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SIMULATION BASED EVALUATION OF THE CAPACITY OF LIUHENG LNG TERMINAL

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ABSTRACT

Liuheng LNG (Liquified Natural Gas) terminal is proposed to serve LNG carriers and LNG tank container ships. However, the capacity of this terminal may be limited by the long entrance channel and traffic rules for LNG transportation. Therefore, to evaluate the capacity of Liuheng LNG terminal, we establish an agent-based microscopic simulation model for ship operation (AMic-SMSO) to simulate the whole process of ship operation in and out of a port. We undertake a series of experiment scenarios to identify the bottlenecks and assess the throughput capability by analyzing waiting times, berth occupancies, and explore the effect of modifying the traffic rules on these indicators. The results show that this simulation model is a useful tool in determining whether traffic rules works well actually, especially for LNG terminal berth configuration plan.

Keywords: LNG terminal, one-way channel, ship traffic simulation, service level

1. INTRODUCTION

Fierce competition hastens port operators' efforts to enhance the capacity and efficiency of channel while maintaining a required service level. However, the terminal capacity is closely related to a great amount of uncertain factors and may be limited by the long entrance channel. Liuheng LNG (Liquified Natural Gas) terminal is proposed to accommodate LNG carriers and LNG tank container ships. So, traffic rules for LNG transportation also need to be considered. For example, the traffic rules such as one-way traffic, moving safety zone and no transit at night may lead to more waiting time and decrease the capacity of an LNG terminal. Therefore, the objective of this study is to identify the capacity and bottlenecks of Liuheng LNG terminal by analyzing waiting times, berth occupancies and LNG throughput.

At present, few works study the throughput capacity of LNG terminals, and most studies concentrate on the capacity in container terminals and bulk terminals. Lin et al. (2014) got the annual throughput of container terminal considering equipment types and berth allocation. Longo et al. (2015) investigated the effect of throughput capacity on the implement of green practices in container terminals. Huang et al. (2013) presented a capacity-assessment simulation system for complex waterway networks. Tang et al. (2014) optimize the channel dimension to improve the capacity and navigation efficiency of channel. Sun et al. (2012) developed a real-time system to determine the container throughput. Meanwhile, some studies devoted to analyze the capacity of bulk cargo terminals using mathematical methods and artificial neural network model (Yan and Zhou 2014, Dragovi et al. 2012). However, different from the container ships and bulk ships, LNG carriers should set up a mobile safety zone and implement traffic control when sailing in the waterway considering the safety requirement of its navigation. Liu et al. (2016) considered the additional security zones of LNG ships and waterway conditions. Then a dynamic ship domain model was created to guarantee the safe navigation of ships. Wen et al. (2013) defined the width of a moving safety zone around LNG carriers based on a quantitative probability model. Lisowski (2014) presented a computer simulation model for ship collision avoidance at sea. It's clear that the high safety requirement make entry and exit of LNG carriers exclusive, which will have a great impact on the entry and exit of ships in the relevant port areas, especially in the case of one-way long channel. As described above, at present, there are little studies have been conducted to evaluate the capacity of LNG terminal considering the navigation safety of LNG carriers simultaneously.

Due to complex interactions between ship entities, combined with special navigation rules of LNG carriers, random factors and uncertainties of port operation, it is difficult to use traditional mathematical models to analyze port service level quantitatively. This necessitates the development of traffic flow simulation models to estimate the port capacity (Moran et al., 2014). Simulation technology is often used to study the characteristics of ship traffic flow. Xiao et al. (2015) introduced a multi-agent simulation model to describes the nautical traffic of autonomous ship. Li et al. (2015) constructed a one-way waterway transportation simulation system and analyzed the ship traffic smoothness and traffic efficiency in the waterway. Chen et al. (2018) established a full mission model to simulate the operation of terminals and ships in consideration of the operational safety of LNG carriers during berthing.

