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FRAMEWORK OF O^{2}DES.NET DIGITAL TWINS FOR NEXT GENERATION PORTS AND WAREHOUSE SOLUTIONS

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ABSTRACT

Innovative solutions are proposed to meet the challenges bringing by the development of next generation ports and warehouses. In order to test the feasibility of the solutions and increase the “wisdom” of maritime logistics facilities, a maritime Digital Twin (DT), SingaPort.Net Suite, is developed and presented in this paper. An object-oriented discrete event simulation (O^{2}DES.NET) framework is proposed as the development framework. Seven functions achieved by O^{2}DES.NET are embedded in the SingaPort.Net Suite and are illustrated in this paper. It is hoped that with the help of SingaPort.Net Suite and O^{2}DES.NET, the maritime logistics DT ecosystem could experience a vivid and healthy growth in the future decades.

1 INTRODUCTION

The concept of next generation ports and warehouses has emerged in the recent decade to meet the challenge of the increasing amount of cargo and higher requirement of efficiency. A large number of innovative solutions are proposed since then for both planning and operation periods. During the planning phase, there are solutions such as mega ports (Maritime Singapore Connect 2018), double-storey ports (National University of Singapore 2013), offshore ports and warehouses (Baird and Rother 2013), shuttle systems/overhead grid rail systems (Zhu et al. 2010; Port of Venice 2018), diagonal container yard blocks (Ivanović 2014), as well as container racks (VMW Systems 2017), etc. On an operational level, an automation trend is rising in response to the development of technology, pursuit of higher efficiency, and shortage of labor. Moreover, more and more frequent severe disruption events, such as the COVID-19, have accelerated the realization of automated ports and warehouses.

Simulation is an effective tool that helps to test if certain innovation is suitable to be incorporated. Levering on simulation, a digital model of the upcoming ports or warehouses could be developed so that designers and users are able to explore all the possible innovative concepts through the model output. However, new challenges are found in traditional simulation models. Firstly, the integration of simulation and optimization are not flexible so that the intelligence of models is limited. Secondly, it is hard to achieve large-scale modeling within a short period of time. Thirdly, real-time linkage between the real world and digital model is lacking for automated ports and warehouses. Thus, the simulation needs to adapt to encompass all the complexities of the real world. Needless to say, simulation needs to innovate to tackle the challenges being faced.

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A possible solution is a concept of Digital Twin (DT), which is believed to be firstly proposed by Michael Grieves in 2002 (Ibrion et al. 2019) and boosted by (Shafto et al. 2012), Siemens (Taylor et al. 2019), and Boeing (Ibrion et al. 2019) along with the evolution of Industry 4.0. In simple words, a DT is an expansion of a traditional simulation model, which could facilitate the decision in the design, produce, and after-sale processes of a product, or the planning and operational process of a system. However, the term DT lacks a commonly agreed definition from industry and academia. Moreover, it is found that although DT has some applications in the maritime domain, such as shipbuilding and offshore engineering (Niculita et al. 2017; Rødseth and Berre 2018; Coraddu et al. 2019; Erikstad 2019; Ibrion et al. 2019; Morais et al. 2019), limited applications of DT in the context of ports and warehouse are shown (Li et al. 2017; Li et al. 2017; Hofmann and Branding 2019). The reason may lie in the limited understanding of industrial needs and the lack of development tools. Thus, this paper aims to (1) give a definition of DT which could reflect and meet the needs of industry, (2) propose a self-developed DT development framework, Object-Oriented Discrete Event Simulation (O^2DES.NET) which could integrate simulation and optimization flexibly, and lastly (3) to present a number of applications developed by O^2DES.NET in the maritime logistics domain.

The rest of the paper is organized as follows: Section 2 proposes a multi-dimensional DT definition. In Section 3, a in-house developed DT development framework, O^2DES.NET (Li et al. 2015), is presented. Subsequently, a suite of maritime logistics DT realized by O^2DES.NET, SingaPort.NET Suite, is shown in Section 4. Lastly, conclusions with the main contributions of this paper are shown in Section 5.

