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Design and Simulation of a Monorail Network for the Inter-terminal Transport

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Abstract: *In line with the trend of global transport volume which has increased rapidly over the years, internal transportation in seaports is always conducted with high frequency. Thus, there is always much potential for traffic jams as well as high transportation costs and emissions. Many efforts have been initiated to streamline the inter-terminal container transport (ITT) through the development of automated vehicles and equipment as well as using private transport facilities to overcome these limitations. The purpose of this paper to develop a framework to design, analyze, and validate the efficiency of a new ITT system in a port area based on the monorail network and automatic vehicles. First, the number of shuttles and loaders was determined depending on the transport demand scenario. Next, a simulation model was applied to evaluate the system performance as well as gain more insight into the working process of the ITT system. Finally, by setting goals for the performance indicators, the results showed that the system was highly efficient with 100% of the containers delivered to their destination on time. Besides, a series of other performance tracking was provided to provide insight into the system's capabilities.*

Keywords: inter-terminal transportation, simulation, vehicle routing, monorail, network design

1. Introduction

Due to growing transport volumes, environmental restrictions and port competition, the productivity and efficiency of port operations needs to be further enhanced to increase the competitiveness of seaports. Important determinants for sustainable growth and competitiveness of ports include improve energy efficiency, logistics cost, GHGs reduction as well as reducing noise and dust generated during transport (Giuliano et al., 2007). A considerable proportion of port-related traffic is produced by inner terminal transportation (ITT). ITT refers to all of the land and sea transportations moving containers between organizationally separated terminal within a seaport (Heilig et al., 2017). Most recent research on ITT focused on evaluating different types of ITT for minimizing the number of vehicles and delivery delays. ITT system for the Maasvlakte terminals in Rotterdam has been investigated by comparing the performance of different types of vehicles such as multi-trailers, automated guided vehicles or automated lifting vehicles (Duinkerken et al., 2017). Another typical research to evaluate the effectiveness of a shared ITT system in a port area has been conducted (Gharehgozli et al., 2017). Results show that the collaboration of container terminals leads to high operational expense savings due to the reduction of labour and economies of scale.

Besides, there are several researches interested to modeling ITT systems using mathematical methods to optimize, reduce operating costs and increase system productivity such as a time-space graph and a tabu search algorithm is proposed to formulate the vehicles routing and container transport problem in an inter-terminal network (Hu et al,. 2016). It is applied to a transport network at the Maasvlakte in Port of Rotterdam; An integer programming model to minimize container delivery delay that takes into account the key components of ITT, including traffic congestion, multiple vehicle types and loading/unloading times, and arbitrary terminal configurations (Tierney, et al,. 2014), etc.

Many ITT systems are multimodal, that is, the infrastructure supports various transportation modes, such as truck, rail or barge. Each type of infrastructure has different characteristics. Road transport required much less capital investment as compared to other modes. The cost of constructing, operating and maintaining roads is cheaper than that of the railways (Lee et al., 2006). However, it is not suited for long-distance as it is less economical and also more time-consuming compared to the railway. Railways have the drawback that it requires huge capital for construction maintenance, the cost and time of terminal operations are also the major disadvantages. Nevertheless, it becomes more economical for long distances since this means of transport is able to carry a bulky amount of goods and products with

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safer and faster than others. While waterway involves the movement of a huge quantity of goods with the very cheapest compared to road or rail.

However, the performance of the system is affected by seasonal variations and a large space is required for operating are the main drawback of this kind of transportation. The above analysis outlines the advantages and disadvantages of current ITT infrastructure. Besides, in the industry with high-level automation elements today, these types of transportation reveal a common weakness that produces a large amount of greenhouse gases (GHG) such as carbon dioxide (CO_2) and also costs an abundant workforce (Doo and Lee., 2013). In response to climate change, governments have put a lot of effort into settings various regulations and targets such as the EU 2011 White Paper on Transport proposed at a high-level target as reducing by the year 2050 transportation-related greenhouse gas emissions by at least 60% with respect to 1990 levels. Other areas of the developed world (including North America, Japan, Korea and Australia, etc) have similar goals for environmental improvement.

