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A SIMULATION STUDY FOR NEXT GENERATION TRANSSHIPMENT PORT

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ABSTRACT

As the global container logistics, especially the transshipment services, keep increasing, substantial improvements on both port storage capacity and port throughput rate are necessary. Besides, the future challenges of getting skilled labor and the rising labor cost have been bothering port operators. Automated Container Terminal (ACT) is a promising solution to these challenges. This study firstly introduced two new conceptual transshipment hub designs. Then the simulation models were designed respectively and the analytical results revealed pros and cons for both systems. Besides, the land utilization and capacity of two ACTs have also compared among advanced contemporary ports in the world.

1 INTRODUCTION

The amount of international trade is rapidly increasing in the past few decades as a result of globalization. More importantly, over 90 percent of the world's trade is moved by ships and containers (Dillon 2000). In the increasing trend of world container shipment, transshipment activity is taking a larger proportion every year and the trend is expected to continue (Zhen, Chew, and Lee 2011). Therefore it is essential to study the transshipment hubs where transshipment of containers is the major activity.

Increasing quantity of containers and limited yard space have brought tremendous pressure to international ports to find new container terminal designs, which have a higher throughput rate and larger storage density. In addition, the future challenges of getting skilled labor and the rising labor cost have been bothering port operators. Therefore, high storage density, automated container terminal is a promising solution to improve the performance of container terminals and to meet the challenges of the future in marine transportation (C.-I. Liu et al. 2002).

The age of Automated Container Terminal (ACT) has come as many of them have been adopted in several ports in the world. Choi and Ha have studied the Automated Storage/Retrieval System under port environment which has been tested in Korea (Choi and Ha 2005). Ioannou and Kosmatopoulos studied loading and unloading algorithms using Grid Rail system (Ioannou et al. 2000). Liu et al. (C.-I. Liu et al. 2002) analyzed and evaluated three different ACT concepts: Automated Guided Vehicle based ACT (AGV-ACT), Grid Rail based ACT (GR-ACT), and Automated Storage/Retrieval System (AS/RS). They used simulation models with the same operation scenario to evaluate their performances and associated costs and result showed both GR-ACT and AS/RS perform better than AGV-ACT. In spite of a variety of studies on new ACTs, most are catering for gateway ports and few have adopted new concepts at the yard side. In addition, ACTs are experiencing similar problems like low system productivity and small storage capacity,

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besides, as quay cranes and transfer devices improve, the bottleneck gradually shifts to the yard side. Therefore the study to raise the yard side efficiency is imperative.

This study addresses the design, modeling, simulation and evaluation of two new automated terminal concepts, namely Frame Bridge based ACT (FB-ACT) system and Goods Retrieval and Inventory Distribution (GRID) system. The FB-ACT design has been developed by Shanghai Zhenhua Port Machinery Company (ZPMC), which utilizes multi-storey frame bridges and rail-mounted trolleys to transport containers between the quay and the yard. The GRID-ACT is introduced for the first time in maritime studies and it takes advantages of both GRID system and Automated Lifting Vehicle (ALV) system. For these new design concepts, this project makes an explorative study to identify the challenges and opportunity for them to be applied in transshipment hubs.