2 A MULTI-DIMENSIONAL DEFINITION OF DIGITAL TWIN

A prevailing connectivity-driven definition of DT is found in Kritzinger et al. (2018), in which the replica of real-world entities is categorized as digital models (DM, no connection between physical and digital twin), digital shadows (DS, one-way connection from physical twin to digital twin), and digital twins (DT, two-way connection between physical twin to digital twin). However, to define DT by connectivity has some limitations. In this paper, a definition of DT considering multi-dimension is proposed.

A Digital Twin is a digital replica of its physical twin that reflects the designing and operations processes, analyzes desired decision making and operational rules, and visualize the results for human stakeholders. Compared with a conventional simulation model, the digital twin is an extension along four dimensions: fidelity, analyzability, connectivity and visibility (as shown in Figure 1).

2.1 Fidelity

Fidelity measures the detail level of the data in the simulation model, which include (1) environment data, (2) configuration data, (c) state variables data, and (d) transitions data. Four levels of fidelity are illustrated below.

2.1.1 Conceptual Level

The conceptual level consists of the minimum amount of data that describes the general information of the system. It usually provides the first-cut analysis for a rough estimation. For example, the modelling a container port or a warehouse by using a queue and server model. It utilizes a lot of assumptions and generalizations to set the rules for the goods flow. No specific layout of the port or warehouse DT is considered at this level.

2.1.2 Planning Level

The planning level involves more details relevant to long-term decision making. In the example of the container port, besides the data considered at the conceptual level, the planning level data also includes additional information of layout design and equipment configuration, as it affects the overall efficiency. The analysis could be used for the port planners to choose among suitable designs with proper equipment

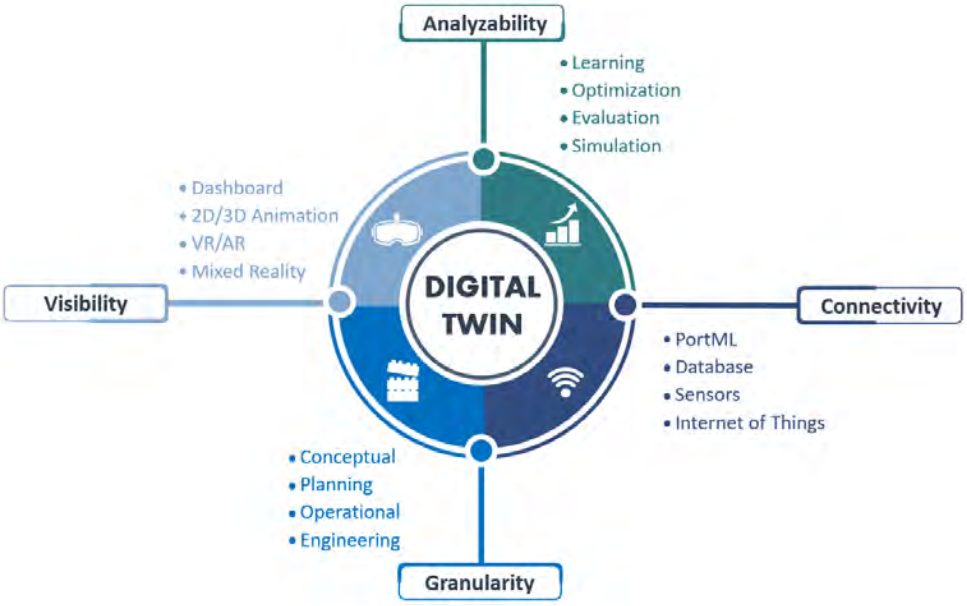

Figure 1: The concept of four-dimensional Digital Twin.

combinations, aiming to satisfy the target key performance indicators (KPIs). For the warehouse designers, this level of fidelity assumes greater importance, which helps to develop new warehouse designs for a greenfield project as well as investment in additional automation equipment in case of already operational warehouses.

2.1.3 Operational Level

This level includes data related to short-term operations such as weekly and daily. Considering a container port, the decisions could be the rules of berth allocation, yard planning, vehicle dispatching, and routing, etc. For the warehouse operations, these functional decisions range from picker route selection, allocation decisions for the SKUs, storage locations of products based on the complementarity, and other such decisions that improve the productivity of the warehouse operations. For both ports and warehouses, another important usage of operational level DT is the identification and subsequent removal of system bottlenecks.