This paper aims to propose a new design of the ITT system using automated electric vehicles together with a monorail network. The purpose of bringing automation to ports is to introduce a whole new level of consistency when handling containers and at reduced labor costs and GHG emissions compared to a manually operated system. The rest of the paper is organized as follows. Section 2 performed an ITT definition review. The new ITT concept and characteristic is introduced in section 3. System modeling is conducted in section 4 and the simulation scenario, testing, and the result are carried out in section 5. Section 6 is conclusions.

2. ITT definition and review

The ITT system involves the transportation of freight inside a terminal and moving containers between port terminals by using a variety of modes (road, waterways or rail network). In which the system uses rail can achieve time-optimization in moving containers between terminals. (Hansen., 2004). Generally, there are three types of intermodal terminals with rail connections in a port area, include railway terminal with road connection (RTR), maritime terminal with both road and railway connections (MTRR) and maritime terminal with road connection and rail off-dock (MTR). ITT is responsible for connecting these terminals, facilitating the smooth exchange of containers between them (Hu et al., 2019). There are a range of different vehicle types in the ITT system with its own characteristics. Those vehicles mainly include regular road trucks, Automated Guided Vehicle (AGV), Automated Lifting Vehicle (ALV), Multi Trailer System (MTS), and Barge. Most transport equipment can carry up to two TEU. Exceptions are the Multi Trailer Service (10 TEU), the Barge (50 TEU) and the Train (50 TEU) (Negenborn, 2014). Several studies on comparing the performance of autonomous vehicles and equipment. MTS is proven that can help to gain the highest performance in terms of punctuality when compared to AGV and ALV. However, the average performance of ALV was concluded to be better and recommend to use in the Port of Rotterdam (Tierney et al., 2013).

There are case studies of designing the ITT system at Maasvlakte 1 and 2 in the Port of Rotterdam. The Maasvlakte 1 (MV1) houses large terminals such as APMT, ECT, and Euromax. The Maasvlakte 2 (MV2) terminals were recently constructed to handle for a growth of 75% in the number of containers flowing through the Port of Rotterdam (PoR) in 2030. It includes an extension of the Euromax terminal, three barge terminal, two rail terminal and several new empty container depots for repair services and storage. These 18 terminals in total will be developed using an ITT system. There are three scenarios given by PoR, including the number of containers to move from 1.42 to 3.34 Million TEU / year. The Port Authority aims to build an ITT system that helps to connect barge and rail terminals to optimize travel times and transport costs. The most typical research that provided a simulation model to determine the most optimal equipment and facilities to satisfy the set conditions. The research shows that a system using AGV is the most cost-effective solution. With increasing container demand, the AGV solution including the infrastructure becomes more favorable than the truck solution on the public road. However, the AGV solution requires a large investment up front because of the development of technology (Negenborn, 2014). From this case study, it can be seen that ITT systems must always be developed and upgraded to meet the fast-growing transportation needs. In the next chapter, a new ITT system is proposed to increase transport capacity and applying environmentally-friendly vehicles.

Overall, the existing research has tackled the performance of different vehicles and equipment in the ITT system based on different natural conditions. However, most case studies were focused on evaluating in terms of working capacity and operating costs while neglecting an environmentally friendly manner. In fact, A building of the ITT system on existing facility or upgrading from an old system would be much more complicated due to space constraints and connectivity problems with other parts of the current infrastructure. In contrast to this work, an automation solution to improve operational efficiency and reduce environmental pollution has been proposed on an existing seaport. Thus, this paper provides the following novel contributions:

1. The first fully defined new system components and functions.
2. Mathematical model of ITT to determine system configuration, including the number of shuttles and loader.
3. Verification system performance by using a simulation approach, with the real demand scenario.

