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Benfei Zhu [a,b], Qiang Zhou [b] and Yu Tian [b,c]

[a]Hydropower and Hydraulic Engineering Institute (Ocean Engineering Institute), PowerChina Huadong Engineering Corporation Limited, Hangzhou, Zhejiang, China; [b]School of Transportation and Logistics Engineering, Wuhan University of Technology, Wuhan, Hubei, China; [c]Department of Science and Technology Information, Shanghai International Port (Group) Co., Ltd, china

ABSTRACT
Considering the diversification of dry bulk terminal types and the complexity of terminal loading and unloading operations, a modular modelling method based on discrete event system specification (DEVS) modelling theory is proposed in this paper. First, we introduced the DEVS into the dry bulk terminal and explained the ideas and main steps of the DEVS-based modular modelling method. Second, a module library and model framework library for dry bulk terminals were developed, and the DEVS expression of the modules and model framework was given. Studies have shown that the production performance of a coal export terminal is generally positively correlated with ship loading and ship arrival density. Terminal operators can improve their ability to respond to future scenarios in two ways: upgrading berth levels and improving ship berthing strategies. The case verifies that the model framework and module library are effective, and the modelling method based on DEVS is feasible.

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KEYWORDS
DEVS; module library; model framework; modular modelling; dry bulk terminal

1. Introduction

A dry bulk terminal is a complex logistics system that presents the characteristics of uncertainty, dynamics, and nonlinearity. As a multi-input and multi-output system, many events in the dry bulk terminal logistics system occur randomly. Additionally, the terminal system is a multilevel complex structure, and the changes in the system state show nonsynchronization and concurrency. In addition, the terminal logistics system is a human-made system that follows the management rules and constraints set by humans. These characteristics have brought many problems to the analysis and optimisation of dry bulk terminal logistics systems. Thus, it is becoming increasingly difficult to rely on traditional mathematical calculation methods to solve terminal engineering problems under these complex conditions. Relying on system simulation methods to obtain acceptable solutions has become a feasible method. At present, the system simulation method has been gradually used to solve some complex engineering problems in the planning, design, construction, and operation of terminals.

Specialised dry bulk terminals include import type, export type, and water-water transshipment type. Their loading and unloading operating subsystems, operating procedures and rules have obvious differences, so their simulation models and internal architecture are different. For export terminals, Zhu et al. (2018) established a discrete event simulation model of a coal export terminal and discussed the changes in the annual throughput of the terminal based on processes and rules. Then, Zhu et al. (2020) established a multiagent-based coal export terminal simulation model to evaluate the changes in performance indicators of the terminal. The model includes planning management, ship arrival, train arrival, yard management and indicator statistics subsystems. For water-water transshipment terminals, they (2019) also established a simulation model of a water-water transshipment coal terminal for comparison and selection of terminal design options. The model covers the sea-going ship arrival subsystem, yard management subsystem, barge arrival subsystem and performance indicator statistics subsystem. For import terminals, Pratap et al. (2018) established a simulation optimisation model for bulk cargo import terminals, which covers areas such as berths, storage yards, and loading stations. These studies have established simulation models for three types of dry bulk terminals. However, these models are aimed at specific terminals and have obvious individual characteristics. This study intends to abstract a general modular modelling theory method based on the existing research results. It can be applied to three main dry bulk terminals for export, import and water-water transshipment.

DEVS modelling theory is the most general formalism for discrete event system modelling (Bergero & Kofman, 2014). It regards each subsystem in the modelling object as a module with an internal independent structure and input and output interfaces. The dry bulk terminal is a typical discrete event dynamic system with

CONTACT Yu Tian tianyu19900219@outlook.com Shanghai International Port (Group) Co., Ltd, 55 Youlin Road, Pudong New Area, Shanghai, China

hierarchical and modular characteristics. Therefore, it is a feasible solution to introduce the DEVS modelling theory into dry bulk terminals. At present, DEVS modelling theory has application cases in many fields, such as enterprise production (Denil et al., 2017), military (Seo et al., 2014), transportation (Huang et al., 2015), ecological environment (Aid et al., 2016), and social systems (Bouanan et al., 2016), but it has not yet been seen in the application of dry bulk terminals. Based on this, under the guidance of DEVS modelling theory, this study attempts to establish a module library covering three types of dry bulk terminals, import, export, and water-water transshipment, and analyse the different connection architectures between the modules. Finally, a standardised module library and architecture library are formed to realise a universal modular modelling method based on DEVS.

The goal of this paper is to provide a modular modelling method for dry bulk terminals based on DEVS theory. By analysing the simulation modules of different operation links of dry bulk terminals and establishing a model framework library for different types of dry bulk terminals, the rapid construction of simulation models of specialised dry bulk terminals is realised. The characteristics of the paper include two aspects. One is the introduction of DEVS modelling theory into dry bulk terminals, and the idea and main steps of a modular modelling method based on DEVS are proposed. Second, to realise this modular modelling method, the simulation module of the dry bulk terminal was analysed, and a model framework library based on information flow was established. This paper is organised as follows: Section 2 gives a literature review. Section 3 proposes a modular modelling method based on DEVS and discusses the connotation, ideas, and specific steps of modular modelling. Section 4 analyses the simulation module library and simulation model framework library. Section 5 is case analysis. An actual terminal is taken as an example to analyse the application of the modular modelling method. Section 6 gives the conclusions and future research directions.

2. Literature review

This section will start from two perspectives of methodologies and practices and analyse the research status from the development and application of DEVS and dry bulk terminal modelling.

2.1. Development and various application of DEVS

2.1.1. Development of DEVS

DEVS is a system modelling and simulation mechanism that supports modularity and hierarchy. It provides a more mature formal modelling theoretical foundation for complex discrete event systems. Based on the good scalability of DEVS, it is expanded into a variety of different forms for modelling and analysis of specific systems, such as parallel and distributed DEVS, Cell-DEVS, real-time DEVS, dynamic structure DEVS, DEVS&DESS (Differential Equation System specification), HLA (High Level Architecture)-DEVS, etc.