2 AUTOMATED CONTAINER TERMINALS

2.1 FB-ACT: Frame Bridge-based Automated Container Terminal System

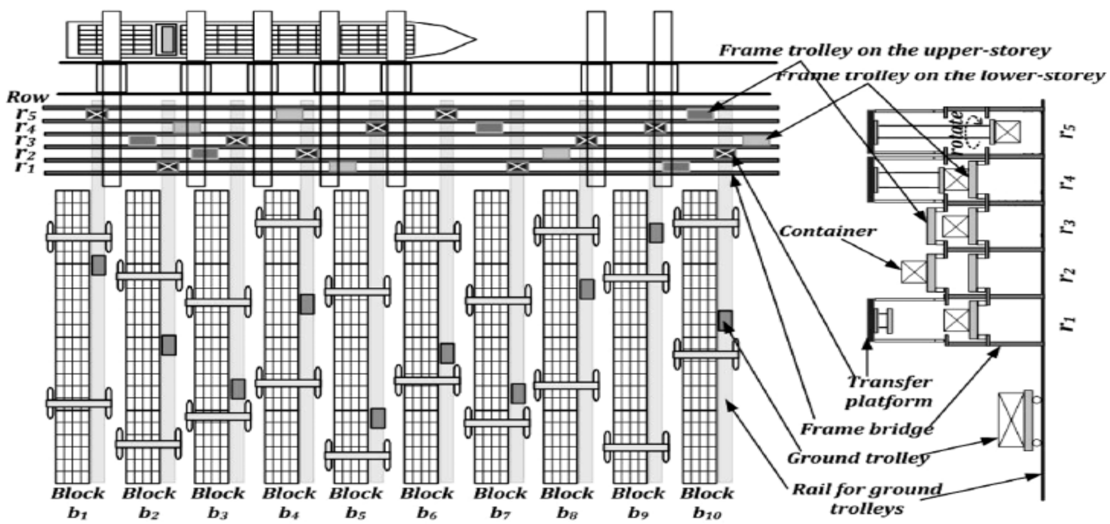

Figure 1: Configuration of the FB-ACT.

As the name suggests, FB-ACT is a new ACT system based on multi-storey frame bridges and rails, on which electric trolleys transport containers between the quay and the yard. Figure 1 is an illustration (not to scale) for a FB-ACT.

As shown in Figure 1, the transport vehicles in FB-ACT are two types of trolleys: ground trolleys traveling in vertical directions on the rails; frame trolleys traveling in horizontal directions on the two storeys of frame bridges. The connection between these two types of trolleys is the transfer platform, which is a type of rail-mounted bridge crane and can move slowly on the rails of the highest storey in frame bridges. During the operation process, the transfer platforms stay at a cross point of a ground rail and a row of frame bridge. They are not stationary, but can move slowly along the frame bridges. The main function of the transfer platforms is to lift (or put down) containers between the ground rails and the rails in multi-storey frame bridges; in this process the containers are also rotated for 90 degrees by the transfer platforms. On the yard side, a vertical yard layout is used and each storage block is accompanied by ground rails with ground trolleys. During the unloading operation, containers are put down from quay cranes (QC) to the frame trolleys and then transported horizontally along the rails. At the transfer platforms, the containers are rotated for 90 degree and put down from the frame trolleys to the ground trolleys. The ground trolleys then transfer the containers along the vertical rails to the planned stacking location. The loading operation is performed similarly in the reverse order.

This interesting new ACT design has several fundamental differences from other mainstream ACT designs. The first difference is that it removes the need for ground transportation vehicles (AGVs) and uses rail-mounted trolleys (flat cars), which reduces the initial investment as AGVs along with their controlling systems are typically quite expensive. In addition, the rail-mounted trolleys also promise higher speed than AGVs. Another merit is the elimination of excessive yard crane (YC) movement. In this design, the ground trolleys are able to deliver (or pick up) containers accurately to (from) the slot in blocks, which reduces the slow movement of YCs. These changes can increase the efficiency of the yard. In addition, some other advantages of FB-ACT are listed as follows: (1) pro-environment: it is powered by electricity without diesel engines, which is both cost effective and environmental friendly; (2) high efficiency: trolleys just run in their dedicated straight rails, thus they can run fast, and each trolley (ground trolleys and frame trolleys) can carry two 40-ft containers, which are placed side by side; (3) simple control: there is no need of drivers, navigation equipment, nor complex control systems; (4) low investments: its cost may be lower than some other commonly used ACT systems.

2.2 GRID-ACT: The Goods Retrieval and Inventory Distribution Automated Container Terminal System

2.2.1 Single GRID Design

The Goods Retrieval and Inventory Distribution (GRID) system was first developed by BEC Industries, LLC (BEC) as a new concept to optimize land utility and improve productivity in a container terminal. The storage yard is covered by a single GRID, which consists of a multi-directional overhead rail and Transfer Units (TU).

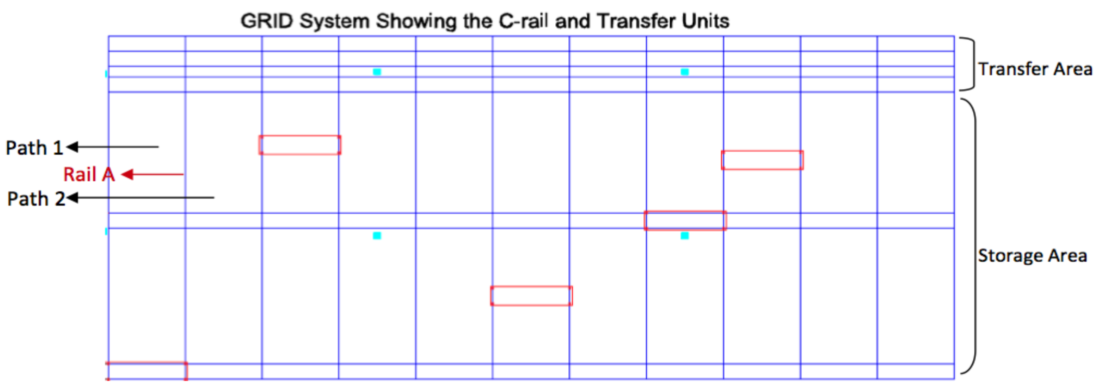

Figure 2: Basic GRID system structure.

