260	358	217	526	624	416	200	672	647	704	454	432	380	8310	8613	7414	7648	8692	7928	8877	200	200	200	103			

20	597	U96	37	697	728	591	971	8016	7259	3532	5360	609	3000	3000	2027	574	295	676	2099	3000	3000	664	U96	648	3000	3000	5960	5000	9137	9508	8673	8839	8570	3000	3000	3000	3000					
19	518	039	368	707	8202	707	9025	8006	8533	3940	5031	3000	3000	447	601	U96	027	405	655	571	662	1223	2935	3000	419	509	U96	5440	8000	9079	8736	9415	8052	8332	331	8205	546	691				
18	462	3000	362	5410	7881	656	9005	619	681	8800	5380	517	551	685	3000	456	636	558	560	138	173	499	3000	704	3000	583	3000	5914	6007	3779	7640	8933	3590	8576	485	603	3000	3000				
17	579	3000	69	629	8240	8162	517	9433	7423	3300	5860	3000	3000	408	499	3000	3610	563	3652	564	3000	3000	441	611	3000	641	6033	681	5900	8161	9121	7597	8362	8320	8073	3000	651	514	3000	3000		
16	048	315	330	481	754	952	7880	7534	8593	3672	5362	538	3000	524	3000	3000	3052	556	219	U96	3000	415	663	530	3000	660	489	593	537	6041	9330	8811	9158	8858	7452	3000	3000	1565	458			
15	353	3000	U96	383	5690	711	8076	8789	8887	3320	3370	3000	3000	673	985	3000	121	382	13	708	3000	3000	3000	3000	3000	608	5205	526	8798	9396	9056	8067	8730	091	6038	26	181					
14	422	202	456	3000	3494	7333	8339	8512	8659	3770	5394	446	U96	532	3000	455	291	1547	1050	3000	691	3000	700	3000	583	658	510	441	449	490	516	5290	5290	9157	8865	8039	8799	7030	473	832	3000	955
13	6185	089	463	3000	8902	8404	8911	7149	7783	335	5280	435	658	3000	573	957	605	272	3000	109	U96	436	567	478	3000	3000	664	6568	583	539	7684	7645	8114	7361	8511	311	075	3000	496			
12	U96	036	4012	3000	8915	7666	880	7671	8053	328	5880	3000	639	525	U96	3000	688	5402	617	U96	3000	496	58	536	414	3000	6325	3000	426	5650	8015	9532	9141	7578	7049	8234	U96	288	3000	3000		
11	2188	065	201	3000	9253	8072	8538	8802	9069	569	5480	625	3000	58	547	654	470	3000	6906	37	3000	705	3000	696	3000	3000	3000	530	843	9064	7078	9189	9470	8808	246	3000	035	497				
10	8810	6356	695	3000	7785	8987	9125	8517	8570	3502	5474	441	3000	697	458	564	316	3000	609	U96	3000	431	453	536	479	579	442	430	470	3064	8367	8304	8211	8226	8316	8512	289	644	278	509		
9	535	326	467	3000	8842	7777	9159	8989	8990	3980	3060	441	658	686	458	3000	599	609	078	484	117	437	318	3000	459	444	589	490	331	834	9351	7068	9264	9148	9588	8248	437	084	2477	3000	3000	
8	8902	338	3000	474	7535	7346	8475	8573	8685	332	5010	406	3000	3000	U96	3000	590	428	124	3000	680	516	3000	U96	710	603	6452	3115	5320	9186	7676	8884	8398	7468	8458	1589	3000	2931	490			
7	3683	1636	3000	263	8376	8994	7361	8125	7253	337	3810	3000	U96	524	3000	3000	220	347	568	439	454	6875	500	661	618	665	3000	3000	350	502	9523	9323	7112	9376	7091	7544	3000	610	414	1151		
6	646	430	285	288	8925	8478	8963	8846	7045	374	5190	3000	485	549	663	613	142	037	682	037	445	3000	386	6555	657	526	427	429	332	507	8758	9543	8802	7301	9205	7989	7053	684	3000	258		
5	523	538	595	1534	292	5680	8140	8167	7999	372	5190	3000	705	640	3000	515	U96	491	702	8869	288	657	3000	641	600	436	333	313	7128	9164	8624	7604	8875	8048	8875	811	629	3000	509	3000		
4	145	U96	3299	270	8948	7349	8545	8348	8967	311	5257	489	621	3000	6238	698	220	170	263	637	492	496	3000	665	628	3000	3000	305	552	8444	9196	7719	8040	7017	9119	061	3000	633	236			
3	U96	368	3000	332	8200	8536	7459	8965	8660	308	5590	564	656	676	412	3000	418	622	254	1011	2185	088	649	411	3000	3000	523	3000	3814	513	7797	7691	9799	8799	8088	7100	582	701	3000	376		
2	196	1395	14	052	7404	8510	8979	8780	8546	3992	552	3000	U96	452	3000	584	U96	386	611	631	3000	520	3000	628	583	3000	399	5290	8120	8789	8515	8833	7872	8039	025	834	058	611				
1	550	025	3000	770	8570	7092	8782	8177	757	572	3000	3000	3000	442	587	U96	410	346	423	421	3000	377	074	403	700	693	532	516	495	589	556	7582	9129	7809	7477	9554	831	820	629	3000	3000	