In the field of parallel and distributed DEVS, Adegoke et al. (2013) developed a unified framework for describing parallel and distributed DEVS simulation architectures. It also provides an abstract method for integrating different heterogeneous DEVS implementation strategies. Cobanoglu et al. (2014) developed a new network modelling and simulation tool D-DEVSNET based on DEVS, which realised the application of the DEVS method in parallel and distributed simulation. Heredia et al. (2015) introduced the parallel DEVS modelling method to the field of biological evolution, established the EvoDEVS model, and described the model mathematically using parallel DEVS. Al-Zoubi and Wainer (2015) developed a general simulation middleware based on RESTful WS. The distributed simulation of DEVS and Cell-DEVS models based on RISE middleware is studied.

In the field of Cell-DEVS, G. G. Wainer and Fernández (2016) used the Cell-DEVS paradigm to define complex cellular automata models and developed executable models based on CD++ tools. Research shows that Cell-DEVS can significantly shorten the development time of cell models, and it can be used for the development of various complex models. Al-Habashna and Wainer (2016) used Cell-DEVS theory to model crowd behaviour, established one-dimensional, two-dimensional, and three-dimensional crowd motion simulation models based on Cell-DEVS, and extended a multistorey building model of crowd movement. The simulation results verify the usability of the proposed model. Wainer (2019) uses Cell-DEVS to build a library that can define different traffic flow models and simulate cell spaces with emerging behaviours.

In the fields of real-time DEVS, dynamic structure DEVS and DEVS&DESS, Sarjoughian and Gholami (2015) proposed an action-level RT-DEVS modelling and simulation method. They introduced action modelling into the parallel DEVS form and designed an abstract simulator protocol to execute the ALRT-DEVS model with limited computing resources. A model example verifies the feasibility of real-time modelling. Steiniger and Uhrmacher (2016) studied the strength coupling in the DEVS model of dynamic structures. The coupling definition based on the component interface in the ML-DEVS model is described, and how ML-DEVS is realised and used in the specific modelling form is discussed. Wainer and D'Abreu (2015) proposed a new architecture for designing modelling tools for continuous and hybrid systems and extended the DEVS theory to allow for such models.

Research on DEVS also involves vector DEVS (Bergero & Kofman, 2014), extended SES (Santucci et al., 2016), modelling language (Hollmann et al., 2015), and visualisation (Maleki et al., 2015). Related research also includes DEVS model verification (Hollmann et al., 2014; Samuel et al., 2020) and model performance testing (Risco-Martín et al., 2017).

2.1.2. Application of DEVS

At present, DEVS modelling theory has been applied in many fields, such as enterprise production, military affairs, transportation, agriculture, the Internet, ecological environment, and social systems. However, there is little literature on the use of DEVS modelling analysis in the terminal field.

Denil et al. (2017) used DEVS modelling in the automotive industry. They evaluated the applicability of DEVS in AUTOSAR-based system modelling and subsequent performance evaluation, established an AUTOSAR-based electronic control unit DEVS simulation model and demonstrated and verified the model through a case study. In the military field, Seo et al. (2014) proposed an engagement-level military simulation modelling method based on DEVS and established a combat entity model. Through simulation tests, the results of the engagement of underwater weapons and their tactical operations were obtained. Luo et al. (2019) studied the data link-based DEVS simulation model in the military field and simulated the tactical information transfer relationship in real-time combat through the model. Huang et al. (2015) applied DEVS modelling to the field of railway infrastructure and proposed a component-based light rail modelling and simulation library in the form of DEVS. The application process proved the effectiveness and scalability of the library. Toba et al. (2020) developed a DEVS model of agricultural machinery movement in response to the problem of field operation planning in agricultural activities and verified the effectiveness of the model through examples.

In the Internet field, Çelik (2016) applied DEVS modelling to the simulation of mobile ad hoc networks, designed a simulation framework for mobile ad hoc networks using DEVS-Suite simulation tools, and applied it to the simulation of wired networks. Kim and Kim (2020) proposed a DEVS modelling method for network security simulation. The case shows that the model can enable security administrators to simulate many network security issues. In the field of environmental modelling, Aid et al. (2016) developed a DEVS model for the modern intelligent building environment to help domain experts reduce building energy consumption and improve comfort. Each object in the model contributes to an environment, namely, thermal, visual, acoustic and air quality. In addition, Bouanan et al. (2016) applied DEVS modelling technology to the field of social networks, established an information diffusion model based on infectious disease propagation algorithms, and verified the effectiveness of the model in a scenario.

It can be seen from the above literature analysis that based on the good scalability of DEVS, it has been extended to a variety of discrete systems for modelling and analysis of different objects. The DEVS modelling method has also been well applied in many engineering fields, but there are relatively few cases of DEVS in the terminal production field.

2.2. Modelling of the dry bulk terminal

According to the different areas covered by the simulation model, the dry bulk terminal model can be divided into partial models such as the terminal apron or yard and the overall model covering all terminals. In addition, the DEVS simulation method is a modular modelling method, so the internal modules and the connection structure of the dry bulk terminal simulation model are two important components of the DEVS-based modelling method.

2.2.1. Partial model and overall model

At present, there are some simulation models that simulate the production operation system of a certain link or area of the dry bulk terminal well and have played a role in solving some practical problems. Wadhwa (1992) established a model of a bulk shipping terminal covering the berthing and unberthing processes of ships and analysed the production performance of the terminal. Wadhwa (2000) studied the optimal configuration of ship unloaders in the apron area of a bulk export terminal. Sanchez et al. (2005) analysed the optimal number and scale of coal unloading terminals. Bugaric and Petrovic (2002, 2007, 2012) established three simulation models (two ship unloaders are not shared, two ship unloaders are fully shared, and three ship unloaders are partially shared) for an inland river bulk cargo unloading terminal with two berths to determine the optimal utilisation rate of the terminal facilities. Tengku-Adnan et al. (2009) studied the berthing rules of coal export terminals and their impact on terminal performance. Van Vianen et al. (2012) studied the choice of bulk cargo transportation routes in dry bulk terminals. Van Vianen et al. (2014) discussed the method of determining the size of the bulk terminal yard. Van Vianen et al. (2015) analysed the production decision-making problem of the stacker-reclaimer in the bulk terminal yard. Xin et al. (2018) established a mixed dynamic model for material distribution in dry bulk terminals. These models are only for one or several production operations in the dry bulk terminal. They do not cover all the production operations of the dry bulk terminal and are partial models.

