Design and evaluation of mega container terminal configurations: An integrated simulation framework

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Abstract
Operators of busy container terminals need to periodically evaluate options for capacity expansion in order to meet the increasing demands for container handling at their terminals. When planning such capital intensive investments, it is important to find an efficient and effective way to design and evaluate various possible terminal layout and equipment configurations. The issue is further complicated for mega-sized container terminals which consist of multiple berths and yards due to pre-existing geological conditions. This paper proposes an integrated simulation framework to facilitate the design and evaluation of mega container terminal configurations with integrated multiple berths and yards. There are two major components in this framework: a geographical information system (GIS) and a multi-agent system (MAS). The former is used to design specific terminal configurations which can be then simulated and evaluated by the latter. An application of the framework to a real container terminal expansion problem demonstrates the validity of the framework. Results obtained from simulation models generated efficiently by the framework are used to help terminal planners make reasonable decisions.

Keywords
Mega-sized container terminal, GIS, multi-agent system, simulation framework

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1. Introduction
With globalization, international trade between countries has been rapidly increasing in volume and value. As essential maritime transportation nodes that play a crucial role since the introduction of containerization, container terminals are getting more and more congested as the volume of containers passing through them increases. Container terminal operators typically arrange for various container vessels to berth at a quay and use terminal equipment (quay cranes, yard cranes and yard trucks) to lift, transport and store containers in the yards and then transport them to some hinterland or other vessels later. Computer simulation is usually the preferred approach to evaluate the efficiency of container terminals in meeting future demands or in new configurations. Most container terminal simulation models tend to assume that berths and yards are regularly shaped (straight, linear berths and rectangular yards) and simplify their topographical relationships (one berth is associated with one yard). However, due to pre-existing geological conditions, many container terminals in the world take on various irregular shapes and layouts for their multiple yards and berths. By considering these real geological constraints, building realistic simulation models becomes much more challenging and requires more effort. Container terminal simulation models consist of resources and logics. Resources accordingly represent physical entities in the real world, such as gates, berths, yards, vessels, quay cranes, yard cranes, yard trucks and containers. Logics imitate the behaviors of those movable resources (terminal equipment) and decision processes made by

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control centers of container terminals. The conventional approach of building a simulation model for a typical container terminal is, first, based on the berth length and yard length and width, to construct a model consisting of one berth and one yard. Then quay cranes, yard cranes and yard trucks as movable resources are added and logics are written for them. Finally, logics for decision processes as external controllers of resources are written. When running the simulation, vessels will be randomly generated as the testing demand which drives other equipment to transport containers. Figure 1 shows a typical container terminal in a simulation. Its layout has been simplified to concentrate on container handling operations. Owing to pre-existing geological conditions, the layout of a real container terminal may not be regular shaped as shown in Figure 2. Although a big terminal with multiple berths and yards can be decomposed and transformed to a few regular shaped terminals, the operations of various devices in the terminal cannot be segregated simply. In fact, as experienced terminal managers would point out, the terminal layout may impact significantly the operations of terminal devices. Thus, when building simulation models for these container terminals, the building procedures mentioned above will no longer be appropriate. It is important to find an efficient and effective method to address this issue. This paper introduces an integrated framework to facilitate building this type of simulation model. A geographic information system (GIS) has been used to help port planners design a container terminal layout. Based on the layout, terminal resources will be inputted and allocated by a sharing policy. Then a multi-agent system (MAS) will take over the configuration and assign a software agent for each device and operation to generate an appropriate simulation model. The simulation model can be used to evaluate the overall terminal operational efficiency with the given terminal configuration. With this integrated framework, a port designer may explore a number of different terminal designs and efficiently generate the corresponding simulation models. The port designer can then make the necessary decision on the terminal configuration based on comparing the simulation results.

In the rest of the paper, a literature review of previous related works is given in Section 2, followed by the problem definition in Section 3. The design of the simulation framework is presented in Section 4 and illustrated via a case study in Section 5. Finally, conclusions are given in Section 6.

2. Literature review

In the recent decade, because of advancements in computer science, simulation, especially discrete-event simulation, has been widely used for studying container terminals.