As shown in Figure 2, the overhead rail consists of two parts: transfer area and storage area. The transfer area is where TUs receive or deliver containers and interchange with the transportation system. The storage area is where containers are stored. The TU, represented by a red rectangle in Figure 2, is essentially an under-slung bridge crane that is capable of moving in the X and Y directions while being suspended from the overhead grid. It has access to any part of the GRID and handles every aspect of container movement within the facility.

2.2.2 GRID-ACT system

GRID-ACT consists of three sub-systems: the quay side, the ALV transportation system and the GRID systems at the yard side, as shown in the Figure 3. The transportation system is the area in between the quay side and yard side, where ALVs travel and transport containers. Compared with another type of mostly-used automated vehicle the AGV, ALV is able to lift a container from the ground, without the help of a crane. Many studies (Yang, Choi, and Ha 2004, Vis and Harika 2004) have demonstrated that ALV is superior to AGV in terms of productivity as well as investment cost. At the yard side, the whole yard is divided into sections with each covered by a GRID system, as elaborated in Figure 4. The GRID systems are categorized into two types. Those beside the quay are categorized as the Bay-Front sections (BFS) while the others are Inner-Yard sections (IYS). The storage area design is the same for both types of GRID but the transfer area design differs.

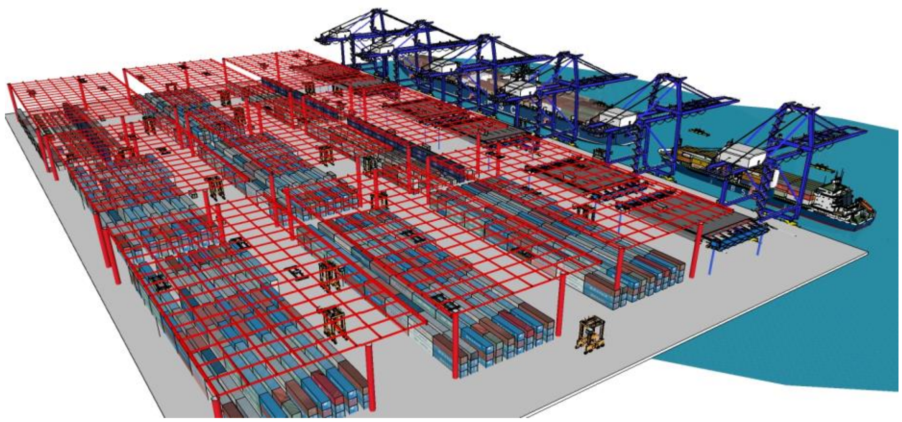

Figure 3: 3D structure of the GRID- ACT.

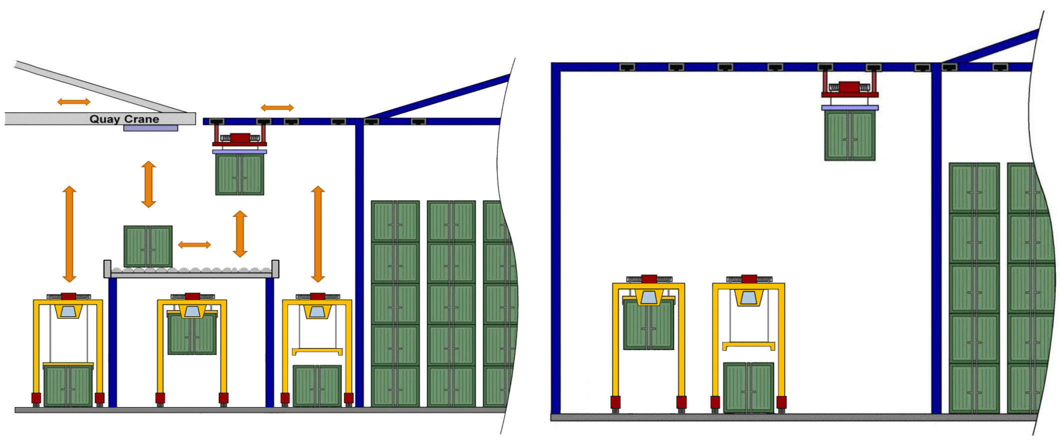

Figure 4: Design of BFS (left) & IYS (right) transfer area.