2.1.4 Engineering Level

A large amount of data shall be included at the engineering level models. The DT at this level is supposed to capture the electro-mechanical behaviors and the communication protocols of certain parts of a system. They are useful to evaluate the engineering performance of the system, such as equipment efficiency, reliability, redundancy, therefore, to analyze the system resilience and assist in making engineering level decisions such as preventive maintenance, and recovery plan due to equipment failures.

2.2 Analysability

The analysability of a DT is about how to use the models to make smarter decisions, which includes evaluation, optimization, and learning, based on the real needs of decision-makers.

In detail, evaluation happens when the decision problems contain multiple objectives, or some managerial factors are needed to be considered. What the decision-makers require are merely the KPIs, and no optimal solutions are needed to be directly output from the analysis.

Currently, the needs for optimization and learning are less than that of evaluation since reality is always complicated, and human intervention is still predominant in the initial stage of decision-making. In some practical cases, modelers are required to conduct an evaluation as a first attempt; then, the decision-makers would analyze the relations among the different KPIs. After the relation structure of KPIs is clearly identified, modelers could move on to a more sophisticated optimization study so that the optimal solution will be given by a more quantitative method. Moreover, as the development of simulation technology, it is believed that more and more needs would rise for optimization and learning.

2.2.1 Simulation Evaluation

The primitive purpose of using a DT is to evaluate one or multiple scenarios and collect essential statistical information to provide to the decision-makers for further decisions. There are two types of evaluations: a simple scenario-based evaluation and an optimization-embedded evaluation. The discussion and comparison of the two types are shown below.

Scenario-based Evaluation

The evaluation can be purely based on the scenario input, e.g., data collected from sensors or database. By simulating the dynamic transitions of the system, the evaluation is able to provide information that the raw data could not show explicitly. For example, such analytics could be a control room that provides statistics of vessels, cargoes, and equipment, trucks at the truck bays, with highlights on their workload and health status, or the hotspots indicating the congestion and bottlenecks of the forklifts.

Optimization-embedded Evaluation

The essential difference between the scenario-based evaluation and optimization-embedded evaluation is whether intelligent algorithms are incorporated. In the scenario-based evaluation, no algorithms are embedded, which means that the operations are driven by specific predefined rules. While in optimization-embedded evaluation, these decisions are determined by algorithms, so that decision-makers could not only compare among different layout designs, but also different operating rules. It should be noted that, although intelligent algorithms are incorporated, this method is still classified as evaluation instead of optimization, as the purpose is not to make decisions, but rather evaluating the performance of alternatives.

2.2.2 Simulation-based Optimization

The optimization's output is a final optimal decision; moreover, the output of KPIs is optional, enabled through an iterative simulation evaluation for alternative designs. There are two types of optimization: ranking and selection, as well as large-scale searching. To put in simple words, in ranking and selection, the solution space is finite, while in large-scale searching, the solution space is much larger, even infinite. The two methods are illustrated below.

Ranking and Selection

The decision is relatively simple. The examples of ranking and selection exist for both planning and operational phases, such as finding the best port/warehouse layout from candidate designs, choose the best combination of equipment and identify the best algorithm to control them in operational time.

Large-scale Search

This is usually applicable related to the design problem with parameters, such as finding the optimal number of bays and rows of a yard block or storage rack, identifying the optimal number of trucks/AGVs in a fleet, and how to dispatch the fleet of vehicles to all the cargoes in the job list. With iterative sampling and simulation evaluation, the large-scale search is usually driven by heuristic algorithms, such as the genetic algorithm (GA), simulated annealing (SAN), and particle swarm optimization (PSO). Alternatively, the search can be guided by a surrogate model, such as the Gaussian Process, which is fitted by simulation evaluation results. It is also notable that for many heuristic algorithms, the ranking and selection can be seen as a sub-problem for their internal procedures. For example, the GA requires to rank all designs based on simulation results in the current population, before generating the next population.