In addition to these models focusing on a certain part of the terminal operation process, there are also some studies that consider terminal operation issues by establishing a global model. Pratap et al. (2018) established a decision support model for an imported coal terminal including ship unloading, yard operations, and coal loading. Zhu et al. (2018, 2019, 2020) established simulation models covering all areas of the sea side, storage yard and land side of the dry bulk export terminal and water-water transshipment terminal. Burdett et al. (2020) proposed an improved scheduling method for optimising coal export terminal operations.

2.2.2. Module and model framework

Each module of the dry bulk terminal simulation model corresponds to one of its production operation subsystems. At present, some simulation models of dry bulk terminals have described their internal operating subsystems. Sanchez et al. (2005) divided the terminal simulation model into a terminal apron area module and a land area module. The ship unloading terminal simulation model established by Bugaric and Petrovic (2007) is composed of an anchorage module and a ship-to-shore operation module. At the same time, the secondary subsystems and logical relationships in the module are given. The coal terminal simulation model established by Harris et al. (2008) is composed of a sea-going ship handling subsystem, barge handling subsystem, and train handling subsystem. Van Vianen et al. (2014) established a simulation model of an imported terminal, describing the model from the queues, ship generators, export generators, and storage yards in the model. Zhu et al. (2018, 2019, 2020) divided the dry bulk export terminal model into ship loading, train unloading and yard subsystems and divided the water-water transshipment terminal model into sea ship unloading, yard management, and barge loading subsystems. For these models established for the production operation system of dry bulk terminals, the division of their internal subsystems is personalised, and the hierarchy and structure of the subsystems are not standardised.

The model framework of the dry bulk terminal defines the connection relationship between the various modules, and this framework is closely related to the terminal production process. At present, there are few studies on the simulation model framework of dry bulk terminals. Zhu et al. (2018) summarised two main model frameworks for bulk export terminals and established a simulation model using a coal export terminal as an example. Then, they (2019) analysed the frame structure of the simulation model of the water-water transshipment coal terminal. In addition to dry bulk terminals, some studies in the container terminal field involve simulation model frameworks, but these frameworks do not define the interaction of logistics and information flow between the various production operation subsystems of the container terminal. For example, Schroer et al. (2008) proposed a conceptual framework for developing seaport simulation models. Sacone and Siri (2009) proposed an integrated framework for container terminals, integrating discrete event simulation models with discrete time modules, and successfully used it to solve the problem of container terminal operation planning. Sun et al. (2013) developed a simulation framework composed of a GIS geographic information system and an MAS multiagent system. Wang et al. (2017) proposed a conceptual framework based on simulation models and optimisation modules and used it in the modelling of a container terminal inspection area design scheme. In addition, some research teams have used simulation and optimisation integrated methods to study the issues of container terminal ship-vehicle coordination (Zhou et al., 2018), terminal space allocation (Zhou, Wang et al., 2020), and yard equipment scheduling (Zhou, Lee et al., 2020).

2.3. Evaluation

It can be seen from the above literature that in the development and various applications of DEVS, it has been extended to various forms of modelling technology, forming parallel and distributed DEVS, cell-DEVS, real-time DEVS, dynamic structure DEVS, DEVS&DESS, etc., and has been practically applied in many engineering fields. However, DEVS modelling theory in the port field has not yet been discovered. On the other hand, in view of the series of engineering problems encountered by dry bulk terminals, some partial models or overall simulation models have been used to find their feasible solutions, and a series of results have been achieved. However, the modules in these bulk terminal models are at different levels, the standardisation of the modules is not enough, and the analysis of the connection structure between the modules is not comprehensive enough.

An important feature of DEVS modelling is modularity, which is suitable for standardised modelling of dry bulk terminals. Therefore, this paper proposes to establish a modular modelling method based on DEVS. By standardising the module of the three types of dry bulk terminal production operation subsystems and then analysing the logistics and information flow interaction between each module, a relatively complete module library and frame library of the dry bulk terminal are constructed. This method can analyse the overall performance of a terminal by establishing a global model, establishing a local model including only a few subsystems to study the local problems of a terminal, or studying only the internal production problems of a module. This method and its model framework and module library help solve practical problems of the terminal and promote the application of DEVS modelling theory in dry bulk terminals. Therefore, the main contribution of the paper is to propose a modular modelling method based on DEVS and develop a module library and model framework library for dry bulk terminals.

3. DEVS-based modular modelling method

3.1. The idea of modular modelling

The idea of modular modelling is to divide the dry bulk terminal logistics system into multiple relatively independent production operation subsystems, establish corresponding standardised modules for the subsystems, and then combine multiple modules into a simulation model.

The modular modelling method considers that a simulation model is composed of a model framework and several modules. The simulation model framework is a large model-level framework that mainly defines the logical connection relationships of various modules within the simulation model. The module inside the model is a small structure, which describes the operation process and rules inside the production operation subsystem. This modelling idea based on a large architecture and several small architectures is the main connotation of this modular modelling method. Various modules are connected, and information is exchanged through interfaces. These modules can be combined through interfaces to construct a large terminal system coupling model. In the modelling process, the modeller does not need to re-establish the modules of each production operation subsystem but only needs to select the module from the prebuilt module library, select the appropriate model framework according to the terminal information flow, and then combine the selected modules into a model according to the logical relationship of the model framework. Therefore, using this modular modelling method to develop simulation models is similar to the process of assembling standard parts or building blocks in industrial-scale production.

3.2. Formal description of DEVS-based models

Discrete event system specification is a formal model standard proposed by Professor Ziegler (Bernard P Zeigler, 1976). It provides a strict formal description method for discrete event systems and a theoretical basis for the standardised description of simulation models. The dry bulk terminal simulation model obtained based on the modular modelling method can also be described in a formal manner, as shown in Equation (1).

$$coupledDEVS_{Bulkterminal} = (X, Y, D, \{M_d\}, \{I_d\}, \{Z_{i,d}\}, Select) \quad (1)$$

In the formula, $X$is the input set of the dry bulk terminal simulation model, namely, $X = \{x_1, x_2, \cdots\}$. Among them, x_1 and x_2, etc. represent ship arrival or train arrival events, system information input, etc. Y is the output set of the model, that is, $Y = \{y_1, y_2, \cdots\}$. Among them, y_1 and y_2, etc. represent ship departure or train departure events, the system information output, etc.D is a collection of modules, namely, $D = \{d_1, d_2, d_3, \cdots\}$. Among them, d_1, d_2 and d_3 represent the modules of dry bulk terminals. For each $d \in D$, $M_d = (X_d, Y_d, S, \delta_{ext}, \delta_{int}, \lambda, ta)$. Each module is a DEVS atomic model, with its input set X_d, output set Y_d, sequence state set S, external transfer function δ_{ext}, internal state transfer function δ_{int}, output function λ, and time advancement function ta. I_d is the set of influencers of module d. $Z_{i,d}$ represents the output transfer function of the model from i to d.