2.2.3 Advantages of GRID-ACT

***Flexibility in size*:** Different from most other ACTs, in which storage block size is limited by the size of Yard Crane (YC), GRID system can easily expand. More importantly, more TUs can be added in the GRID if necessary. Therefore, different versions of GRID-ACT can be implemented in container terminals with different requirements. For example, a container terminal that concentrates more on land utilization rate may build larger GRIDs, deploy more TUs in each GRID and reduce ALV paths.

***Capacity*:** The GRID system configuration allows storage of containers up to seven or eight high and eliminates the need for aisles within the storage footprint. It significantly increases the container storage density and the capacity of container terminals.

***Throughput and land utilization*:** Our simulation results have proven that the throughput of GRID-ACT is significantly larger than other ACTs. Besides, the land utility is more efficient due to the large container storage density. More details of are given in later sections.

3 MODELING

3.1 FB-ACT

In the FB-ACT design, there are three types of handling machines, namely ground trolleys (GTs), transfer platforms (TPs) and frame trolleys (FTs). According to the flow of the containers as well as the resources available for the FB-ACT system, the whole simulation could be divided into 3 sub-systems: QC sub-system, GT sub-System and FT sub-system, while TPs are simulated as the handover point between FT and GT. Some assumptions of this model are listed as follows.

1. The delivering process is triggered by the arriving of vessels and external trucks. Once a vessel moors at a berth, it starts discharging containers, then starts loading container after finishes discharging, and finally leaves the berth after finishes loading. On the other hand, there are two kinds of external trucks that transport containers to (from) hinterland, one is for truck-out activities, whose arrival triggers the unloading operation from storage yard to external trucks; and the other is for truck-in activities, whose arrival triggers the loading operation from external trucks to storage yard.
2. The terminal is assumed to be operating under full load condition. Once a vessel leaves a berth, another vessel will moor at the berth immediately.
3. This project focuses on the interactions between vessel and storage yard, and tries to minimize the effects of interaction between storage yard and external trucks. Therefore, most of containers on a vessel are set to be transshipment containers.

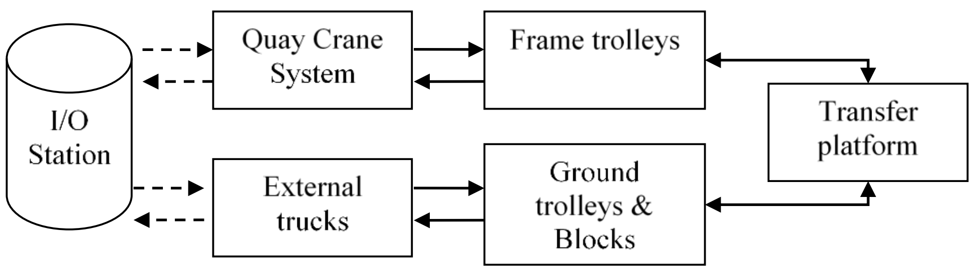

Figure 5: Simulation model for FB-ACT.

3.2 GRID-ACT

For each single GRID, the following logic is used to route TUs, solve conflicts and prevent deadlocks.

Principle 1 *TUs are always seeking the shortest path to its destination.*
Principle 2 *TUs always travel horizontally first, unless they encounter a conflict.*
Principle 3 *There is no reserved path for each TU. A TU makes real time decision, which enables TUs to adjust its path whenever conflicts happen. There is a rule to solve each possible conflict and prevent deadlock.*

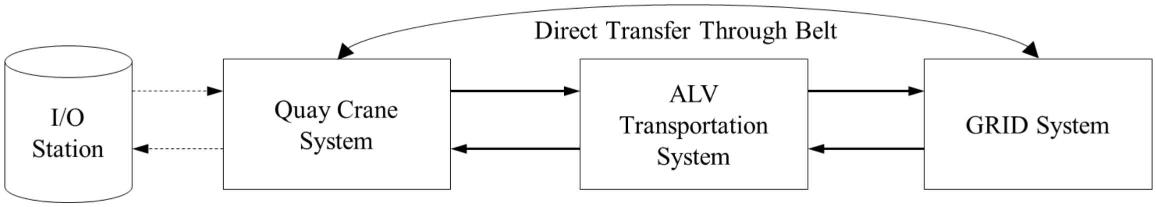

Figure 6: Simulation model for GRID-ACT.