Gambardella et al. built a decision support system focused on the resource allocation problem and used a terminal simulation model as a test bed for checking the
validity and robustness of the system. Nevins et al.\textsuperscript{2,3} developed a seaport simulation model that computes the throughput capability and determines resource utilization at a high level of detail. The simulation allows for multiple cargo types as well as multiple ship types. Shabayek and Yeung\textsuperscript{4} proposed a simulation model of the Kwai Chung Container Terminals in Hong Kong to investigate the extent by which a simulation model could be used to predict the actual container terminal operations with a higher order of accuracy. Demirci\textsuperscript{5} used simulation experiments to find that the most critical bottlenecks were created by loading/unloading vehicles and an investment strategy was applied to the model for load balancing in the port. Parola and Sciomachen\textsuperscript{6} tried to simulate the logistic chain of the northwestern Italian port system as a whole to evaluate a possible future growth in container flow. Bielli et al.\textsuperscript{7} elaborated on an object-oriented design of a simulator for container terminals. Every piece of equipment, queue or area is implemented as an object and communications among objects are implemented as messages. Zeng and Yang\textsuperscript{8} proposed a simulation model for scheduling loading operations in a container terminal and then embedded this model in an optimization routine to find an optimal scheduling scheme. Cartenı and Stefano\textsuperscript{9} presented different microscopic discrete event simulation models for a container terminal to find out the best approach to adopt to simulate handling activity time duration and the best level of detail that should be pursued. Huynh and Vidal\textsuperscript{10} addressed the need by terminal operators to optimize the yard crane operations at seaport terminals. They introduced a novel agent-based approach to model yard cranes, where each crane acts as an autonomous agent that seeks to maximize its utility.

There are some papers related to simulation and container terminal layout. Nam et al.\textsuperscript{11} used a simulation model with four scenarios to examine the optimal size for the Gamman Container Terminal in terms of berths and quay cranes. Liu et al.\textsuperscript{12} used simulation models to demonstrate the impact of automation and terminal layout on terminal performance. In particular, two terminals with different but commonly used yard configurations were considered for automation using Automated Guided Vehicles (AGVs). Lee et al.\textsuperscript{13,14} developed simulation models to investigate how different vehicles and different yard layouts can affect the efficiency of port operations. They further built a program, named Automated Layout Generation, to generate different simulation models. Hartmann\textsuperscript{15} introduced an approach for generating scenarios of sea port container terminals. The scenarios can be used as input data for simulation models. Furthermore, they can be employed as test data for algorithms to solve optimization problems in container terminal logistics such as berth planning and crane scheduling. Ottjes et al.\textsuperscript{16} introduced a generic simulation model structure for the design and evaluation of multi-terminal systems. The model is constructed by combining three basic functions: transport, transfer and stacking. Petering\textsuperscript{17} developed a comprehensive simulation model to address issues in terminal design, storage and retrieval location and yard crane control. Sun et al.\textsuperscript{18} proposed a general simulation framework which can generate different simulation models for different regular container terminals. We note that none of the above works in the literature is concerned with arbitrarily shaped container terminals with multiple berths and yards, which is the key issue investigated in this study.

3. Problem definition

This study is motivated by the problem faced by terminal designers in the port of Singapore, one of the world’s largest and busiest container ports. A large part of the port premises currently occupies an area that is very close to the central business district. As the commercial price of land around the port rises with the demand for commercial land, it is becoming inevitable that the container terminals have to make way. The obvious choice is to relocate the container terminals to the south western corner of the island nation by reclaiming land from the sea for container terminal operations use. The port designers need to decide on the sizes and shapes of the reclaimed land to construct a new mega-sized container terminal that will fit into the given geological constraints. It is thus necessary that the mega-sized container terminal will include multiple berths and yards which will make modeling and analysis more complicated. Terminal designers thus face the challenges in analyzing and evaluating different designs.

This study covers the areas of computer-aided design and port operations planning and simulation. In a computer-aided design system, accurate geographical information needs to be used. Port operations planning should take into account the problems associated with resource sharing. The simulation structure needs to be flexible and reusable for automated model generation.

4. Framework design

The proposed framework is designed based on MicroCity\textsuperscript{19} which is originally a spatial analysis and simulation framework. It provides many useful functions and has an open architecture which consists of three software layers; namely, the function layer, the application layer and the extension layer (Figure 3). Different layers are bound by application programming interfaces (APIs). The two major parts of this study, a GIS and a MAS, are built into the extension layer and the application layer of MicroCity, respectively. Base functions in the function layer of MicroCity supports the application layer where we construct the MAS. The MAS interprets the terminal configuration parameters from the extension layer into...
simulation models. Users only need to manipulate the extension layer to set up different terminal configurations. A graphical user interface is used for communication with users on input parameters, such as the number of quay cranes, the length of a yard block, the vessel calling pattern and so on. The GIS employed in the extension layer assists users in designing and modifying berths and yards visually and accurately.