Therefore, considering the one-way long channel and complex operation system in Liuheng LNG terminal, this paper establishes an agent-based simulation model to study the capacity of the LNG terminal.
The remainder of this paper is organized as follows. The study case is presented in Section 2. The simulation model is implemented in Section 3 in detail. The simulation results are analyzed in Section 4. Finally, the main conclusions are drawn in Section 5.

2. PROBLEM DESCRIPTION

Due to the dimensions of shoreline and water area, Liuheng LNG terminal could accommodate 4 berths at most as shown in Figure 1, which comprise two 20000-DWT (Dead Weight Tonnage) LNG container berths (B2 and B3) and two 150000-GT (Gross Tonnage) LNG berths (B1 and B4). According to the capacity of the landside LNG handling system on each berth, the annual capacity of this LNG terminal is estimated to reach 10~20 Mt. However, the actual capacity of a port system is dependent on not only LNG handling system, but also the capacity of wet infrastructure (e.g., entrance channel, turning basin, et al.) and traffic rules for ship navigation and maneuvering.

2.1. Wet infrastructure

As shown in Figure 1, the wet infrastructure consists of a very long entrance channel (24.5 km) to the LNG terminal and 2 turning basins (TB1 and TB2). The entrance channel provides two-way traffic only for less than or equal to 20000-DWT container ships loaded with LNG tank containers, but one-way traffic for larger than 20000-DWT LNG tank container ships or LNG carriers. One-way traffic means that this channel allows ships to move in the same direction, while ships moving in the opposite direction have to wait until the channel is evacuated (McCartney et al. 2005, Tang et al. 2013). When one-way entrance channel is too long, the situation becomes more serious (Tang et al. 2013). With the increase of traffic volume, unacceptable wait will definitely lead to poorer port performance and capacity.
In addition, as shown in Figure 1, the turning basins TB1 and TB2 occupy part section of the entrance channel, which causes hindrance to ship traffic. When an LNG ship is maneuvering in turning basin, no other ship is allowed to be in this channel section for safety, which also increase waiting time of LNG carriers.

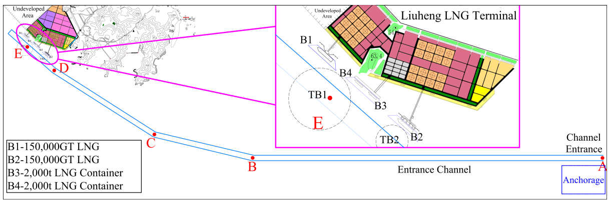


Figure 1: Schematic Diagram of the Proposed LNG Terminal with Its Wet Infrastructure

2.2. Traffic rules

To ensure the safety of LNG carriers and LNG tanker container ships, more management measures (e.g., one-way traffic, moving safety zone and no transit at night) are taken during LNG carriers or LNG tank container ships transit from the open sea to its terminal berth and return to sea.

1. **Traffic rules for LNG carriers**
   a) One-way traffic: Encounters and overtake maneuvers with vessels are prohibited during LNG carriers transiting through the channel area.
   b) Moving safety zone: No other ships are permitted to enter the safety zone around a transiting LNG carrier. From the practice of existing Chinese LNG terminals, the recommended size of safety zone is 1 n mile distance in front and behind, and 150 m from port side and starboard side.
   c) No transit at night: Entry and departure commence only during daylight hours.
2. **Traffic rules for LNG tank container ships**
   a) Two-way traffic: Less than or equal to 20000-DWT LNG tank container ships are allowed to pass each other.
   b) One-way traffic: Encounters and overtake maneuvers with vessels are prohibited when larger than 20000-DWT LNG tank container ships are transiting through the channel area.
   c) Safety zone: Its size varies with ship speed and ship length and determined based on the fuzzy quaternion ship domain theory (Chen P et al., 2018).
   d) No transit at night: Entry and departure commence only during daylight hours.

In conclusion, these traffic rules will cause more waiting and complicate the navigation system of wet infrastructure in Liuheng LNG terminal. Moreover, ship arrivals and ship unloading/loading time are also stochastic. Therefore, a traffic flow simulation model is developed to estimate the port capacity.