For GRID-ACT, the model is modularized into three sub-models: QC, ALV transportation system and GRID, as shown in Figure 6. Modularization allows the three sub-models to be modified or extended separately, and therefore makes the model flexible. ALV transportation system and the transfer belt in GRID provide sufficient buffer areas at both the quay side and yard side and therefore the handshakes between subsystems are greatly reduced and in turn, improve the system throughput. The ALV path is designed to be single directional to avoid conflicts. In addition, bypaths are attached path to avoid blocking on the main path. This model can either generate random data by itself or link to outside data source.

4 RESULTS AND DISCUSSION

4.1 FB-ACT system

In our simulation model, the scale has been set according to the real system as follows. The simulation model will adopt all the specifications to make the simulation as real as possible

- The width of each frame bridge rails is 5 meters.
- The safety space designed between the frame bridges areas and the yard area is around 2.5 meters.
- The bay length is 6.5 meters which is a container length plus the safety area between the bays.
- There are total 25 bays per block which in total the length of the yard area is 162.5 meters.
- The width of a block is 49.5 meters.
- Every 8 blocks serve 1 berth, and the distance between each of the 8-blocks is 25 meters.
- Only Twenty-foot Equivalent Units (TEU) are considered in the model.
- There is assumed to be enough transfer platform (TP) in the system. A TP is always ready when required.

4.1.1 Bottleneck Analysis

By varying the scale of the simulation model, the performance of the sub-systems can be summarized in Table 1.

Table 1: Throughput per berth under horizontal expansion.

Overall	**1 berth**	**2 berth**	**3 berth**	**4 berth**
System	104.78	174.21	222.43	250.48
QC	227.51	456.44	681.93	904.57
FT	198.23	277.47	309.13	316.53
GT	232.03	430.17	634.03	757.33

The QC throughput remained constant as the number of berth increases, since the QCs in different berth are independent of each other. As long as there is enough FT to pick up the containers at the respective TPs at Frame Bridge, the QC will continue working. The throughput of GT will decreases slowly as the number for berth increases from one to four, this is because there are interactions between the GTs in different berth. For example, if there is a containers is going to be unloaded from berth one to berth two, however, the GTs at berth two are all busy serving other containers, then waiting will occur. As the number of berth increases, the probability for the described scenario to happen will increase, thus the GT throughput slowly decreases. For FT, as the number of berth increases, the throughput level drops obviously. The main reason is that when the number increases, there will be increasing number of FTs sharing the same track. This lead to increasing interference among the FT jobs, thus reduces the FT throughput.

Similarly, as the number of berth increases, the throughput per berth of the overall system is decreasing, despite the fact that the QC throughput is kept constant and the GT throughput is kept almost constant and way above the system throughput line. This shows that the FT is the bottle neck of the FB-ACT system.

4.1.2 Analysis of storage allocation strategies

The different types of unloading strategies are list below:

- Unload to the section where the container is going to be loaded later, if the resources are not free, the container will wait on the vessel. (To Load Section or Wait)
- Unload to the unloading section, if the resources are not free, the container will wait on the vessel. (To Unload Section or Wait)
- Unload to the section where the container is going to be loaded later, if the resources are not free, then unload to the unloading section, if the resources are not free also, unload randomly. (To Load Section >Unload Section > Random)
- Unload to the unloading section, if the resources are not free, unload to the section where the container is going to be loaded later, if the resources are not free also, unload randomly. (To Unload Section > Load Section > Random)
- Unload randomly (base case)

Table 2: Throughput per QC per hour under different storage allocation strategies.

Number of Berth :	**1**	**2**	**3**	**4**
To Load Section or Wait	26.19	21.78	18.54	15.66
To Load Section > Unload Section > Random	26.19	21.06	17.48	13.98
To Unload Section or Wait	26.19	20.65	16.87	13.63
To Unload Section > Load Section> Random	26.19	20.10	16.37	13.21
Random	26.19	20.04	15.41	12.16

From the data obtained above in Table 2, it shows that unload to loading section is the best allocation strategy, as the throughput associated with this strategy is the highest compared to other smart allocation strategies. For one berth scenario, there is no difference in the throughput since there is no section crossing activities at all regardless of the strategies.

This evaluation is based on a strong assumption that each vessel will arrive according to the berth previous assigned to it. Therefore, the system can prepare in advance, where to store the unloaded containers to its loading section. While in reality, this may not be the case. However, these smart allocation strategies also suggest that unload to unloading section could be an alternative solution as compared to unload randomly when the loading section is unknown. There is still an improvement of 12%.