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19	3000	1439	177	3000	8800	8054	8555	8579	8471	8850	560	449	3000	685	515	103	208	3000	694	1849	3797	3000	3000	582	421	467	3000	5640	818	7960	9446	9057	8753	7397	564	1222	601	U96	3000			
18	431	8880	040	682	9188	7168	820	8081	8013	823	5270	612	3000	418	3000	618	U96	642	353	663	553	117	3692	431	518	460	3000	433	U96	5664	5530	9535	8110	9202	7469	7650	1506	3000	129	3000		
17	3000	625	3000	3436	8176	8370	7942	8240	8620	3350	3000	3000	444	3000	507	138	426	3121	496	U96	528	U96	3000	6681	631	6281	3000	567	5740	7694	9408	7118	9556	8532	3000	3000	589	3000	3000			
16	154	195	326	452	8470	7245	8430	8063	8667	8230	5690	3000	511	627	1534	504	622	524	3000	598	653	405	3000	434	3000	634	3000	567	8384	7756	7347	9327	8749	9424	577	642	829	6729	3000	3000		
15	029	433	500	275	8496	7443	7772	8002	8044	8840	321	589	408	6277	570	429	695	200	205	1065	3000	3028	518	679	565	418	443	635	593	552	578	9035	7972	8725	8001	5511	184	3000	275	081		
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13	3000	063	169	471	8313	8972	7869	9481	7655	8230	5800	427	675	5678	410	3000	310	356	3000	220	3000	5773	U96	495	3000	3000	452	3000	325	5702	7036	8936	8738	7634	8529	074	2563	352	633			
12	U96	159	3815	170	3229	7084	8011	8623	7498	823	5360	3000	418	564	3000	6414	U96	405	642	3000	3000	642	405	642	490	3000	606	4990	5272	3354	7156	7913	8766	8514	8882	428	048	700	U96	3000		
11	2381	1319	379	3000	9589	8135	7013	8559	7121	3692	575	521	474	3000	3000	265	3000	3000	3000	3000	446	571	U96	433	6062	590	U96	5420	529	7689	9283	7339	9586	8081	298	407	3850	3000	3000			
10	1452	3000	697	691	8975	8431	8413	8469	8928	886	526	6988	492	595	542	3000	090	593	125	543	533	2010	559	3000	U96	516	3000	563	5290	8379	8405	8513	7716	7908	9214	849	435	024	3000	3000		
9	3000	032	469	3000	7692	7977	8196	8991	9281	328	309	676	3000	3000	576	3000	U96	2530	519	087	3000	166	472	55	456	463	58	335	343	9163	7118	7180	7431	9043	964	451	612	1022	599			
8	1434	232	6742	669	7979	8492	8816	7959	8823	3420	5210	459	424	550	3000	655	3000	3000	3000	3000	3000	405	3000	405	U96	479	U96	5718	582	5497	8558	7624	9399	9278	8664	7966	1031	U96	665	040		
7	2795	3620	3000	183	8059	8130	8969	8632	8123	3830	652	543	3000	432	3000	176	028	551	400	3000	5657	3000	706	3000	502	6406	485	342	594	5598	9142	8036	8129	9556	8660	3000	506	650	8285			
6	417	526	308	282	7958	8913	7773	9211	8022	327	5970	3000	553	627	511	3000	089	2837	406	220	432	3000	286	6611	697	3000	559	551	420	518	8330	7024	8924	7515	8491	8049	3406	200	U96	127		
5	681	3000	555	2938	9340	8763	9333	8281	8960	3720	5550	U96	U96	666	U96	482	320	682	484	3923</																						

20	1522	2221	045	6207	343	761	7174	325	3497	343	529	572	609	531	535	134	472	3642	522	2882	446	646	456	431	649	555	532	543	3680	7592	342	3548	7020	273	2146	045					
19	572	1488	095	776	776	703	180	7444	9144	3032	5190	409	656	6993	629	270	227	496	688	521	2322	1210	537	5784	596	613	547	528	3966	3279	324	7178	3231	028	2242	711	452				
18	445	2699	2851	6091	7147	3337	262	3161	3330	5482	5730	496	680	473	390	253	2799	525	2042	691	239	253	488	639	418	526	5931	7951	9124	7405	3420	3447	1599	586	392	040					
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15	1326	055	1262	069	3331	7538	387	3079	3497	312	5065	676	488	488	488	6172	430	114	091	128	453	1348	20	623	669	641	478	70	592	333	3919	7144	3244	374	3745	168	098	3214	1892	081	
14	2437	2525	046	503	3500	3017	3105	3221	7492	3627	5645	420	6311	496	505	469	047	174	2267	535	3450	2069	602	409	453	6104	5473	5530	3390	3291	3778	773	3291	3025	0420	2941	1888	534			
13	5826	151	030	418	7863	3183	7096	3878	7254	3430	3350	5954	428	6732	420	420	247	174	670	104	232	5396	509	602	6909	488	6695	5152	5812	7888	3669	7763	775	364	1429	1258	1888	040			