3. ITT design and its characteristics

There are many monorail systems currently in operation but mostly use for various types of passenger transportation. As urban transit systems, they transport passengers between airport terminals (such as Newark's Liberty International Airport), or visitors in the theme parks (Timan 2015). There are very few systems used for freight transport. A new ITT system is proposed based on the monorail system structured as shown in Fig 1.

The monorail system is arranged to connect between the terminals using a single rail as a guideway. The system has two lanes that allow containers to be transported in two directions independently so that help to reduce waiting time due to traffic jams or collision unlike single lane as in traditional railway system. Containers are transported by the electric shuttles which are wider than the guideway that supports them. They operate individually and fully automated by using a computer. The advantages of this technology are introduced by Timan (2015). Fully automated operation is a key factor allowing this system to achieve economic efficiencies through minimized operating and handling labor costs and also reduced waiting in traffic. Shuttle operation is based on electric power provide low noise and very minimal air pollution emissions.

In general, two types of monorails have been widely used since the beginning, including the suspension railway systems on which the vehicle hangs under the fixed track and straddle-beam monorail system uses a vehicle that straddles a reinforced beam. At each terminal, a loading station to exchange containers between trucks and shuttle is setup. Containers are transferred from storage yard areas to the ITT station by truck, then loader picks up containers and place onto the shuttle to move to other terminals. This station consists of a number of lanes. There are several loading cells located in each lane to load and unload containers by using a loader (see Fig. 2). Another part of monorail known as change stations, which are located between terminals to help shuttle change direction. Switching at the change station could be beam replacement or multi-position pivot switches. The beam replacement switches are used on the mainline and multilocation pivot switches are used in storage yard areas. In this paper, beam replacement is used as shown in Fig. 1. Since vehicle and equipment configurations have an essential impact on the ITT performance in terms of productivity, efficiency and environmental, the mathematical model to calculate the number of shuttles and loaders is presented in the next section.

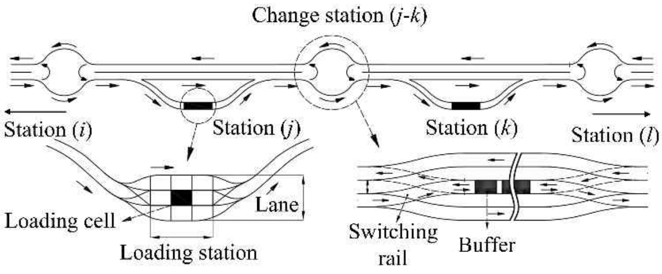

Fig. 1 ITT system structure

4. Mathematical model

ITT is modeled on traffic flows graph to model the traffic flow at the main rail, change station and loading station. Those indicators can be used to determine the performance and cost impact for each possible coalition and each transport alternative. The model is designed that can incorporate not only for monorail system but also for different vehicles, equipment used for ITT as well as for any type of facility. Routing strategy plays an important role in optimizing travel distance and operating costs in the transportation system. The optimal routing algorithms depend on the configuration of the transportation facility and it is divided into two types: non-closed loop and closed loop structures. The closed-loop traffic system is known as there are multiple paths connected between terminal. Thus, it makes the routing strategy more complicated to define an optimal route for the shuttle. In terms of a Non-closed loop system, only one path exists between terminals, so planning the route becomes simpler. Both configurations are modeled in this paper.