4.1.3 Evaluation of Express Way

By replacing one layer of frame with an Express Way, the system is simulated for three days to compare with the original system. With Express Way FTs to eliminate all the section crossing activities, the throughput has increased significantly by 31% with the same amount of resources been used. It also achieved around 80% of the upper limited determined.

Actually the number of FTs to use for Express Way will directly affect the system throughput. Therefore a sensitivity analysis is carried out to determine the most efficient and effective number of FT to use for the Express Way.

Table 3: System throughput affected by highway (4 berth simulation).

Without Express Way (2 Frame Layers)	15.66
With Express Way (1 Frame Layer and 1 Express Way)*	20.54
% Improvement	31.2%

** 16 express way FTs were used to ensure fair comparison*

Table 4: Express Way sensitivity analysis (4 berth simulation).

No. of FTs on Express Way	4	6	8	10	12	13	14	15	16
Throughput	9.46	13.87	16.89	18.27	19.64	20.05	20.27	20.46	20.54

From Table 3 and 4, as the number of FT increases on the Express Way, the throughput will increase at a decreasing rate. Cost-effectiveness tests need to be done to determine the optimal FT number for different systems.

4.2 Simulation analysis of GRID system

4.2.1 Single GRID Layout Analysis

Basic Layout: The basic GRID layout has a length of 136 meters and a width of 64 meters. It allows two QC at the quay size. In order to find the maximum throughput of the GRID-ACT system, excluding QC, we treat each quay crane as one input point, which always has jobs available.

Table 5: TU capacity for single GRID (box/hour/IO point).

TU	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Throughput	8.6	16.3	23	29.3	34.5	38.4	41.5	41

As shown in Table 5, system throughput improves as the number of TUs increases until it reaches 7, which results in the largest system throughput of 43.9 containers per input point per hour. However, system throughput starts to decline without more TUs due to the conflicts. TUs spend more time on solving conflicts, for example, waiting for other TUs to pass by or detouring. As there are two input points in each GRID, the system throughput of the whole GRID is 87.8 containers per hour. Compared with other Yard Cranes, such as the Twin rail mounted gantry (RMG) and Cross-Over RMG which have a throughput of 49 containers per hour (Saanen and Valkengoed 2005), GRID system is a much better choice at the yard side.

Horizontal Expansion: The GRID layout length is increased by three times. The expanded model is 408 meters long and 64 meters wide and allows six quay cranes (input points) at the quay side. This expanded GRID system can achieve a maximum throughput of 27.1 when there are 18 TUs in the GRID. If we compare the basic model with the expanded model, it is obvious that as the system length increases, the system throughput drops dramatically. The trend is mainly caused by the following reasons. Firstly, longer horizontal travelling time per trip is required for a bigger grid system because of the expansion in length. Secondly, the extra horizontal movement increases the number of TU conflicts due to the limited number of horizontal paths in the system. Therefore, TUs speed more time solving conflicts. Thirdly, due to the increasing conflicts, the optimal number of TUs in the larger system is only 18, which means the number of TUs per input point decreases from 7/2=3.5 to 18/6=3.

Vertical Expansion: For the purpose of exploring the relationship between GRID layout width and system throughput, in this section, the storage area width is increased by two and three times and the throughput is analyzed. Because of the same transfer area size, those models still allow the same number of input points. The expansion is done for both the basic model, which is 136 meter long and the expanded model, which is 408 meters long.

Table 6: Summarized results of the vertical expansions.

Layout Type	Basic Model	Double Width	Treble Width
Layout Length (m)	136	136	136
Layout Width (m)	64	116	168
Optimum TU	7	9	11
Maximum Throughput	43.9	43.0	44.8
Cycle Time (min)	4.8	6.3	7.4

As observed in Table 6, as the layout width increases, more TUs are required in order to achieve the maximum throughput. However, different from the horizontal expansion, the vertical expansion does not decrease the maximum throughput per input point. It is observed that the maximum throughput per quay crane is almost the same for all the layout designs with the same length of 136 meters.

There are two primary reasons why the vertical expansion does not have a large impact on system throughput. First, longer vertical travelling time per trip is required for because of the expansion in width. However, the extra vertical travelling time is much less than the extra horizontal travelling time. Then since every TU will pass the transfer area, the number of TU conflicts in the transfer area increases when there are more TUs and transfer area keeps the same. This is another advantage of GRID system as compared to other Yard Cranes (YC), such as RMG. When the yard size increases, the throughput of most YC declines because of longer travelling time. However, GRID simply allows more TUs in the system to keep the same level of productivity.