Module set D in the model is a particularly important modelling element. Each module in the set corresponds to a production subsystem. The production operation process of the dry bulk terminal involves a train unloading operation subsystem, ship loading operation subsystem, ship unloading operation subsystem, train loading operation subsystem and yard operation subsystem. Therefore, these subsystems are the main elements in the module set. In addition to logistics activities, there are many information flows inside the terminal, such as the activities of the planning management subsystem and the data statistics subsystem. Each subsystem can be regarded as a DEVS atomic model. From the perspective of module structure, each standardised module is composed of input, internal logic flow and output. The module first receives the entities and information passed by the outside world, distributes and processes the entities and information through the internal logic main body, and then outputs the processing results to complete the execution process of the module. These modules are the core of the modular modelling method. On this basis, modules and modules are combined into a simulation model through a specific internal architecture.

The input set X and output set $Y$of the model include information and entities. On the one hand, a dry bulk terminal DEVS model will have many information interactions. For example, the main production operation plan of the terminal, the arrival time and loading capacity of ships and trains, the operation instructions of each production operation link, the production operation statistics information, etc. This information is transmitted within and between modules. On the other hand, in addition to the interaction of information, the model also has some entity input and output, such as the departure and arrival of trains and ships and coal transportation between ships, trains, belt conveyers, and storage yards.

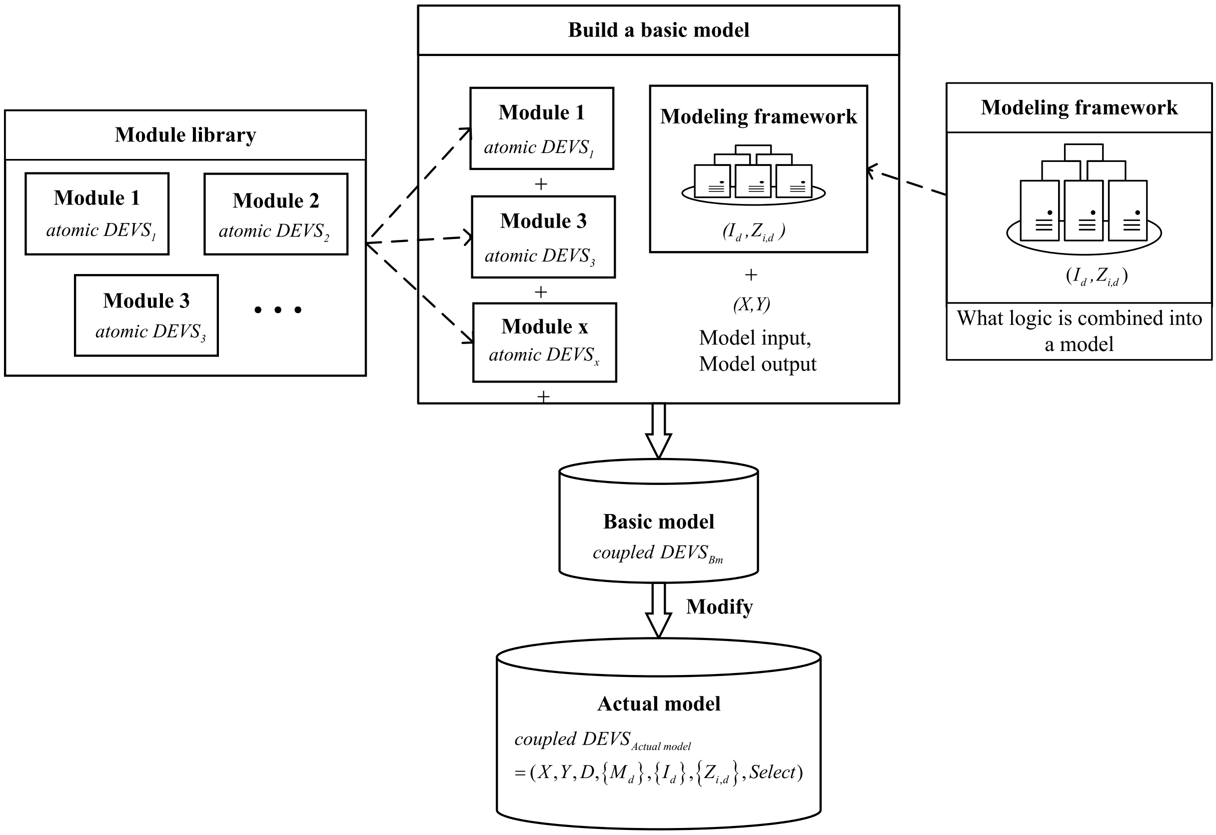

Figure 1. DEVS-based modular modelling method.

3.3. Modelling steps based on DEVS

The implementation process of the modular modelling method based on DEVS is shown in Figure 1. Its specific steps are as follows:

3.3.1. Establishing a module library

According to the process and logic of each production operation subsystem of the dry bulk terminal, the corresponding modules, namely, the atomic model *atomic DEVS*, are established to form an atomic model library $\{atomic\ DEVS_1, atomic\ DEVS_2, \cdots\}$ covering various bulk operation subsystems. The facilities and equipment in each module are set with initial values. Each module is equipped with an information exchange interface. The modules corresponding to each subsystem can be further subdivided into multiple atomic models as needed.

3.3.2. Determine the model framework

The model framework is the skeleton of a simulation model, expounding the logical connections between the modules. The model framework is related to the information flow of terminal production operations. It affects the coupling relationship of the modules, that is, it affects I_d and $Z_{i,d}$ in the model. Corresponding model frameworks are established for the information flow of various dry bulk terminals, and a model framework library is formed. The framework library is a virtual knowledge base, which is a collection of architectural descriptions. Compared with the actual existing module library, the framework library does not exist in certain software. They are only used by model developers in the modelling process and are reflected in the internal architecture of a simulation model.