12	428	2176	1225	176	7457	3792	3145	7925	7499	3542	5950	433	436	533	6153	3011	463	2182	685	520	412	649	500	6756	638	5230	6307	4410	512	5610	3397	7595	7331	362	7714	3556	6895	067	040	672	
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9	035	204	4021	512	7568	3363	7104	3543	7559	3430	5670	500	436	438	6545	3218	587	217	3222	221	087	528	346	457	550	491	3307	3400	3334	3871	3004	3581	3326	3577	054	2791	2632	600			
8	1989	076	1737	486	3743	7340	3587	3388	7369	3927	5250	420	638	705	520	630	5792	2603	529	259	051	473	1421	631	6031	465	665	6789	3172	5157	3592	3047	3845	7542	7134	3444	2813	3370	1587	6053	
7	2470	3678	620	071	3734	3583	3373	3367	3242	3913	537	483	507	688	619	085	3071	441	026	575	6401	087	706	707	579	6216	510	336	5890	7298	7073	7965	3696	3015	7332	5521	040	523	3078		
6	3702	064	174	3929	7303	3752	3792	3766	3810	540	540	504	5774	484	392	3854	311	578	102	578	102	260	6063	607	510	500	645	543	538	3977	3498	3317	7355	7348	3157	2260	1481	040	045		
5	6440	3659	053	1048	3024	7922	3097	7138	7660	3701	5510	570	5896	420	5896	1946	040	626	1946	040	2575	123	425	610	5618	475	529	529	5587	3832	3201	3976	7165	3600	362	6796	040	040			
4	071	1887	3878	063	7224	3321	7188	7588	3377	3650	538	415	426	426	051	1606	1243	4630	046	040	475	446	412	467	664	6836	3900	5827	3571	3586	3173	3599	7074	3418	083	3148	423	118			
3	346	6987	064	3647	3479	238	3971	3507	3170	526	488	646	544	040	477	300	346	2070	2169	2972	434	405	457	040	040	373	535	3268	3738	3813	7187	7847	3445	404	059	462	372				
2	237	2694	1919	1207	3050	7583	7330	3973	3163	3410	5630	427	5401	476	428	051	051	2225	2346	6830	2118	462	539	451	340	574	3254	7829	7462	7054	7155	3985	155	152	192	231	040				
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20	2649	3613	2366	6689	3723	3489	3362	3080	3951	3112	5770	524	665	413	072	1352	560	3453	094	6598	461	416	412	556	429	548	546	5760	3462	3863	3448	3731	3487	300	306	1736	2894				
19	470	2272	1953	6478	3175	3094	3794	3554	3754	315	569	500	433	5767	583	30	132	476	462	2981	2114	711	5820	526	6880	4910	453	5100	317	3485	3462	3655	3267	7124	244	2771	403	454			
18	1116	1136	3327	392	310	325	3276	349	3107	592	556	457	643	607	670	520	3304	299	101	078	3384	5010	641	6449	710	584	532	3852	7419	7235	731	3008	3344	491	178	040	040				
17	538	6624	048	3431	3572	3174	337	3116	7169	3110	5040	697	420	564	447	396	430	2224	056	088	1799	499	641	040	502	6335	5720	302	7817	7990	3528	3641	3564	040	2679	040	450				
16	106	1216	3693	2702	3862	3365	3984	3496	3629	3902	3350	532	548	4910	463	3878	7125	068	1306	6341	1912	4030	529	6260	630	5290	325	7322	7281	7776	7281	7776	7281	7776	7281	7776	7281	7776	526	549	
15	2459	2889	3472	083	3904	7774	3270	3549	3539	3074	448	5944	7075	5710	3397	62	044	1784	054	508	1950	048	471	530	475	492	040	5290	325	7322	7281	7776	7281	7776	7281	7776	7281	7776	526	549	
14	1920	1783	476	6096	3929	3856	3513	729	3408	396	3110	645	6958	6049	6128	7068	1282	2704	2859	4390	3925	1937	4250	417	6787	563	538	6319	582	3390	3097	3603	3480	3118	3849	064	3100	083	054		
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12	5487	3032	3451	361	7622	3417	321	3338	3524	3322	5460	4790	539	5651	040	610	2725	562	178	040	671	0430	5888	639	6608	6894	6067	6614	5490	5540	3350	3400	7939	3872	7757	3538	3859	5489	089	097	530
11	2155	1277	3706	462	7079	7528	223	3917	7336	3942	5840	6844	6643	482	6133	523	6670	1405	2018	1651	1651	497	550	16848	6894	6067	6614	5490	5540	3350	3400	7939	3872	7757	3538	3859	5489	089	097	530	
10	2643	512	1647	7940	3640	3584	708	7110	338	548	6912	486	492	587	38	5320	085	422	3245	2092	4660	040	5558	6899	5840	3901	7647	7300	7394	7962	3975	2493	556	1477	5307	040	040				
9	1665	230	3279	6521	3050	3133	7199	3887	3440	326	568	436	423	6581	3995	54	074	3272	1053	3221	502	046	531	538	040	316	565	3054	7154	3239	7001	3370	3923	1715	3049	1568	454				