4.1 Set up of mega container terminals in GIS

Due to pre-existing geological conditions, the layout of a mega container terminal may necessarily be irregular in shape. As mentioned before, it is inefficient and tedious for users to describe outlines of berths and yards with just numbers. The GIS built upon the extension layer of MicroCity is the key component to address this issue. Through the GIS, users can not only set parameters and load and save planning templates, but also accurately adjust the layout of the terminal in a simple drag and drop manner.

4.1.1 Geographical representations of berths and yards. The structure of the GIS component integrated in the framework is shown in Figure 4. Under the graphic user interface, GIS related tools are provided to users to draw the outline of the berths and yards. As the reference, satellite maps of the port of interest can be imported and incorporated as the background. Berths will be depicted as polylines in which one berth may have several discontinuous segments for sharing the same group of quay cranes. Yards will be depicted as polygons in which one yard may have several discontinuous parts for sharing the same group of yard cranes and yard trucks. While users are sketching the berths and yards, parameters for the container terminal are updated at the same time. These parameters associated with the berths and yards are partially inputted by users and partially implied by the shapes. Once users have completed the design, the related information will be stored in the geographical information database which will then be extracted by the layout analysis module.

4.1.2 Resource allocation. After users finish their layout design of the berths and yards, the resources in the terminal need to be allocated for further use. This process can be performed by users at the design phase or performed by the system when the program runs. Here we describe the systematic procedure of allocating the resources to multiple berths and yards. The general idea of allocating resources in this framework is based on the ratios among demands. For example, suppose there are two berths, one is twice as long as the other. Twelve quay cranes are available. If the chances for vessels berthing at two berths are equal, the longer berth may have twice demand of the shorter one. Owing to the allocation policy, the number of quay cranes allocated to a berth is proportional to the length of that berth. For this example, the longer berth will have eight quay cranes while the shorter one can have four quay cranes. The same resource allocation policy is used in allocating yard stacks and yard cranes. The flow chart
of the procedures and data for resource allocation is shown in Figure 5. The properties and geographical information of berths and yards are stored in the database listed at the right of Figure 5 and will be extracted and analyzed. First, container stacks are generated and located for every yard based on the yard geographical outline and properties. Then a certain number of yard cranes are assigned and distributed to each stacking zone in a yard according to the ratio of the number of stacks in the zone to the total number of stacks in the terminal. In the end, a certain number of quay cranes are assigned to each berth according to the aforementioned allocation policy and evenly distributed along the berths.

4.1.3 Yard sharing policy. For yard resource allocation, there is another issue related to irregular-shaped container terminals with multiple berth stretches and yards that we have to address in our framework. If the number of berths and yards are equal and every berth has its dedicated yard, then the whole terminal can be decomposed into several independent parts. If this situation does not happen, yards can be shared by berths. Figure 6 illustrates the yard sharing policy embedded in the layout analysis module. Buffers alongside berths are used as the determination criterion. Every yard stack covered by a buffer can be accessed by the corresponding berth. If a yard stack is covered by two or more buffers, this stack is shared by the corresponding berths. The first container arriving at this stack will lock the stack to this container’s source berth until the stack becomes empty. There are several strategies to avoid congestion. The basic idea behind the strategies is to assign limited tasks in these areas. This situation will lead to a reduction in the number of vehicles and relieve the congestion. Our simulation framework provides a default policy and lets developers further improve it.

4.2 Simulate container port operations in MAS

When the terminal layout design and resource allocation is done, MAS will obtain the output data and perform a simulation of the container handling operations on the current design. We consider eight generic operations in a container terminal: berth allocation, quay crane assignment, quay crane scheduling, yard storage location assignment, yard crane deployment, yard crane dispatching, yard truck dispatching and yard truck routing. Most of these operations consist of simple rules, like first-in-first-out, free-rotating, free-random, etc., which can be extended by users with external modules. Here, a pertinent assumption of the berth allocation algorithm needs to be highlighted. To minimize the inter-yard and inter-berth container flow, vessels carrying the same groups of containers are likely to be allocated to the same berth. This study assumes this problem has already been solved, so that vessels are separately generated for every berth. Then the normal berth allocation can be applied to allocate vessels at certain wharf marks in the continuous berth stretch.

4.2.1 Agent generation. To dynamically generate simulation models, the MAS is implemented with the dynamic programming language Lua. Every agent in MAS is implemented as a co-routine in the system and represented as an entity in the real world. We dynamically generate agents according to the number of the devices in the terminal. Every device has its representative agent. Agents generated
by the initialization procedure are all idle at the beginning. Then, they will be activated by decision process agents which are implemented as normal functions.