3.3.3. Build a basic model

According to the production subsystem contained in the modelling object, select the corresponding module in the module library. According to the information flow of the production operation of the terminal, the model framework of the model is determined. Then, the modules are combined into a basic model according to the logical connection relationship of the model framework. The basic model of formula (2) has the same logical relationship and operating subsystem as the modelling object and is the prototype of the final model.

$$coupledDEVS_{Basicmodel} = \left(X, Y, D, \{M_d\}, \{I_d\}, \{Z_{i,d}\}, Select\right) \quad (2)$$

3.3.4. Modification and application of the basic model

According to the production process and equipment configuration of the terminal, the logical connections and parameters of each module in the basic model are revised to form a simulation model that conforms to the actual situation of the modelling object. The focus of the correction is to adjust the number and parameters of the facilities and equipment of each module in the basic model, correct the corresponding relationship of the equipment, and review the operating rules and logical processes within each module. The revised model can be expressed as Equation (3).

$$coupledDEVS_{Actualmodel} = \left(X, Y, D, \{M_d\}, \{I_d\}, \{Z_{i,d}\}, Select\right) \quad (3)$$

4. Module library and model framework library of dry bulk terminal

4.1. DEVS model form of the module

Each production subsystem of the dry bulk terminal has some specific resources to complete specific functions. These subsystems correspond to the modules in the simulation model. Each subsystem can be further subdivided. For example, the train unloading subsystem is composed of trains, port front stations, dumper sheds, dumpers, and receiving belt conveyers. These facilities and equipment can be regarded as atomic models. Therefore, the train unloading module can be divided into a train atomic model, port front station atomic model, dumper shed atomic model, dumper atomic model, receiving belt conveyor atomic model, train unloading dispatch atomic model, etc. This hierarchical and modular feature is an important feature of DEVS modelling. This section takes the train unloading subsystem as an example to illustrate the expression of the DEVS model of the module.

(1) Train atomic model

Initially, the train atomic model is in a *full* state. When its input interface *itrains* receives the arrival command of the unloading dispatching atomic model, the train atomic model enters the moving *movep* state. When its input interface *itrains* receives the arrival command of the train unloading dispatch atomic model, the train atomic model turns into the *movep* state. After the train arrives at the port front station, its output interface *otrainp* sends arrival information to the atomic model of the port front station and switches to the *waitingp* state. When its input interface *itrains* receives the instruction to enter the dumper shed from the unloading scheduling atomic model, it passes the information to the port front station atomic model through its output interface *otrainp* and transfers to the *moved* state. After the train arrives at the dumper shed, the output interface *otrainds* sends a message to the dumper shed atomic model that it has arrived at the dumper shed, and the output interface *otraind* sends a dump request to the dumper atomic model and then transfers to the *waitingd* state. When the input interface *itraind* of the train atomic model receives the instruction to start unloading from the dumper atomic model, it switches to the *serving* state. When the unloading is completed, the train atomic model's output interface *otrains* sends a message to the unloading dispatch atomic model, and the output interface *otrainds* sends a message to the dumper shed atomic model and then it transfers to the *finish* state. When the train atomic model input interface *itrains* receives the departure command issued by the unloading dispatch atomic model, the train atomic model switches to the *leave* state.

The DEVS expression of the train atomic model is as follows:

$$Xd = \{itrains, itraind\};$$

$$Yd = \{otrainp, otrainds, otraind, otrains\};$$

$$S = \{full, movep, waitingp, waitingd, moved, serving, finish, leave\};$$

$$\delta_{int} = \left\{ \begin{array}{c} \delta_{int} movep = waitingp \\ \delta_{int} moved = waitingd \\ \delta_{int} serving = finish \end{array} \right\};$$

$$\delta_{ext} = \left\{ \begin{array}{c} \delta_{ext} full, itrains = movep \\ \delta_{ext} waiting, itrains = moved \\ \delta_{ext} waitingd, itraind = serving \\ \delta_{ext} finish, itrains = leave \end{array} \right\};$$

$$\lambda = \left\{ \begin{array}{c} \lambda(movep) = otrainp \\ \lambda(waitingp) = otrainp \\ \lambda(moved) = otrainds, otraind \\ \lambda(serving) = otrains, otrainds \end{array} \right\};$$

$$ta = \left\{ \begin{array}{l} ta(full) = ta(waitingp) = \\ ta(waitingd) = ta(finish) = +\infty; \\ ta(movep) = timemp; \\ ta(moved) = timemd; \\ ta(serving) = timeserving; \\ ta(leave) = timel; \end{array} \right\}$$

where *timemp* in the time advancement function, *ta* represents the travel time of the train to the port front station, *timemd* is the time for the train to go to the dumper shed, *timeserving* is the time for the train to dump, and *timel* is the time for the train to depart from the terminal.

(2) Port front station atomic model

Initially, the atomic model of the port front station is in the *free* state. When its input interface *iptrian* receives the arrival information of the train atomic model, it will switch to the *serving* state. When its input interface *iptrian* receives the information that the train leaves the port front station, the atomic model of the port front station turns to the *free* state. At the same time, its output interface *ops* sends relevant information to the unloading dispatch atomic model. The DEVS expression of the atomic model of the port front station is as follows:

$$Xd = \{iptrian\}$$

;

$$Yd = \{ops\}$$

;

$$S = \{free, serving\}$$

;

$$\delta_{int} = \{\}$$

;

$$\delta_{ext} = \left\{ \begin{array}{c} \delta_{ext}(free, iptrain) = serving \\ \delta_{ext}(serving, iptrain) = free \end{array} \right\}$$

;

$$\lambda = \{\lambda(serving) = ops\}$$

;

$$ta = \left\{ \begin{array}{c} ta(free) = +\infty \\ ta(serving) = timeserving \end{array} \right\}$$

;

In the formula, *timeserving* represents the staying time of the train at the port front station.