2.2.3 Simulation-based Learning

In reality, when the scenario changes frequently, a conventional simulation-based optimization may fail to respond to the in-time decisions due to the high computational effort required. Therefore, simulation-based learning for decision-making rules is critical. In general, it identifies the mapping between the scenario and the optimal designs under respective scenarios. It can be achieved by machine learning modules that taking features and responses from the offline result of simulation-based optimization, identifying the mapping for online application. It involves integrated consideration of sampling and evaluation of scenarios, designs, and replications. The examples can be the same as those in simulation-based optimization, especially for those with a strong requirement on timeliness, e.g., how to respond to the incoming vessels and make the stowage plan. Similarly, the warehouse DT can learn from the data to decide on the number of manpower to be engaged on the contractual basis based on the number of inbound and outbound shipments.

2.3 Connectivity

Connectivity is the dimension to measure how strong a DT is linked with its physical counterpart. Three connectivity level are presented, which include offline connectivity, online connectivity, and real-time connectivity.

2.3.1 Offline Connectivity

The primitive way to connect a DT with its physical counterpart is via manual or offline processing. The most basic manner is via hard coding or console input with parameters. Better user experience could be achieved by GUI applications and the exchange of information with data files.

2.3.2 Online Connectivity

Faster communication could be achieved by making all necessary information online and accessible by authorized parties when required. This calls for either a centralized or distributed database to store the information to be updated and proper APIs that regulate how the data shall be passed among different parties.

2.3.3 Real-time Connectivity

To improve the efficiency of communication, more advanced technologies could be applied, such as spatiotemporal databases, and IoT devices. In addition, standards and protocols at various layers of communication become extremely critical, as it allows smooth data exchange between different components of DTs and between digital and physical systems.

2.4 Visibility

DT could be visible to human beings through different manners. According to the advanced level of technologies involved, the visibility of DT can be classified into the following four levels.

2.4.1 Text

This is the easiest way to display information from a DT model. It allows quick setting and modification and provides precise numerical information, which is usually adopted by modelers and developers to gain a quick understanding of the model. However, the text display is intuitive, thus is hard to perceive by layman users.

2.4.2 Dashboard

The dashboard display is essential for the users/decision-makers of the system. It provides various types of tables, figures, and charts for the aggregated information and analytical results that necessary for decision-making. It can be further integrated with interactive controls that connect human operators to the physical systems.

2.4.3 Graphics

Through 2D and 3D computer graphics and animation, DT could be visualized in more detailed manners. This could be a reference for decision-makers to have a quick view to understand the exceptional cases. For other stakeholders, such as supervisors, students, and interns, the 2D/3D graphic is an ideal way to learn and understand the system details.

2.4.4 X-Realities

There are emerging technologies providing a sense of reality to human beings, such as virtual reality (VR), augmented reality (AR), and mixed reality (MR). The technologies could be used in the planning phase when everything is virtual, in the operational phase, when the virtual information is superimposed to the reality, or in the training phase when there is a need to create an experience of reality to the trainees.

2.5 Summary

The proposed definition of the Digital twin on multi-dimensional considerations has been explained in the preceding subsections. This classification provides a common platform for various digital twins to be evaluated and compared. It must be borne in mind that each of the digital twin has a different purpose for which it has been built. A selected digital twin may be good on one or some of the dimensions explained in these sections depending on the final use of that digital twin. In the next section, this paper presents development of such a digital twin based on O^{2}DES.Net. This digital twin attempts at encompassing all the four dimensions that were discussed earlier and develops various aspects in parallel.

3 PROPOSED DIGITAL TWIN DEVELOPMENT FRAMEWORK

As shown in Figure 2, the DT development framework, O^{2}DES.NET hybrids both event-based and state-based formalism, and implement them in an object-oriented programming language. Optimization algorithms and techniques could be embedded so that the DT does not just faithfully mirror the real-world complex systems but also facilitates and support decision making at all levels.