4.1 Determining container flow at the change station

Firstly, to evaluate the performance of each terminal, the container flow is monitored. Let $i \in n$ is the terminal node, *n* is the number of terminals. Thus, the traffic flow graph of the system is described as Fig.2. Calculating the operating frequency of switching from which to design change station with sufficient productivity and thus reduce waiting time at these positions. Transfer volume that used change station calculation is defined as

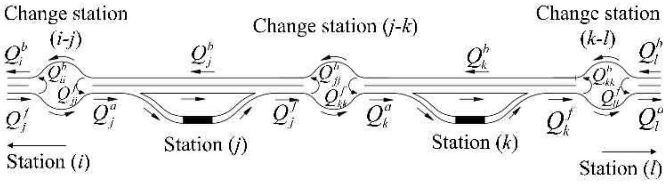

Fig. 2 Container flow in the system

$$Q_{j-k}^{ch} = Q_{jj}^{b} + Q_{kk}^{f} \tag{1}$$

where Q_{j-k}^{ch} indicate the number of the container through change station *j-k,* Q_{jj}^{b} and Q_{kk}^{f} represent the number of containers move forward and backward of *j-k* change station respectively.

In the case of the non-closed loop:

$$Q_{jj}^{b} = \sum_{\alpha=1,\alpha<j}^{z} Q_{j\alpha}^{O} \tag{2}$$

$$Q_{kk}^{f} = \sum_{\alpha=k+1}^{z} Q_{\alpha k}^{I} \tag{3}$$

where $Q_{j\alpha}$ indicate the transfer volume from *j* station to α station, $(\alpha \in n)$, $Q_{\alpha k}$ is total transfer volume from α to *k* station. In case of a close loop system, those parameters are defined as

$$Q_{jj}^{b} = \sum_{\alpha=1,\alpha\neq j}^{z} Q_{j\alpha}^{O}\ ,\ \forall \alpha \in z \text{ satisfying } D_{j\alpha}^{l} < D_{j\alpha}^{r} \tag{4}$$

The constrain $D_{j\alpha}^{l} < D_{j\alpha}^{r}$ to ensure containers are moving from *j* station to *α* station by the shortest distance. $D_{j\alpha}^{l}$ and $D_{j\alpha}^{r}$ represent the travel distance from *j* to *α* from the left and right side of *j* station respectively. $Q_{j\alpha}^{O}$ indicate the total transfer volume from *j* station to *α* station. Similarly, the number of containers change direction from the right site of *j-k* change station can be expressed as

$$Q_{kk}^{f} = \sum_{\alpha=1,\alpha\neq k}^{z} Q_{\alpha k}^{I}\ ,\ \forall \alpha \in z \text{ satisfying } D_{\alpha k}^{l} > D_{\alpha k}^{r} \tag{5}$$

where $D_{\alpha k}^{l}$ and $D_{\alpha k}^{r}$ are travel distance from *α* to *k* station by railway on the left and right of *j* station. $Q_{\alpha k}^{I}$ indicate total transfer volume from *α* to *k* station. The constraints $D_{\alpha k}^{l} > D_{\alpha k}^{r}$ to guarantee that vehicle move on the shortest path. When design the ITT system, the number of vehicles and loaders is needed to be considered to meet transport demand. These constraints are discussed in the following sections.

4.2 Determining the number of shuttles

The transshipment of a container among the terminal is composed of different steps. When the empty shuttle arrives at the loading station to pick up the container, the loader moves loaded and drops the container to the shuttle, then the shuttle moves the container to another terminal in the port area. The transshipment cycle time can be defined as

$$\mathrm{T} = \frac{D^{\min}}{V} + T_{ch} + T_{ac} + T_{lo} + T_{out} \tag{6}$$

where $D^{\min} / V_{sh}$ is shuttle travel time in the main rail; The time to position the spreader for loading/unloading is T_{lo}, T_{ch} represent for changing time at change station. T_{ac} and T_{out} indicate accessing and move out time at station respectively.

With a given transshipment matrix, the duration of shuttle travel time can be calculated in advance. The duration of the empty move is sequence-dependent. To meet the transfer demand at terminals, the number of shuttles should be considered, which need to be limited to optimize the investment and operation cost. The number of shuttles needed depends on the transfer volume between the terminals, can be calculated as follows

$$N_s = \frac{Q\ T\ f_p f^{TEU}}{W_y W_d} \tag{7}$$

where Q be the annual transfer volume among container terminals (TEU), W_y is the number of working days (d) of the terminals, 350-365 d; W_d is working time (h), 12-24h. f_p represent the peak factor per hour from the container demand scenario and f^{TEU} is the TEU factor, which is the ratio of 20ft to 40ft containers.