(3) Dumper shed atomic model

Initially, the atomic model of the dumper shed is in an *free* state. When its input interface *idstrian* receives the arrival information of the train atomic model, it will switch to the *serving* state. When the input interface *idstrian* of the dumper shed atomic model receives the message that the unloading of the train atom model is completed, it immediately switches to the*free* state. At the same time, its output interface *odss* sends a message to the atomic model of the unloading dispatch centre. The DEVS expression of the atomic model of the dumper shed is as follows:

$$Xd = \{idstrian\}$$

;

$$Yd = \{odss\}$$

;

$$S = \{free, serving\}$$

;

$$\delta_{int} = \{\}$$

;

$$\delta_{ext} = \left\{ \begin{array}{c} \delta_{ext}(free, idstrain) = serving \\ \delta_{ext}(serving, idstrain) = free \end{array} \right\}$$

;

$$\lambda = \{\lambda(serving) = odss\}$$

;

$$ta = \left\{ \begin{array}{c} ta(free) = +\infty \\ ta(serving) = timeserving \end{array} \right\}$$

;

In the formula, *timeserving* represents the staying time of the train in the dumper shed.

(4) Dumper atomic model

Initially, the atomic model of the dumper is in an *free* state. When its input interface *idumpers* receives the instruction issued by the unloading dispatching atomic model, it shifts to the *waiting* state. When the train travels to the designated location of the dumper shed, the dumper atomic model input interface *idumpert* receives the unloading request of the train atomic model and then switches to the *dumping* state. At the same time, through its output interface *odumperb*, it sends a message that unloading starts to the atomic model of the receiving belt conveyor. Currently, the dumper atomic model unloads the train atomic model and loads the atomic model of the receiving belt conveyor. After dumping the train, its output interface *odumpers* sends a message to the unloading scheduling atomic model, and then it transfers to the *finish* state. If there are remaining trains to be dumped in the batch, the dumper atomic model shifts to the *waiting* state; if the batch of trains has been completely unloaded, it shifts to the *free* state. The DEVS expression of the dumper atomic model is as follows:

$$Xd = \{idumpers, idumpert\}$$

;

$$Yd = \{odumpers, odumperb\}$$

;

$$S = \{free, waiting, dumping, finish\}$$

;

$$\delta_{int} = \{\delta_{int}(dumping) = finish\}$$

;

$$\delta_{ext} = \left\{ \begin{array}{c} \delta_{ext}(free, idumpers) = waiting \\ \delta_{ext}(waiting, idumpert) = dumping \\ \delta_{ext}(finish, idumpert) = waiting \\ \delta_{ext}(finish, idumpers) = free \end{array} \right\}$$

;

$$\lambda = \left\{ \begin{array}{c} \lambda(waiting) = odumperb \\ \lambda(dumping) = odumpers \end{array} \right\}$$

;

$$ta = \left\{ \begin{array}{c} ta(free) = ta(waiting) = ta(finish) = +\infty \\ ta(dumping) = timedumping \end{array} \right\}$$

;

In the formula, *timedumping* is the train unloading time.

(5) Receiving belt conveyor atomic model

Initially, the atomic model of the receiving belt conveyor is in an *free* state. When its input interface *ibelts* receives the instruction issued by the unloading scheduling atomic model, it immediately switches to the *waiting* state. When its input interface *ibeltd* receives the signal of the dumper atomic model, it will switch to the *conveying* state. At this time, the materials dumped by the dumper atomic model are transported to the yard. When the train's material transportation is completed, its output interface *obelts* outputs relevant information to the unloading dispatch atomic model. If there are remaining trains to be dumped in this batch, the atomic model of the receiving belt conveyor switches to the *waiting* state; if the batch of trains has been completely unloaded, it switches to the *free* state. The DEVS expression of the atomic model of the receiving belt conveyor is as follows:

$$Xd = \{ibelts, ibeltd\}$$

;

$$Yd = \{obelts\}$$

;

$$S = \{free, waiting, conveying, finish\}$$

;

$$\delta_{int} = \{\delta_{int}(conveying) = finish\}$$

;

$$\delta_{ext} = \left\{ \begin{array}{c} \delta_{ext}(free, ibelts) = waiting \\ \delta_{ext}(waiting, ibeltd) = conveying \\ \delta_{ext}(finish, ibeltd) = waiting \\ \delta_{ext}(finish, ibelts) = free \end{array} \right\}$$

;

$$\lambda = \{\lambda(conveying) = obelts\}$$

;

$$ta = \left\{ \begin{array}{c} ta(free) = ta(waiting) = ta(finish) = +\infty \\ ta(conveying) = timeconveying \end{array} \right\}$$

;

In the formula, *timeconveying* is the conveying time of the belt conveyor.

4.2. DEVS model form of the model framework

The model framework mainly elaborates the logical connection between the various modules in the model. This section takes the yard and demand-driven dry bulk export terminal as an example to illustrate the DEVS model form of the model framework. The dry bulk export terminal model is composed of a plan management module, a ship loading module, a yard module, a train unloading module, and a statistics module. Each module is regarded as a functionally independent subsystem, which is a higher level than the atomic model described in the previous section.

(1) Ship loading module

Initially, the ship loading module is in an *free* state. When its input interface *ishipplan* receives the instruction issued by the plan management module, the ship loading module switches to the *waiting* state and sends demand information to the yard module through the output interface *oshipyard*. Then, the ship laoding module was transferred to the *auoperating* state and began to complete a series of auxiliary operations before the shipping operation. After the auxiliary operation is completed, the ship loading module sends a reclaiming command to the yard module through the output interface *oshipyard* and transfers to the *loading* state. At this time, the ship loading module starts to receive the dry bulk delivered by the yard module. When the ship's loading operation is completed, the ship loading module outputs the loading information to the statistics module through the output interface *oshipsta* and then transfers to the *finish* state. If there are subsequent ships that need to be loaded, the ship loading module will switch to the *waiting* state; if the batch of ships has been fully loaded, it will switch to the *free* state. Therefore, the DEVS model of the ship loading module is expressed as follows:

$$Xd = \{ishipplan\}$$

;

$$Yd = \{oshipyard, oshipsta\}$$

;

$$S = \{free, waiting, auoperating, loading, finish\}$$

;

$$\delta_{int} = \left\{ \begin{array}{c} \delta_{int}(waiting) = auoperating \\ \delta_{int}(auoperating) = loading \\ \delta_{int}(loading) = finish \end{array} \right\}$$

;

$$\delta_{ext} = \left\{ \begin{array}{c} \delta_{ext}(free, ishipplan) = waiting \\ \delta_{ext}(finish, ishipyard) = waiting \\ \delta_{ext}(finish, ishipplan) = free \end{array} \right\}$$

;

$$\lambda = \left\{ \begin{array}{c} \lambda(waiting) = oshipyard \\ \lambda(auoperating) = oshipyard \\ \lambda(loading) = oshipsta \end{array} \right\}$$

;

$$ta = \left\{ \begin{matrix} ta(free) = ta(finish) = +\infty \\ ta(waiting) = timepres \\ ta(auoperating) = timeaus \\ ta(loading) = timeloading \end{matrix} \right\}$$

;

Among them, the external state transition function $\delta_{ext}(free, ishipplan) = waiting$ indicates that the ship loading module is driven by the plan management module, which is an important feature of the yard and demand-driven terminals. *timepres* in the time advance function *ta* is the preparation time of the ship loading subsystem, *timeaus* is the auxiliary operation time of the ship loading subsystem, and *timeloading* is the working time of loading a ship.