In detail, different from the current commercial and open-source simulation packages that implement activity-based formalism, the kernel of the O^{2}DES.NET framework is event-based. This is to ensure maximum flexibility to describe any sophisticated logic in real-life operations. On top of the event-based kernel, a state-based formalism is adopted to encapsulate properties and behaviors from sub-systems, so as to increase the re-usability of the developed models. This tremendously improved modeling efficiency and enabled system modeling at multi-fidelity levels.

O^{2}DES.NET is a native object-oriented program package that fully utilizes abstraction, inheritance, polymorphism, and delegation, to ease the modeling procedure and define relationships among modules and various model components. It is developed in C#, which facilitates flexible integration with the latest academic research in simulation analytics and enables the connection to a variety of industrial-standard modern developments from the .NET ecosystem, including mobile applications, enterprise software, Mix-Reality, and Artificial Intelligence.

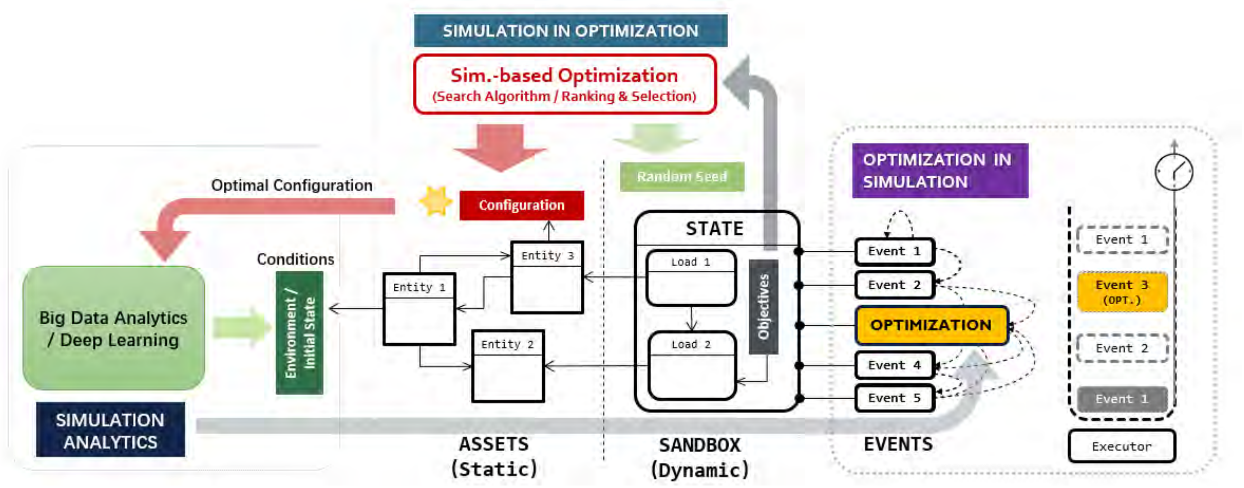

Figure 2: The O^{2}DES.NET Framework for development of smart digital tiwns.

4 SINGAPORT.NET SUITE

The SingaPort.NET is the suite of DT developed by O^{2}DES.NET for solving various modeling, simulation, and optimization problems faced by the maritime logistics industry. Many of the DTs developed have been validated and are currently in use by both academia and industry. The SingaPort.NET currently contains seven primary functions serving maritime logistics facilities planning and operations. Each of the functions is given a catchy name reflecting its purpose and is introduced in the following sections.

4.1 SingaPort.NET Essence

As shown in Figure 3, the SingaPort.NET *Essence* is a flagship product of the suite, which could model a mega container port within a short period of time. As introduced in the fidelity section, it leverages on 24 modules as building blocks, capturing the behaviors of a container port at five hierarchical levels. The SingaPort Essence has been used to solve problems such as comparing the pro and cons of alternative port designs, which is used by stakeholders such as the planning committee.

Figure 3: The SingaPort.NET Essence.

4.2 SingaPort.NET OpsFidelity

The SingaPort.NET *OpsFidelity* is an extension of the Essence with features capturing high-fidelity operational details, such as irregular ground slots, AGV traveling routes, and equipment controlling protocols. It is an ideal testbed for experimenting with operational algorithms and rules that to be applied in the next-generation ports and optimize them for achieving higher efficiency in the future. The DT has been adopted for the development of innovative AGV routing algorithms, and study of yard management strategies considering the reshuffling. An illustration of OpsFidelity is shown in Figure 4.