4.3 Determining the number of loaders

The number of loaders arranged at each terminal depends on the transfer demand of each terminal and the loader's productivity, which can be calculated as follows

$$N_l = \frac{Q_j f_p f^{TEU}}{W_y W_d p_{sp}} \tag{8}$$

W_d is working time (h), 12-24h. f^p represent the peak factor per hour from the container demand scenario and p_{sp} indicate productivity of loader. Now assume that there are N_{sp} spreaders in a single lane, so the number of loading station lanes can be calculated as follows:

$$N_j^{lane} = \frac{Q_j f_p f^{TEU}}{W_y W_d p_{sp} N_{sp}} \tag{9}$$

where N_j^{lane} is the number of lanes in j station.

5. Simulation and results

5.1 Simulation scenario

The simulation was developed using the terminal layout in Fig. 3. The scenario of demand is based on the available handling capacity for ITT in Busan Newport for the year 2030. Annual transport demand is approximate 3,367,756 TEU/year. Detail transfer volume at each terminal is shown in Table 1. The layout dimensions are includes in Table 2. Based on practical container operations data in the port, assuming that 20ft and 40ft containers are accounted for about 35% and 65% transfer volume respectively. Moreover, the arrival and departure of containers at each terminal in the port are not equally distributed over time, there is assumed that 80% volume is carried out in 12 hours (10 PM to 10 AM). The simulation consists of verifying the system uptime based on hourly conversion demand, which is similar to the method analyzed by Nieuwkoop, F. E. (2013). Hourly transfer volume is calculated as follows

$$Q_h = \frac{Q f_p f^{TEU}}{W_y W_d} \tag{10}$$

Assuming $W_y = 360,\ W_d = 12$, from the above condition, the TEU factor is calculated as $f^{TEU} = 0.675$, the peak factor is given $f_p = 1.25$.

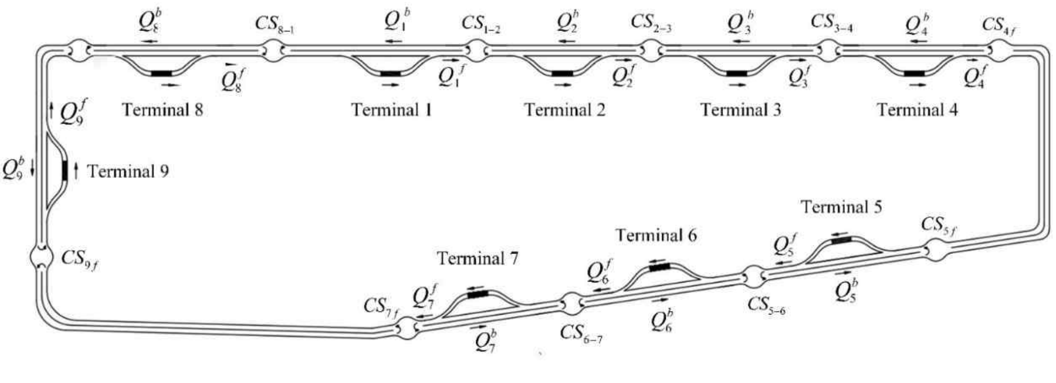

Fig. 3 ITT layout scenario

Table 1 Annual transfer volume (Unit: TEU/year)

Terminal	Ter 1	Ter 2	Ter 3	Ter 4	Ter 5	Ter 6	Ter 7	Ter 8	Ter 9	Total
Ter 1	-	27,152	27,152	26,116	21,442	27,184	35,937	35,937	26,388	227,308
Ter 2	23,007	-	-	19,371	15,904	20,163	26,655	26,655	19,573	151,330
Ter 3	23,007	-	-	19,371	15,904	20,163	26,655	26,655	19,573	151,330