(2) Train unloading module

Initially, the train unloading module is in an *free* state. When its input interface *itrainyard* receives the replenishment instruction issued by the yard module, the train unloading module enters the *waiting* state. Afterwards, the train unloading module starts a series of auxiliary operations and turns into the *auoperating* state. After the auxiliary operation is completed, the train unloading module sends a stacking instruction to the yard module through the output interface *otrainyard* and transfers to the *unloading* state. At this time, the train unloading module starts to output dry bulk cargo to the yard module. When the unloading operation of the train is completed, the train unloading module outputs the unloading information to the statistics module through the output interface *otrainsta* and transfers to the *finish* state. If there are subsequent trains that need to be unloaded, the train unloading module transfers to the *waiting* state; if the batch of trains is completely unloaded, it transfers to the *free* state. The DEVS model of the train unloading module is expressed as follows:

$$Xd = \{itrainyard\}$$

;

$$Yd = \{otrainyard, otrainsta\}$$

;

$$S = \{free, waiting, auoperating, unloading, finish\}$$

;

$$\delta_{int} = \left\{ \begin{matrix} \delta_{int}(waiting) = auoperating \\ \delta_{int}(auoperating) = unloading \\ \delta_{int}(unloading) = finish \end{matrix} \right\}$$

;

$$\delta_{ext} = \left\{ \begin{matrix} \delta_{ext}(free, itrainyard) = waiting \\ \delta_{ext}(finish, itrainyard) = waiting, free \end{matrix} \right\}$$

;

$$\lambda = \left\{ \begin{matrix} \lambda(auoperating) = otrainyard \\ \lambda(unloading) = otrainsta \end{matrix} \right\}$$

;

$$ta = \left\{ \begin{matrix} ta(free) = ta(finish) = +\infty \\ ta(waiting) = timepret \\ ta(auoperating) = timeaut \\ ta(unloading) = timeunloading \end{matrix} \right\}$$

;

Among them, the external state transition function $\delta_{ext}(free, itrainyard) = waiting$ indicates that the train unloading module is driven by the yard module, which is another important feature of the yard and demand-driven terminals. *timepret* in the time advance function, *ta* is the preparation time of the train unloading subsystem, *timeaut* is the auxiliary operation time of the train unloading subsystem, and *timeunloading* is the working time of unloading a train.

(3) Yard module

Initially, the yard module is in a *free* state. On the one hand, when its input interface *iyardship* receives the demand information of the ship loading module, the yard module enters the *waiting* state. When its input interface *iyardship* receives the reclaiming instruction from the ship loading module, it will switch to the *reclaiming* state. At this time, the yard module starts to output dry bulk cargo to the ship loading module. After completing this reclaiming operation, the yard module outputs reclaiming information to the statistics module through the output interface *oyardsta* and transfers to the *finish* state. If there are dry bulk cargoes in the batch that need to be loaded on the ship, the yard module will switch to the *waiting* state; if the batch has been fully reclaimed, it will switch to the *free* state. On the other hand, the yard subsystem will perform yard inventory information statistics according to established rules. When the statistical result meets the replenishment condition, the yard subsystem sends a replenishment command to the train unloading module through the output interface *oyardtrain* and transfers to the *waiting* state. When its input interface *iyardtrain* receives the stacking instruction from the train unloading module, it will switch to the *stacking* state. At this time, the yard module receives the dry bulk delivered from the train unloading module. When the stacking operation is completed, the yard module outputs the reclaiming information to the statistics module through the output interface *oyardsta* and transfers to the *finish* state. If there are dry bulk cargoes in the batch that need to enter the yard, the yard module will switch to the *waiting* state; if the batch has been fully stockpiled, it will switch to the *free* state. The DEVS model of the yard module is expressed as follows:

$$Xd = \{iyardship, iyardtrain\}$$

;

$$Yd = \{oyardtrain, oyardsta\}$$

;

$$S = \{free, waiting, stacking, reclaiming, finish\}$$

;

$$\delta_{int} = \left\{ \begin{array}{c} \delta_{int}(free) = waiting \\ \delta_{int}(stacking) = finish \\ \delta_{int}(reclaiming) = finish \end{array} \right\}$$

;

$$\delta_{ext} = \left\{ \begin{array}{c} \delta_{ext}(free, iyardship) = waiting \\ \delta_{ext}(waiting, iyardship) = reclaiming \\ \delta_{ext}(finish, iyardship) = waiting, free \\ \delta_{ext}(waiting, iyardtrain) = stacking \\ \delta_{ext}(finish, iyardtrain) = waiting, free \end{array} \right\}$$

;

$$\lambda = \left\{ \begin{array}{c} \lambda(waiting) = oyardtrain \\ \lambda(stacking) = oyardsta \\ \lambda(reclaiming) = oyardsta \end{array} \right\}$$

;

$$ta = \left\{ \begin{array}{c} ta(free) = +\infty, presettime \\ ta(waiting) = ta(finish) = +\infty \\ ta(stacking) = timestacking \\ ta(reclaiming) = timereclaiming \end{array} \right\}$$

;

Among them, the internal state transfer function $\delta_{int}(free) = waiting$ indicates that the yard module itself has a trigger mechanism. At the same time, it also receives the trigger information of the ship loading module through the external state transition function $\delta_{ext}(free, iyardship) = waiting$. If one of the two conditions is met, the *free* state of the system will change. There is a parallel relationship inside the yard module, which carries out information interaction and material transmission with the ship loading module and the train unloading module at the same time. There may be reclaiming operations and stacking operations in the yard module at the same time. *timestacking* and *timereclaiming* in the time advancement function *ta* are the operation times of stacking and reclaiming.