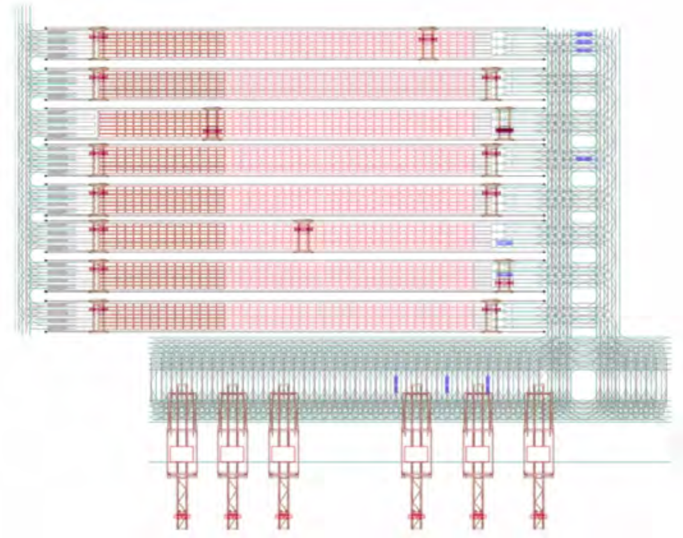

Figure 4: The SingaPort.NET OpsFidelity.

4.3 SingaPort.NET Yard-Template

As shown in Figure 5, the *Yard-Template* is a dedicated toolbox for the yard planning for next-generation container ports, with the simulation and optimization engine to allocate each ground slot to a specific origin and destination vessel pair. With flexible and accurate algorithms, it is a cutting-edge decision support solution that unlocks the capability of the container port from conventional yard planning policies. The DT has been validated with real operation data and refined for better performance.

4.4 SingaPort.NET AGV-Perspective

The *AGV-Perspective* is the first engineering level DT for the next-generation port equipment in the suite. From a very detailed level of an AGV, the application simulates the steering mechanism of the vehicles and abstracts necessary performance measurements regarding its trajectory and other Electra-mechanical behaviors. The DT has been adopted to analyze the layout of AGV transponders in the design of an automated container port. An illustration of AGV-Perspective is shown in Figure 6.

4.5 SingaPort.NET ConsTraffic

The ConsTraffic is a DT for simulating and analyzing both land and sea traffic generated by the construction project of new port terminals. It provides a unified portal for users to define construction activities and their impact on the change of terrains, simulates the induced traffic flows, and optimizes the project schedules so as to avoid congestion and lower the risk of collisions in the construction site. The DT has been adopted in the construction project of a container port.

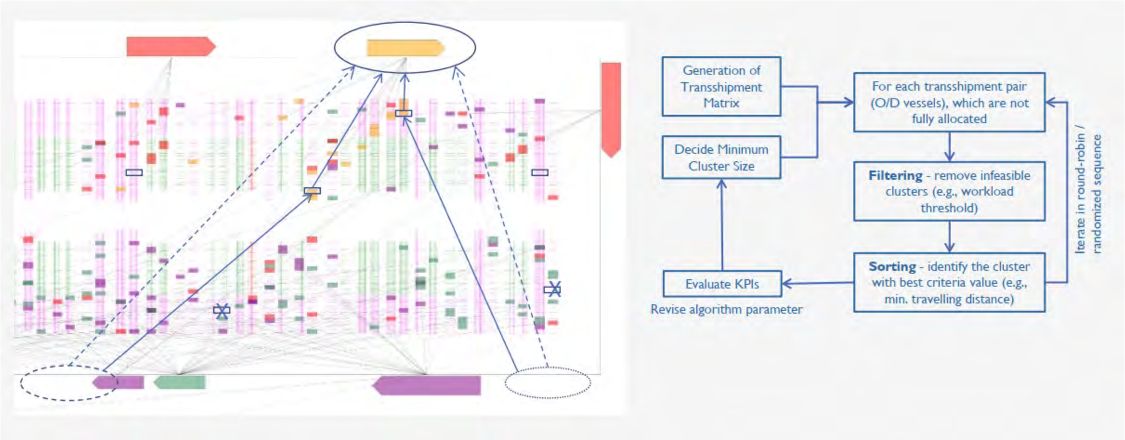

Figure 5: The SingaPort.NET Yard-Template.