Ter 4	31,757	27,798	27,798	-	21,952	27,831	36,792	36,792	27,017	237,737
Ter 5	29,332	25,676	25,676	29,332	-	25,706	33,983	33,983	24,954	228,641
Ter 6	25,392	22,226	22,226	21,378	17,552	-	29,417	29,417	21,601	189,212
Ter 7	25,420	22,251	22,251	21,402	17,572	22,277	-	29,450	21,625	182,248
Ter 8	25,420	22,251	22,251	21,402	17,572	22,277	29,450	-	21,625	182,248
Ter 9	17,897	15,666	15,666	15,069	12,372	15,685	20,735	20,735	-	133,825
Total	201,232	163,021	163,021	173,442	140,270	181,286	239,625	239,625	182,357	3,367,756

Table 2 Travel distance among terminals (Unit: m)

Terminal	Ter 1	Ter 2	Ter 3	Ter 4	Ter 5	Ter 6	Ter 7	Ter 8	Ter 9
Ter 1	-	1,050	2,050	3,150	6,310	7,590	7,563	1,863	3,448
Ter 2	1,050	-	1,000	2,100	5,260	6,540	7,765	2,913	4,498
Ter 3	2,050	1,000	-	1,100	4,260	5,540	6,765	3,913	5,498
Ter 4	3,150	2,100	1,100	-	3,160	4,440	5,665	5,013	6,598
Ter 5	6,310	5,260	4,260	3,160	-	1,280	2,505	8,173	6,620
Ter 6	7,590	6,540	5,540	4,440	1,280	-	1,225	6,925	5,340
Ter 7	7,563	7,765	6,765	5,665	2,505	1,225	-	5,700	4,115
Ter 8	1,863	2,913	3,913	5,013	8,173	6,925	5,700	-	1,585
Ter 9	3,448	4,498	5,498	6,598	6,620	5,340	4,115	1,585	-

Table 3 Calculated system configuration

Terminal	Ter 1	Ter 2	Ter 3	Ter 4	Ter 5	Ter 6	Ter 7	Ter 8	Ter 9	Total
Number of shuttles	5	3	3	4	4	4	6	5	4	38
Number of loaders	1	1	1	1	1	1	1	1	1	9

From Eq (6)-(9), the number of loaders and shuttle is calculated in Table 3 based on the amount of transported volume each terminal and the distance between them (Table 1&2).

5.2 Simulation method

The features of simulation software are real-time simulation port operation of a new design of ITT, determining the shortest path to transfer volume between terminal under consideration of both closed and non-closed loop case by using A* algorithm. Fig. 3 shows the direction of shuttle movements in the system. First, it was assumed that all the empty shuttles are allocated at each terminal at an initial time. As soon as there is an available task to loading/unloading at loader, the system will scan all empty shuttle locating in layout and then the closest shuttle is assigned to this task. The assigned shuttle moves from idling position to loading station to execute the task. For each container, its destination has been defined before transport, an algorithm is developed by using the A* algorithm to find an optimal route from the loading station to the destination terminal. The shuttle is returned to the closest idling position after completing the task. If there is no vehicle available, the loader at the station is under waiting status until the shuttle has completed the previous job and come to available. Table 4 provides some input value of a constant parameter for the simulation system.

Table 4 System configuration design

Time constant	Value
Change station	55 (s)
Loading/unloading at station	15 (s)
Move-in to station	10 (s)
Move out from the station	10 (s)
Shuttle velocity	70 km/h
Safety distance between shuttle	10m

5.3 Performance evaluation

By far the most important outcome of the ITT system is to deliver the containers to their destination in time. To find out how well the designed configurations perform, the target is set at 100% of the considered volume are delivered to the destination within 60 minutes. If the completion of transportation time exceeds this time limit, it will be accounted as non-performance. Because hourly transport demand is used for simulation, if all containers are imported and exported within an hour at all terminals, the system can meet the desired capability. Other important performance indicators include the productivity and performance of the loader and shuttle as well as tracking the total distance traveled by the vehicles.