3. METHODOLOGY

In this study, we define the capacity of Liuheng LNG terminal is the annual LNG throughput with complex traffic rules dependent on the required service level in terms of acceptable average waiting times and berth occupancies. Therefore, we establish an agent-based microscopic simulation model for ship operation (AMic-SMSO) to simulate the whole process of ship operation in and out of a port. The objective of the traffic flow simulation study is to identify the bottlenecks of Liuheng LNG terminal by analyzing waiting times, berth occupancies and LNG throughput.

3.1. Logical model

The whole process of the ship in and out of a port is illustrated in Figure 2. Ship operation begins with an inbound ship's arrival. The ship may or may not have to wait in anchorage area, depending on the congestion at the berth and traffic rules for LNG transportation in Section 2.2. If all these states are favorable, the ship is assigned to a berth, and transit to berth via entrance channel and turning basin. After berthing, the LNG or LNG tank container are unloaded to storage tanks or container yards, and the outbound ship travels through the entrance channel and leaves the port when the channel is accessible.

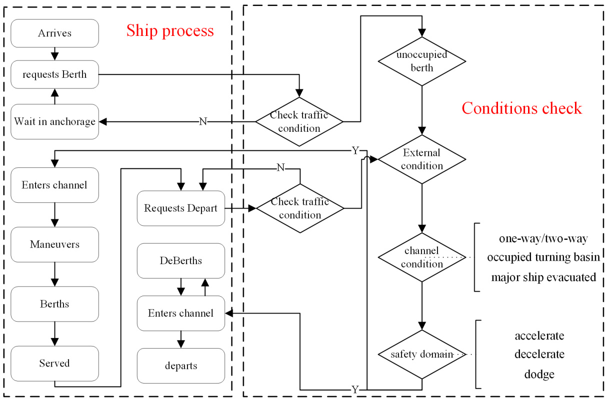


Figure 2: Logic Flowchart of Ship Operations

1. **Ship arrivals**
Ship arrivals occur at random times (PIANC 2014), and the inter-arrival times between successive ship arrivals are exponentially distributed with 1/ λ hours. Thus, the probability density function is:

$$f(t) = \lambda e^{-\lambda t} \quad (1)$$

where λ = ship arrival rate, i.e., the number of arrival ships per hour from historical data.

2. **Requesting berth and checking channel availability**
After inbound ship arrives, it requests the quay master for a berth first. Then the VTS (Vessel Traffic Services) checks currents, water levels and traffic situation based on traffic rules in Section 2. The ship enters and berths on days with good weather in case no problem exists. Otherwise, this ship waits in the outside anchorage until all these states are favorable.

3. **Ship sailing/maneuvering**
When the ship is sailing in the channel area, it checks whether its safety zone meets the requirements, and then accelerate, decelerate according to the separate distances between ships. Then it arrives at the turning basin and maneuver to berth with tugs, and no other ship is allowed to enter this channel section.

4. **Ship loading and unloading**
The berth service time includes auxiliary operations time, loading and unloading operations time. According to the statistics of neighboring port, berth service time follows an exponential distribution with 1/ μ hours per ship. Its probability density function is as follows:

$$f(t) = \mu e^{-\mu t} \quad (2)$$

where μ is the service rate, i.e., the number of ships serviced per hour.

5. **Ship mooring and departure**
After finishing unloading/loading operation, the VTS is again asked for permission to leave the port. If no problem exists, the outbound ship leaves berth, enters channel and leaves port.