4.6 SingaPort.NET WareHouse

The *WareHouse* is a toolkit for the modeling of logistic warehouses. The toolkit consists of essential modules for modeling an integrated warehousing system to analyze its operational efficiency, as well as individual components such as storage and material handling system for solution providers to understand their working mechanisms and KPIs. As it shares the same technology backbone with other suite applications, part of the WareHouse modules could be reconfigured and transplanted to the port system, for the purpose of exploring and evaluating novel ideas for in the designing period. Currently, the toolkit has been successfully applied to several industrial projects. Moreover, it will be a continuous effort to evolve and enrich the library of ”WareHouse” modules to cope with future challenges in the next-generation ports and logistics system. A demonstrations of WareHouse are shown in Figure 7.

4.7 SingaPort.NET PortML Studio

The *PortML* is a mark-up language proposed by authors with the research team for the configuration of port DT across different platforms. The PortML Studio is the GUI tool incorporated in the suite for configuring various components used in other applications. It provides a friendly environment for users to build and visualize the port components and edit their properties via both graphical view and the XML code. An advanced version of the application will support the hierarchical structure for the port DT modules, subversions of various PortML components, and the extension of PortML standard for the new port components. An illustration of PortML Studio is shown in Figure 8.

5 CONCLUSION

Next generational ports and warehouses are proposed to tackle the increasing cargo volume in the context of Industry 4.0. Simulation has emerged as the natural tool to test the feasibility of the innovative solutions. Challenges are found in traditional simulation tools, such as the limitation to integrate simulation with optimization, fast modelling and real-time linkage with physical systems. In fact, the simulation must innovate in its application in order to meet these requirements. DT is one such innovation that takes the simulation theory and application further ahead. In this paper, a definition of DT considering four dimensions is proposed, which include fidelity, analysability, connectivity, and visibility. Subsequently, a maritime logistics DT, SingaPort.NET Suite, is presented with seven primary functions. The SingaPort.NET Suite is developed by a self-developed DT development framework, O^2DES.NET. The mechanism and advantages of O^2DES.NET are introduced.