5.4 Simulation results

Several experiments have been performed to evaluate the ITT configurations that have been defined in section 4 and to gain more insight into the working of the ITT system. The system performance is shown in Fig. 6. The results showed that 100% of containers were delivered to the destination in time. The average transport duration at each terminal is around 39 minutes. While all the tasks in terminal 2 are completed the fastest within 31 minutes, it recorded the slowest process at terminals 7 which took about 45 minutes. The result showed that the system configuration is able to carry out the transportation demand.

In terms of loaders performance, productivity and tracking time (working time, idling time and waiting time) are shown in Fig. 6-7. Fig. 6 indicates the actual loader productivity at each terminal. Actual loader capacity at terminals is uneven, ranging from 20-30 movement/hour, the lowest performance is observed at terminal 5 and achieved highest at terminals 7 and 8. The tracking time of the loader in Fig.7 illustrates that the loader waiting time at some typical terminal is significantly higher compared to the working time. For instant, the largest waiting time distributed at terminal 9 accounts for 61.7% of the system uptime. By observing through the real-time counter system on the simulation, this waste is caused by the difference in loader and shuttle cycle times and it can be optimized to handle even larger transfer volumes by increasing shuttle quantity.

In terms of shuttle performance, Fig. 8 shows the total travel distance of the top 5 shuttles with the highest performance and top 5 shuttles with the worst performance. The average travel distance of the group with the highest efficiency is 42 km, of which shuttle 3 and 5 have the longest travel distance, about 44 km. In contrast, the lowest-performing group only achieved an average of about 30 km, especially shuttle 6 had the shortest total travel distance, recording about 28 km. Fig. 9 illustrates the tracking performance of shuttles, including working and idling time.

The average shuttle working time is about 26 minutes, of which the best performing group has a longer working time, accounting for 58.6% of the total system uptime, while the lowest-performing group only accounts for 33.3 %. Besides, the top 5 shuttles with the highest performance have a total working time without load only about 4.7% while the other group has reached 16%. Non-load operation cause wastes energy and reduces the efficiency of the whole system.