In conclusion, system throughput drops as the GRID layout length expands and it almost keeps constant when the GRID layout width increases. However, the throughput per TU declines because of a larger number of TUs in the vertically expanded model. Therefore, the optimal layout is the basic model, which is 136 meters long and 64 meters wide, and it has the largest throughput of 43.9 containers per input point per hour.

4.2.2 GRID-ACT Analysis

Horizontal Expansion: Here we expand the quay length by three times and therefore allow six QCs (input points) at the quay side. Three basic models are deployed beside the QCs to store the containers, as shown in the Figure 7 below.

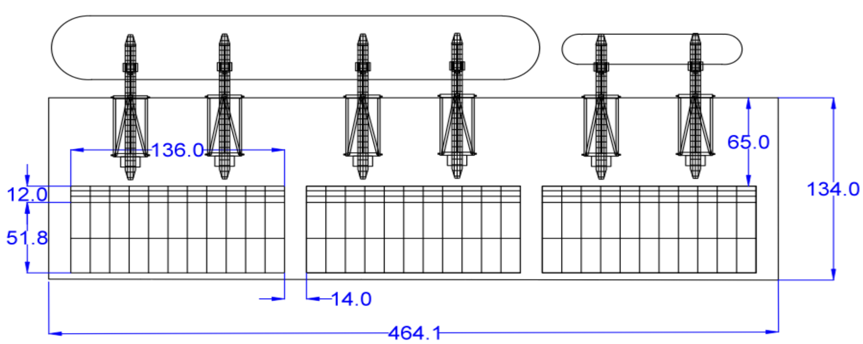

Figure 7: GRID-ACT with three GRIDs.

As observed in Figure 8, when the number of ALVs increases, system throughput goes up and it reaches a maximum of 42.9 when there are 25 ALVs in the system. ALVs start to queue up under the transfer areas or quay cranes when the number exceeds 25 and therefore throughput goes down.

As shown in Table 7, it is apparent that the throughput of the GRID-ACT is much larger than the throughput of the expanded model. GRID-ACT greatly reduces the possible congestions, especially among the transfer area, are avoided by using the ALVs instead of TUs when the containers are going to other sections. However, the GRID-ACT requires more equipment such as TUs and ALVs and therefore a higher investment cost. The trade-off between the throughput and investment cost has to be considered by port operators.

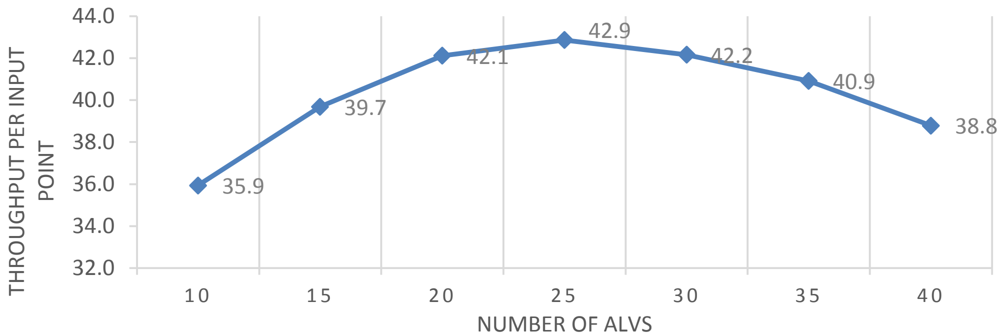

Figure 8: Throughput of the GRID-ACT with three GRID sections.

Table 7: Comparison of the large GRID and GRID-ACT system.

	System Throughput	**Number of TUs**	**Number of ALVs**
One large GRID (Single GRID layout)	27.1	18	0
Three smaller GRID (GRID-ACT)	42.9	21	25

Vertical Expansion: To explore the GRID-ACT performance in a larger port and increase storage capacity of the container terminal, more IYS are added at the yard side and connected by the ALV system. The storage area is expanded by two and three times vertically, which is to add one or two tiers of IYS at the yard side.