3.2. AMic-SMSO Simulation

Using AnyLogic, we revised a verified and validated ship operation system (Tang et al. 2013), establish AMic-SMSO to fulfil the precise simulation of ship operation in Liuheng LNG terminal. The AMic-SMSO comprises five agents including Main, Ship, VTS, PortOperation and QuayMaster. How these agents be organized and what things they are responsible for are contained in Figure 3. The detail description of agents is as follow:

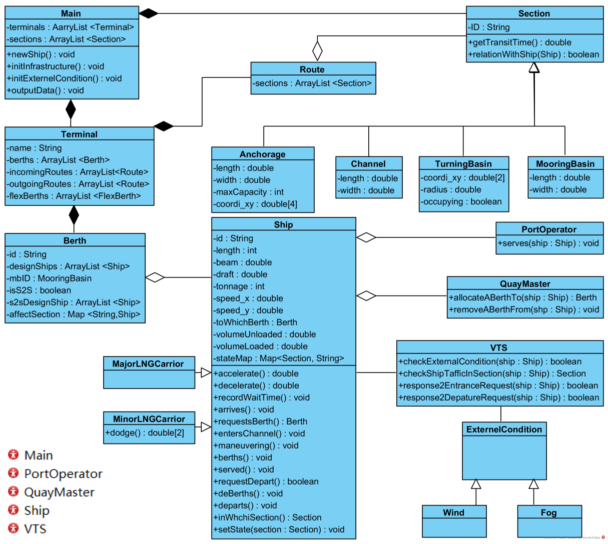
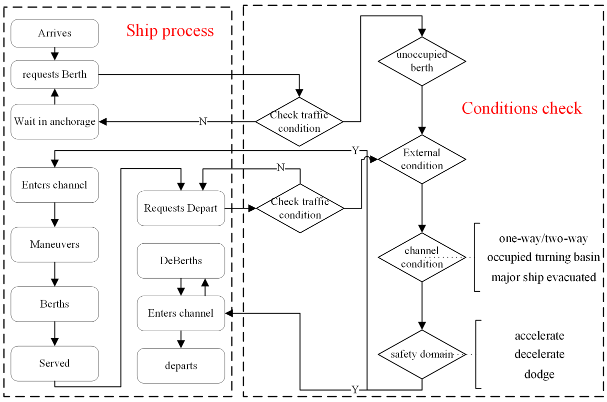


Figure 3: Static Class Diagrams of AMic-SMSO Framework

1. **Main Agent**
Main Agent as the basis of the simulation model, is responsible for initializing simulation parameters (ship traffic volumes, the number of ship arrivals), port infrastructure (berths and water area) and traffic rules and generating ship agents according to ship arrival pattern. Also, Main agent controls the whole simulation process and outputs simulation results once the simulation run is finished.

2. **Ship Agent**
Once the ship agent is generated by Main Agent, the ship process is activated and performs the ordered activities in Figure 2. The ship operation is simulated by states and transitions in AnyLogic. The states of a ship agent include

the berth and traffic rules for LNG transportation in Section 2.2. If all these states are favorable, the ship is assigned to a berth, and transit to berth via entrance channel and turning basin. After berthing, the LNG or LNG tank container are unloaded to storage tanks or container yards, and the outbound ship travels through the entrance channel and leaves the port when the channel is accessible.



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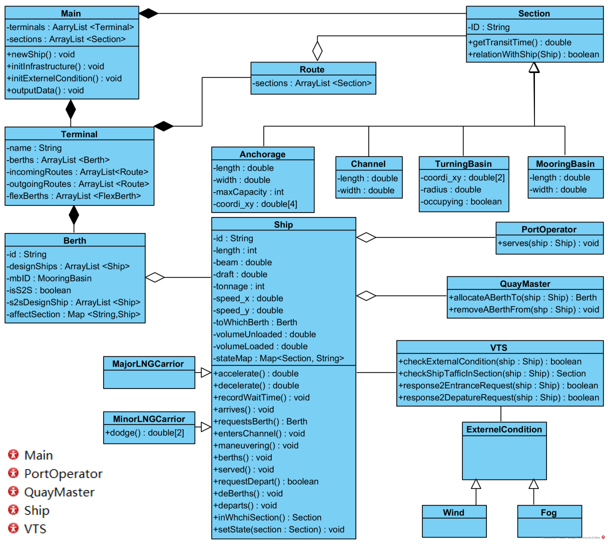

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2. **Ship Agent**
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arrival, mooring, waiting, navigation, operation, etc., which corresponds to the process of ship operation in Section 3.1. As illustrated in Figure 4, the ship agent changes from one state to another and modifies speed avoiding collision dynamically based on the distance between the ship and the facilities in the water area or when some conditions are met.