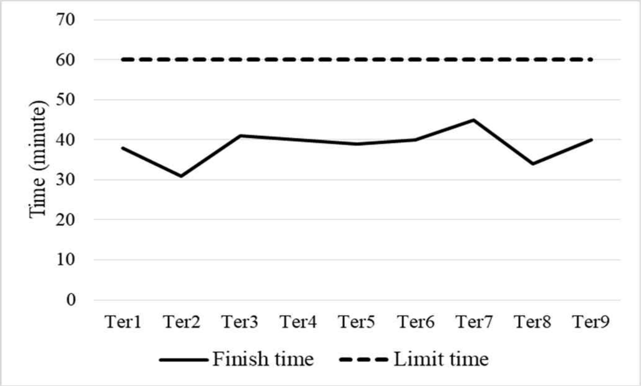

Fig. 6 System performance

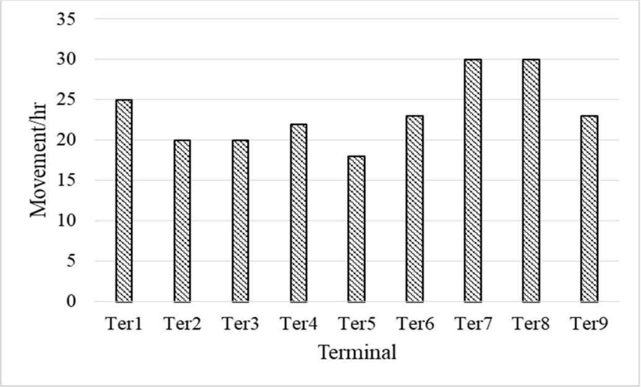

Fig. 7 Actual loader productivity

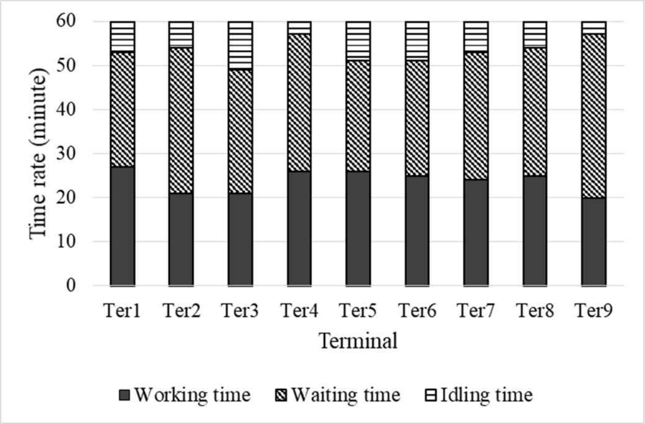

Fig. 8 Loader performance

Minimizing the movement without load can be done by improving the shuttle's routing algorithm, to assign tasks as the nearest loading stations as possible.

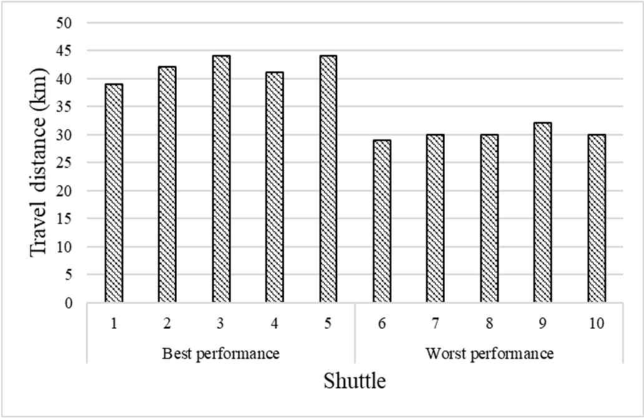

Fig. 9 Shuttle travel distance

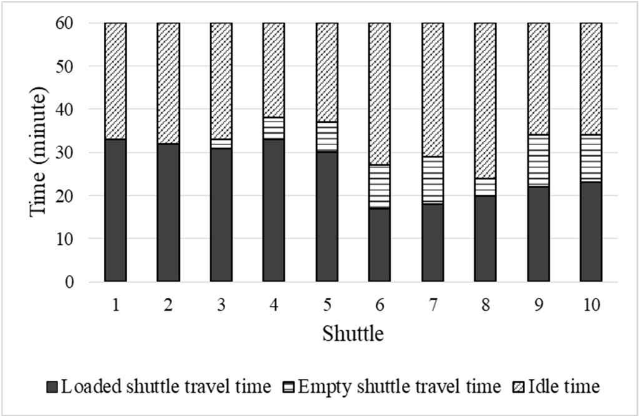

Fig. 10 Shuttle performance

6. Conclusions

This paper presented a design model of the ITT system based on the combination of electric shuttle operating on the monorail system. First, the formulas to calculate the system parameters are defined. Followed by a transport scenario calculated based on the real case of Busan New port capacity estimation in 2030.

Finally, the simulation has been conducted to evaluate and verify the designed system parameters. As a result, the design system is capable to deal with demand scenarios through a highly efficient with 100% of the containers being delivered to their destination on time. Besides, several operational parameters of the system such as loader performance, operation time and travel distance of shuttles are collected for actual system improvement and construction in the future. The simulation results also show that if increasing the number of shuttles or improve the routing algorithm, the system capacity can be extended to handle larger volumes.

In summary, the ITT system has the disadvantage of high investment cost, but many long-term benefits overcome the drawback such as reducing operating costs, increasing efficiency and being more environmentally friendly than other transportation methods.

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