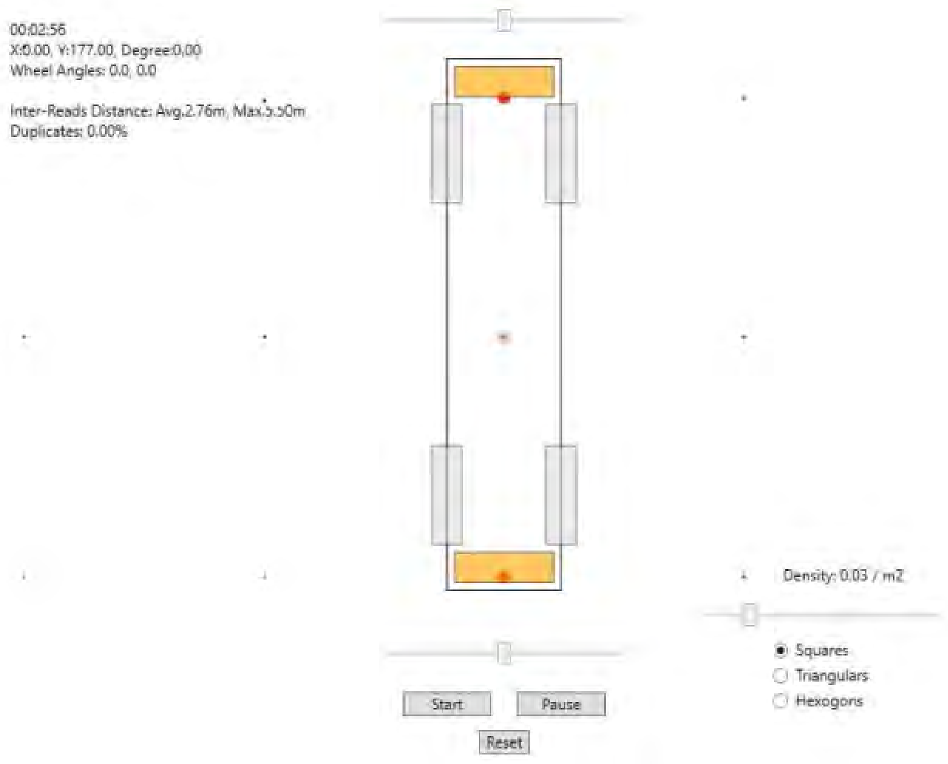

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Figure 6: The SingaPort.NET AGV-Perspective.

There are three significant contributions of this work to academia and industry. Firstly, a multi-dimensional definition of DT is given for the first time, with each of the dimensions being illustrated. Secondly, a flexible DT development tool, O^{2}DES.NET, is presented, with which the four dimensions are able to be customized so that all stakeholders could benefit from the DT developed. Thirdly, useful insights are obtained from the developed DT, SingaPort.NET Suite. The maritime logistics industry is able to make smarter decisions in processes of port and warehouse construction and operation, which could influence the revenue in the future decades. It is hoped that with the proposed O^{2}DES.NET and developed SingaPort.NET Suite, both academia and industry could effectively learn from the experience of developed ports and warehouses and create a ”smart” co-operative ecosystem. This could potentially stimulate the enthusiasm of researchers, protect intellectual property rights, and improve the intelligence of the maritime logistics industry in general.

6 ACKNOWLEDGMENTS

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Figure 7: The SingaPort.NET WareHouse.

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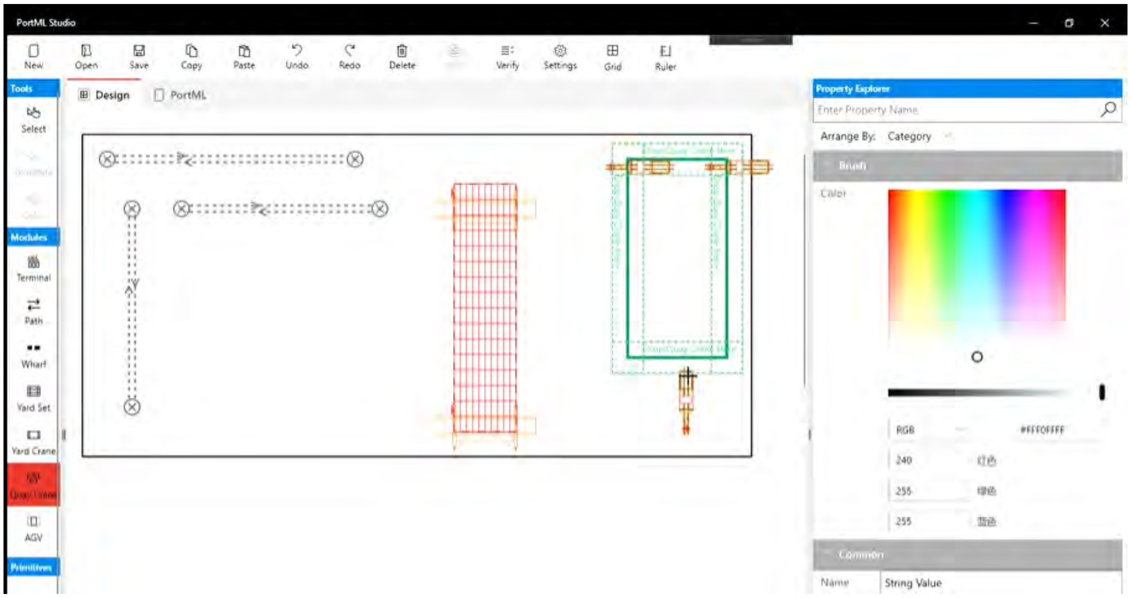

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Figure 8: The SingaPort.NET PortML Studio.

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