8	2680	339	2102	7050	3996	3642	3300	3113	322	5470	560	570	448	451	040	3718	3498	447	049	1140	063	3392	4720	5554	638	689	5390	7011	3411	7019	3491	3954	3468	2977	2278	3557	040	040			
7	2626	2854	064	7015	7275	3138	3300	3113	322	5470	560	570	448	451	040	3718	3498	447	049	1140	063	3392	4720	5554	638	689	5390	7011	3411	7019	3491	3954	3468	2977	2278	3557	040	040			
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4	3408	1249	2970	174	7354	7454	779	3513	3512	347	5430	616	488	508	5704	479	3736</																								

20	068	867	892	872	859	837	801	725	688	688	882	819	961	994	990	889	771	209	759	944	956	840	792	205	913	950	867	883	867	848	969	810	797		
19	027	85	835	820	770	802	800	853	2017	814	872	924	96	863	889	10	728	12	293	749	738	83	739	969	734	907	873	941	805	833	820	921	777		
18	150	888	858	800	800	800	800	868	800	872	824	96	863	889	10	728	12	293	749	738	83	739	969	734	907	873	941	805	833	820	921	777			
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13	618	836	902	890	840	831	714	778	800	800	277	869	800	800	754	119	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	
12	851	401	891	866	880	877	805	800	800	800	610	825	875	840	942	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	
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9	885	955	884	777	815	898	899	911	737	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	
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7	866	163	95	775	837	839	836	812	725	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	
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20	990	754	011	030	800	854	801	778	876	869	2066	108	800	800	876	895	726	800	282	092	898	800	800	800	800	800	800	800	800	800	800	800	800	800	
19	143	876	880	805	855	757	847	780	800	800	777	107	99	965	829	800	18	879	727	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	
18	730	888	965	818	816	820	808	801	879	967	117	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	
17	040	748	948	843	817	837	794	824	117	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	
16	732	847	724	833	808	866	959	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
15	802	991	926	701	766	776	898	877	879	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
14	818	992	831	897	766	848	765	959	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
13	822	868	808	801	862	749	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
12	238	131	812	788	813	701	855	712	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
11	145	895	942	897	843	841	848	892	870	740	698	840	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
10	815	877	728	769	797	819	899	928	779	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
9	143	731	677	804	797	849	831	795	832	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
8	279	862	891	805	813	896	863	812	733	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
7	762	894	845	795	891	747	821	802	800	842	805	804	98	770	846	800	263	8054	852	800	926	861	800	800	800	800	800	800	800	800	800	800	800	800	800
6	800	921	293	834	876	833	828	866	988	796	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
5	283	240	100	835	871	805	752	846	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
4	93	863	796	855	837	808	865	785	812	111	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
3	262	869	911	851	854	803	877	949	718	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
2	277	714	856	876	877	878	819	893	799	894	672	869	806	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
1	180	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
20	998	04	731	751	752	732	782	893	800	934	995	862	864	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	
19	900	771	801	882	780	820	834	858	806	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
18	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895	895
17	002	718	060	854	821	831	823	876																											