3. **VTS Agent**
   This navigation channel, mostly one way, is subject to traffic rules, therefore a VTS service controls all the inbound and outbound traffic of Liuheng port. The VTS agent interacts with Main Agent, Ship Agent to check ship traffic in wet infrastructure. To check ship traffic, the VTS component uses the ship traffic rules, specified for each port section.

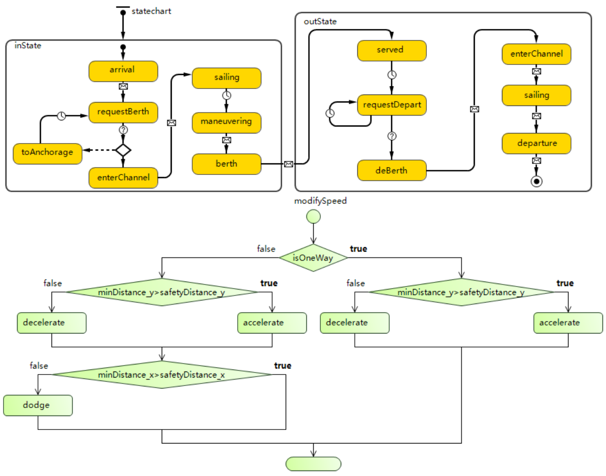

Figure 4: State Diagram of Ship Agent Implemented by AnyLogic Software

4. RESULTS AND DISCUSSIONS

4.1. Berths and traffic volumes scenarios

Before running the simulation model, baseline studies of environmental conditions were performed, and there are 43 days/year with adverse weather that are uniformly distributed over the period of 1 year in the simulation experiment. The berth service time follows an exponential distribution, and $1/\mu$ for 10000 and 20000-DWT LNG tank container ships are 10.7 hours and 12 hours, and for 100000 and 150000-GT LNG carriers are 51 hours and 56 hours respectively.

This study first evaluates 4 options for berth combination of LNG berths (n_{lng}) and LNG tank container berths (n_{con}), i.e., $\mathbf{B}(n_{lng}, n_{con})$= {{2, 2}, {2, 1}, {1, 2}, {1, 1}}, to evaluate the capacity of LNG terminal, then to identify the bottlenecks of Liuheng LNG terminal by analyzing waiting times and berth occupancies.

To explore the actual annual throughput capacity (ActT) for different berth combinations, we evaluate a series of scenarios of estimated annual number of ship arrivals and their responding estimated LNG throughputs (EstT) as shown in Table 1. And the inter-arrival times between successive ships are exponentially distributed with $1/\lambda$ hours, which is determined by the number of ship arrivals.

In general, the acceptable waiting times vary with the cost of a vessel, but no exact accepted criteria are available (PIANC 2014). To investigate the effect of long channel and traffic rules on ActT, we adopt the waiting time for berth and channel as port performance indicators, not considering the constraint of transit at night in this case study. Besides, the adopted average waiting time for each type of ships should be lower than the predetermined value, as follows: a) Container ships: 5-10 % of the service time (1.5 h); b) Gas carriers: 10 % of the service time (6 h).

Table 1: The Scenarios of Number of Ship Arrivals and Their Estimated Throughputs

Ship type and size		Estimated number of ship arrivals			
		No.1	No.2	···	No.15
Container ship (DWT)	10,000	5	8	···	70
	20,000	10	16	···	130
Estimated LNG tanks throughput (10^4 tons)		20	50	···	400
LNG carrier (GT)	100,000	19	30	···	270
	150,000	1	2	···	14
Estimated LNG throughput (10^4 tons)		140	220	···	1900

4.2. Simulation results

We run the simulation experiments for 60 scenarios (15 EstT for 4 options) for one year, and the simulation results including average waiting time (AWT), ActT are shown in Figure 5 and Figure 6 respectively. The berth occupancies of the expected EstT are listed in Table 2.