Figure 7 outlines the overall simulation flow. The simulation model repeatedly generates vessel arriving events. These events then trigger a series of decision processes. These processes make long-term, short-term and real-time decisions for various types of terminal equipment which, in turn, set job schedules for terminal devices. The various equipment pieces take their job schedules as prior rules and interact with each other to move containers around the terminal. They will in turn trigger decision processes when they reach certain states.

4.2.2 Agent interaction. The interactions among three major devices (quay cranes, yard cranes and yard trucks) consisting of the container handling activities is the key component to model for our MAS. There are five types of interactions between devices: interference between quay cranes, interference between yard cranes, interference between yard trucks, interactions between quay cranes and yard trucks and interactions between yard cranes and yard trucks. Because quay cranes and yard cranes are assumed to move on a single lane during the simulation, they cannot move through each other. Hence, the minimum safety spacing between quay cranes and yard cranes are mainly controlled by the decision processes. The minimum safety spacing for quay cranes and yard cranes are set in the initialization of a simulation run. During the simulation, when two quay cranes or yard cranes get too close, the corresponding decision process will be triggered to rearrange the schedules of the two devices to change the current moving destinations of at least one of the two devices. The interference between two yard trucks can cause collisions. Autonomous agents are responsible for avoiding collisions during the simulation. When two yard trucks get too close, each of them will make a detour but still move toward the same destinations.

As to the interactions between quay cranes and yard trucks, as well as interactions between yard cranes and yard trucks, queues are the proper data structures used to model. When a yard truck is dispatched to a quay crane for loading or for discharging jobs, it will be added to the waiting queue associated with the quay crane. The quay crane will then decide which yard truck in the queue should be served first. When a yard truck is dispatched to a yard location, it will be added to the waiting queue associated with the corresponding yard slot. A yard crane waiting at the slot, or to be dispatched to this slot, will serve the yard trucks in the queue in a first-come-first-serve manner.

There is a common issue in a MAS. As agents compete for limited resources, they will cause frequent deadlocks which can halt the entire simulation process. In this study we use a ‘guarantee’ policy by default to ensure the resource which an agent will access is available and designated to the agent. This strategy can easily eliminate the deadlock.

5. Case study
To validate this framework, we choose Brani Terminal, one of the four major container terminals in the port of Singapore. Figure 8 shows a screenshot of the framework.
when the program was running a configuration for Brani Terminal. A satellite map is imported as the background to aid users in adjusting the layout of the terminal. There are in total 15 quay cranes, 63 yard cranes and 60 yard trucks serving in the terminal. The terminal resources are allocated according to the sharing policy. We randomly generate vessels to assess the terminal’s operational efficiency. The vessel’s length is assumed as a normal distribution $\mathcal{N}(10,5)$ in hatches. A new vessel will arrive at the terminal in $\mathcal{N}(20,5)$ hours’ interval during 48 weeks. The blue lines in Figure 8 represent the berths. The red polygons represent the yards. The yellow dashed lines outline a piece of land currently not in use but one that will be developed as a new yard in our terminal expansion plan.

We first calibrated the configuration of the terminal in the simulation model to match the current actual situation of Brani Terminal. We then test the expansion plan which contains an additional yard. A total of 12 replications were performed in approximately two hours. Each replication runs for one year of simulation time. A summary of the results of our experiments are listed in Table 1. For equipment performance, we provide average values, taken over all devices over the 12 replications. For each configuration, we list two indicators for vessels, an indicator each for three land-side device types, the annual throughput and the average berth and yard utilization rates. The results indicate that the planned expansion of Brani Terminal will bring approximately a 6.2% increase in annual maximum throughput mainly because of improved quay crane productivity. The performance of yard cranes and yard trucks remains almost unchanged, whilst the yard utilization rate is slightly decreased as a result of the added yard spaces. As a result of improved quay crane productivity, vessel turnaround time is reduced which in turn accounts for the reduction in the berth utilization rate. The most significant improvement is in the reduction of average vessel waiting from 4.38 hours to 3.52 hours.

To assist decision makers in their investment decision concerning devices for Brani Terminal, Figure 9 shows another experiment performed to determine how the total number of yard cranes in this terminal affects the terminal productivity which is measured by the average quay crane productivity.

![Figure 8. Screenshot of the framework running a configuration for Brani Terminal.](image-url)
productivity or gross crane rate (GCR). As can be seen in Figure 9, as the number of yard cranes increases, GCR increases at a decreasing rate.