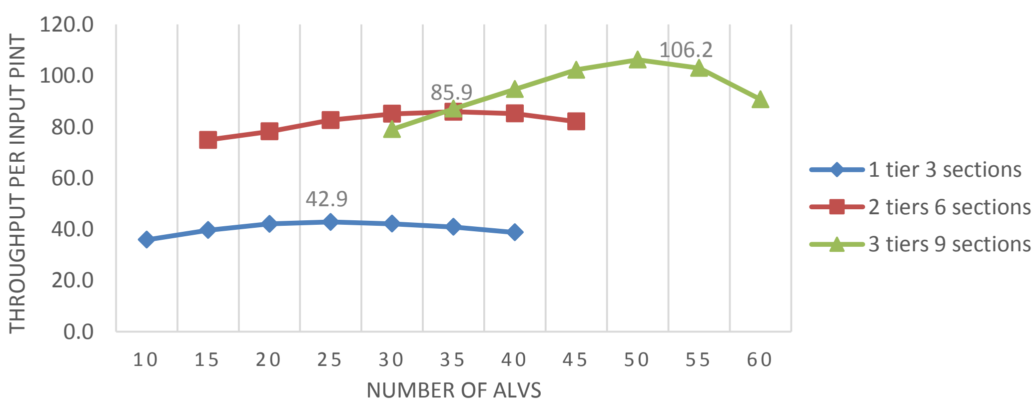

Figure 9: GRID-ACT throughput in different layout.

As shown in the Figure 9, the system throughput is increasing at a decreasing rate. It is due to the increasing workload and limited space at the quay side, where many TUs are queuing and waiting for loading containers from or unloading containers to the quay cranes. Therefore, this ALV system cannot make sure every GRID has jobs available at all times and TUs are sometimes idle, which leads to throughput decline in every section.

To summarize, with a layout size of 136 meters long and 64 meters wide, the GRID system best perform at a maximum throughput of 43.9 containers per input per hour at the yard side. The GRID-ACT is able to achieve a maximum throughput of 106.2 when there are nine GRIDs in the yard and implemented as three tiers, three in each tier. With the high productivity of the GRID-ACT system, QCs are the bottleneck in the ACT and throughput of the ACT is limited by the productivity of QC.

5 COMPARISONS OF DIFFERENT TERMINAL DESIGNS

According to the previous sections, the main differences among the GRID-ACT system, FB-ACT system, normal AGV-ACT system and conventional terminal can be summarized in Table 8.

Table 8: Comparison of the container terminal systems.

Category	GRID-ACT	FB-ACT	AGV-ACT	Conventional Terminal
System flexibility	Flexible	Rigid	Limited	Limited
Cost	High	Low	Medium	Low
Conflict area	GRID rails	Frame bridge	Vehicle path	Vehicle path
Control dimension	2D	1D	Simple	Simple
System extension	All directions	Vertically	Vertically	Vertically
Throughput (Move/QC/hour)	43	26	30-40	30-40
Bottleneck	Transfer unit	Frame trolley	Ground vehicles	Ground vehicles

Our study shows that GRID-ACT is a promising design in terms of overall system throughput. Despite its high construction cost, GRID-ACT has a good flexibility to be applied to different scenarios.

Previous studies have proven that FB-ACT is efficient in import/export terminals. However, our study shows that it is not the same in transshipment terminals. On the contrary, conflict of FT is the main drawback for the system and limits the overall system throughput.

6 CONCLUSION

In the study, we have designed, modeled, simulated and evaluated two new automated terminal concepts, namely FB-ACT system and GRID system in a transshipment port. The FB-ACT design has been developed by Shanghai Zhenhua Port Machinery Company (ZPMC), which utilizes multi-storey frame bridges and rail-mounted trolleys to transport containers between the quay and the yard. The GRID-ACT is introduced for the first time in maritime studies and it takes advantages of both GRID system and ALV system.

For the FB-ACT system, FT is found to be the bottle neck of the overall system and conflicts of FT is the main drawback for the system when the system scale gets larger. Operations strategies such as sectioning strategy on frame rails and smart allocation strategies are been introduced to minimize the drawback and an express way is been implemented to further eliminate the section crossing activities. According to the result generated from the simulation model. All strategies are been proven effective, while applying the smart allocation strategies together with the express way strategy has the greatest improvement of 31% in overall system throughput.

For the GRID system, we discovered the relationship between layout size and its productivity. Our simulation proved that GRID throughput decreases as the layout length increases because of a larger TU cycle time and smaller number of TUs per input point. Besides, GRID throughput almost keeps constant as the layout width expands because of larger TU cycle time and larger number of TUs per input point. Therefore, the basic and smallest GRID layout was deployed in the GRID-ACT. The GRID-ACT system as a whole has been tested. It is shown that the system throughput is very close to the maximum throughput of one GRID as we add more GRIDs horizontally. Adding GRIDs vertically will increase the throughput at a decreasing rate. It has also been proved that GRID-ACT performs better than other ACTs in terms of system productivity with enough ALVs equipped.

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