1. **Waiting time and actual throughputs**
   As shown in Figure 5 and Figure 6, AWT of LNG carriers go beyond the acceptable waiting time (about 6 h) when its EstT is larger than 780 $\times 10^4$ t and the AWT for all scenarios of LNG tank container ships far exceed the acceptable value (about 1.5 h), which shows that Liuheng LNG terminal provides poor service under expected EstT. When n_{lng}=1, the maximum throughput capacity is 1090×10^4 t for **B**(1, 2) and 1145×10^4 t for **B**(1, 1). Moreover, the ActT of LNG carriers will decrease when LNG berth increases from 1 to 2. The reason for this is that there are more LNG tank container ships in channel and LNG carriers must wait until it is cleared. Similarly, the ActT of LNG tank container ships will also reduce with one more LNG berth.
2. **Berth occupancies**
   From the viewpoint of berth occupancies of LNG berths, if two berths are planned for LNG

carriers or LNG container ship, the occupancy of one is too low (0.9~24.9% as shown in Table 2), which means it is a waste of berth resources. Therefore, the long one-way channel and traffic rules indeed limit the capacity of LNG terminal.

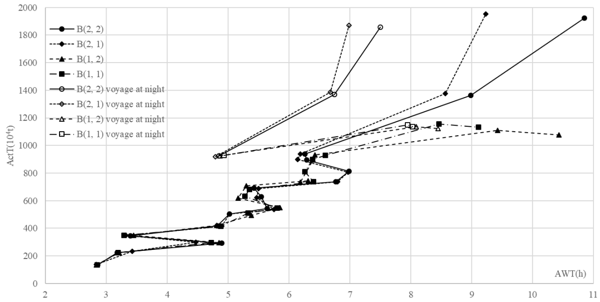

Figure 5: AWT and Actual Throughputs Diagram of LNG carriers

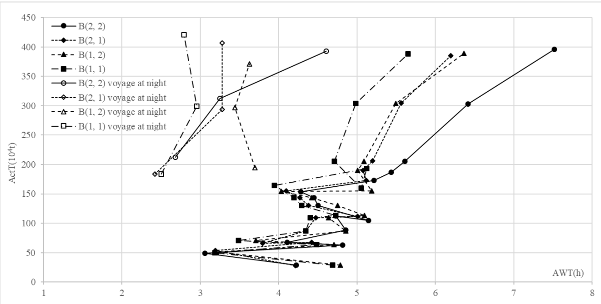

Figure 6: AWT and Actual Throughputs Diagram of LNG tank container ships

Table 2: The Simulation Results of Berth Occupancies (%)

No.	B(2, 2)		B(2, 1)	
	LNG	Container	LNG	Container
1	5.2	0.9	5.3	1.9
2	8.4	1.5	8.8	3.0
3	11.2	1.9	11.5	3.9
4	13.1	2.1	13.2	4.2
5	15.8	2.8	15.7	5.5
6	19.2	3.3	19.2	6.5
7	20.5	3.3	20.4	7.1
8	23.7	3.9	23.6	7.8
9	26.2	4.4	26.2	8.8
10	27.7	4.9	27.8	9.8
11	30.7	5.3	30.6	10.6
12	33.9	5.9	33.9	11.7
13	35.4	5.9	35.4	11.7
14	51.9	9.3	52.0	18.5
15	73.2	12.5	74.0	24.9
No.	B(1, 2)		B(1, 1)	
	LNG	Container	LNG	Container
1	10.5	0.9	10.5	1.9
2	16.9	1.5	16.9	2.9
3	22.6	1.9	22.5	3.9
4	26.4	2.1	26.4	4.2
5	31.7	2.7	31.5	5.5
6	38.1	3.2	38.5	6.5
7	41.0	3.6	41.0	7.1
8	47.0	3.9	47.4	7.8
9	52.8	4.4	52.1	8.8
10	55.8	4.9	56.3	10.0
11	55.7	4.9	62.3	10.7
12	67.7	5.9	65.9	11.5
13	70.7	5.9	70.5	11.7
14	83.7	9.3	87.4	18.5
15	81.6	12.5	86.1	24.9