6. Conclusions

This paper introduced a general simulation framework suitable for mega-sized container terminals which are not regularly shaped and thus which inevitably must have multiple berths and yards. Two key components in the proposed framework provide convenient features for developing simulation models for these container terminals. Simulation models are generated efficiently through a MAS implemented in the dynamic programming language Lua. The GIS component allows users to conveniently design and explore different terminal layouts visually and accurately in a drag and drop manner.

Through the case study we have demonstrated that a comprehensive simulation model for a real container terminal can be generated efficiently using this framework. Various analyses can then be performed by using the simulation model to provide useful information for port operators and designers. Obviously, the integrated framework will greatly reduce the modeling effort and contribute to the design of efficient integrated operational configurations for container terminals by allowing decision makers to explore and evaluate a larger number of designs and scenarios using this framework.

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References

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Zhuo Sun has his beginnings in Dalian, which is known for its thriving port, efficient bus and light rail systems. Having finished a dual bachelor’s degree in civil engineering and computer science from the Dalian University of Technology, he decided to travel East Asia in pursuit of knowledge. He went to South Korea for his master’s course in the field of water resources and then went to Japan’s Nagoya University to finish his PhD focusing on spatial analysis of urban systems. Early in his undergraduate studies, it dawned on him to develop a software tool that would help analyze transport systems. The following years served as an incubation period for his idea and after almost ten years of contemplation and devotion to hard work, his idea was finally realized as ‘MicroCity’. He now carries with him the innovative spirit working as an adjunct research fellow in the National University of Singapore’s (NUS) Centre for Maritime Studies, doing research on shipping network design, port planning and port operation.

Kok Choon Tan received his BSc (1st Class Hons) in Mathematics from NUS and his PhD in operations research from the Massachusetts Institute of Technology (MIT). He was an NUS Overseas Post-Graduate Scholar at the Operations Research Center, MIT. He has held appointments as assistant professor and departmental manager in the Department of Mathematics, Faculty of Science, NUS, as well as manager (operations research) and container terminal process manager in PSA Corporation Limited and manager (operations research) in PSA International’s Group Technical and Operations Development Department. He was also seconded to the Land Transport Authority as operations research manager and had been adjunct associate professor in the Department of Industrial and Systems Engineering, NUS.

Loo Hay Lee is an associate professor in the Department of Industrial and Systems Engineering at NUS and was a visiting professor at the Department of Systems Engineering and Operations Research at George Mason University. He received his BS (electrical engineering) degree from the National Taiwan University in 1992 and his SM and PhD degrees in 1994 and 1997 from Harvard University. He has published more than 60 papers in international journals and is currently the associate editor for the Institute of Electrical and Electronics Engineers (IEEE) Transactions on Automatic Control, the Institute of Industrial Engineers (IIE) Transactions, the Flexible Services and Manufacturing Journal and the Asia Pacific Journal of Operational Research. He is currently the associate editor for the Journal of Simulation and is a member in the advisory board for Operations Research (OR) Spectrum. He is a senior member of IEEE and has served as a council member in the simulation society of the Institute for Operations Research and Management Sciences. His research focuses on the simulation-based optimization, maritime logistics which includes port operations and modeling and analysis for the logistics and supply chain system. He has co-authored a book: Stochastic Simulation Optimization-Optimal Computing Budget Allocation (World Scientific) and co-edited the book Advances in Maritime Logistics and Supply Chain Systems. He has won the Best Paper Award at the First International Conference on Advanced Communications and Computation (INFOCOMP 2011). He has also served as the assistant dean in charge of research for the Faculty of Engineering of NUS from 2001 to 2003, and is now the deputy head of research and graduate study for the department.

Ek Peng Chew received his PhD in Industrial Engineering from the Georgia Institute of Technology, USA. He is currently an associate professor and deputy head (ADMIN) in the Department of Industrial and Systems Engineering at NUS. He was also a member of the task force involved in the early formation of the Logistics Institute-Asia Pacific (TLI-AP) at NUS. His current research areas are in the maritime logistics and supply chain systems and simulation optimization. Some of his research works are published in journals such as IIE Transactions, the European Journal of Operational Research, Naval Research Logistics, Transportation Science and Transportation Research B. He is serving on the editorial board of OR Spectrum, the Flexible Services and Manufacturing Journal, the Asia Pacific Journal of Operational Research and the International Journal of Industrial and Systems Engineering. He has also been involved in industrial consulting, conducted a number of training programs related to operations research and industrial engineering, sits on the examination board of the Singapore Quality Institute and has served as a validation panel member and an external examiner to education programs in polytechnics in Singapore.