3. **LNG tank container ships voyage at night**

Considering LNG tank container ships make only a small contribution to throughput, deregulate the night voyage to alleviate LNG carriers' waiting for long channel and to meet the expected throughput of port owners is worth a trial. As can be seen from the Figure 5 and Figure 6, the relationship between AWT and actual throughputs varies greatly at No.13~15. So, the results of these scenarios deregulating the night voyage constraint are shown in these two figures and the berth configuration for 4 options for are shown in Figure 7.

According to Figure 5 and Figure 6, the waiting time reduces significantly by 15.1% of LNG carriers and 82.3% of LNG tank container ships on average, compared to the scenarios with night voyage constraint. Meanwhile the waiting time is lower than the acceptable time of LNG carriers when Est lower than 1200×10^4 t. But the AWT of LNG container ship still does not meet the requirement. It can also be seen that the ActT keep invariant when we deregulate the night voyage, because the increase in the number of small ships offsets the reduction in the volume of large ships.

Figure 7 shows that two LNG berths or two LNG tank container berths will also result in the resource waste of one berth in case of cancelation of no transit at night rules for LNG container ships. The berth occupancies of LNG container berth are too low (1.4%~29.5%) to spend money to build.

In summary, it's not worth to construct the LNG container berth if there is no mandatory demand and it can be built in adjacent container ports. Considering acceptable ships' waiting time and berth occupancy, **B(**1, 1**)** is suitable for this port.

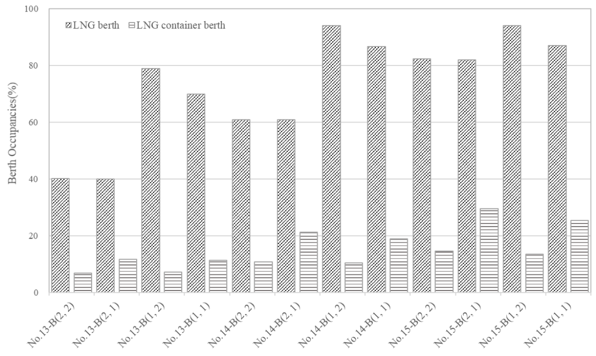

Figure 7: Berths Occupancies for Deregulating Night Voyage of LNG Container Ships

5. CONCLUSIONS

To provide decision support for berth configuration of Liuheng LNG terminal, this paper focuses on the ship traffic simulation problem and aims to determine the throughput capacity under acceptable the service level requirement. To better simulate and analyze the port operation system, we consider the LNG carrier traffic rules, long one-way channel which occupied by the turning basin and try to find out the balance between the capacity and the service level.

A simulation model is then proposed based on AnyLogic software, all parameters of which is based on historical statistics provided by the operator of Liuheng Port area. We undertake total 44 experiments to identify the bottlenecks of Liuheng LNG terminal by analyzing waiting times, berth occupancies and LNG throughput and explore the effect of modifying the traffic rules on waiting time and berth occupancies. The results allow us to affirm that simulation has good performance and can effectively determine the optimal terminal size under acceptable port service level. Moreover, this simulation model is a useful tool in determining whether traffic rules works well actually, especially for LNG terminal berth configuration planning.

However, the handling technology of LNG carriers is not be considered in-depth and the operation in port land area is at an early stage. Also, more valuable and feasible measures such as adding a buffer area in entrance channel or selecting priority rules will be taken in the future study.

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