4.3. Module and model framework library

4.3.1. Module library

The production operation system of the specialised dry bulk terminal is composed of many subsystems. The dry bulk export terminal is composed of the plan management subsystem, the train unloading subsystem, the yard subsystem, and the ship loading subsystem. The bulk cargo import terminal includes the plan management subsystem, ship unloading subsystem, yard subsystem, and train loading subsystem. The production system of the water-water transshipment terminal is divided into a plan management subsystem, ship unloading system, barge loading subsystem, and yard subsystem. Therefore, the main modules included in this module library are the plan management module, ship loading module, ship unloading module, train loading module, train unloading module and yard module, data statistics module, etc. These modules can all be expressed as a DEVS model. The last section analysed the internal logic flow of the train unloading module in the form of the DEVS model. Except for the plan management module, other modules are similar. This section discusses the logical flow of the plan management module.

The logic flow chart of the plan management module is shown in Figure 2. According to the basic information of the terminal, the module generates temporary entities according to a certain distribution. This temporary entity represents the master plan of the terminal's production operations. The temporary entity then enters the plan buffer area. According to the type of dry bulk terminal, the plan of the buffer area is transported to the corresponding module through the output interface of the module. Under different dry bulk terminal operation modes, the output interface of the plan management module varies. One or two of the ship loading modules, the train unloading module, the ship unloading module, and the train loading module may be its output object.

4.3.2. Model Framework Library

The information flow of dry bulk terminals is the driving source of logistics activities, and it is the basis for establishing a simulation model framework. Information on the arrival of ships on the sea side of the dry bulk terminal and the arrival of trains on the land side is one of the most critical pieces of information that triggers the operation of the terminal, and it is also one of the main factors that determine the framework of the terminal model. Dry bulk terminal driving modes can be divided into five main modes: demand-driven, supply-driven, yard and demand-driven, yard and supply-driven, and demand and supply-driven. Of course, some of these patterns may be more common, and some patterns may be rare or even exist in certain ideal situations. The previous section

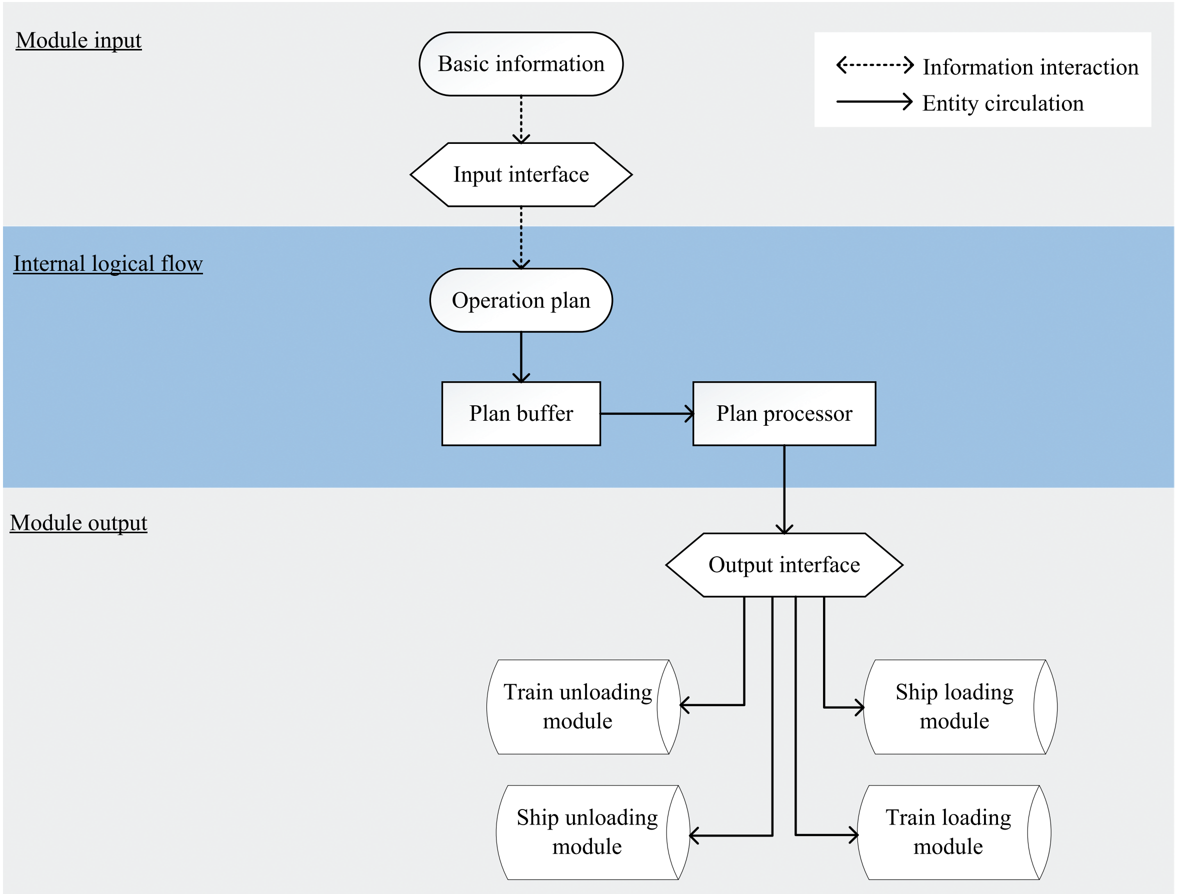

Figure 2. Logical flow chart of the plan management module.

has explained the DEVS model framework of the storage yard and demand-driven dry bulk export terminal, and the model framework of other types of terminals can be deduced by analogy.

4.3.2.1. Demand-driven mode. In a demand-driven operation model, a dry bulk terminal can be regarded as a transit station for cargo transshipment. The role of the terminal is the loading and unloading, storage and transshipment of materials. The arrival of dry bulk cargo is driven by the demand of the demand side. Under this model, there may be a cooperation agreement between the three participants in the supply chain where dry bulk is located, namely, the demander and the supplier, and the terminal operator. The demand side of bulk cargo will make a demand plan according to its own production plan and send it to the supplier. After receiving the demand plan, the supplier arranges transportation vehicles to transport the bulk cargo to the terminal yard. The actual departure of bulk cargo is based on the arrival of the demand side's means of transport. In short, the departure event of dry bulk cargo is generated

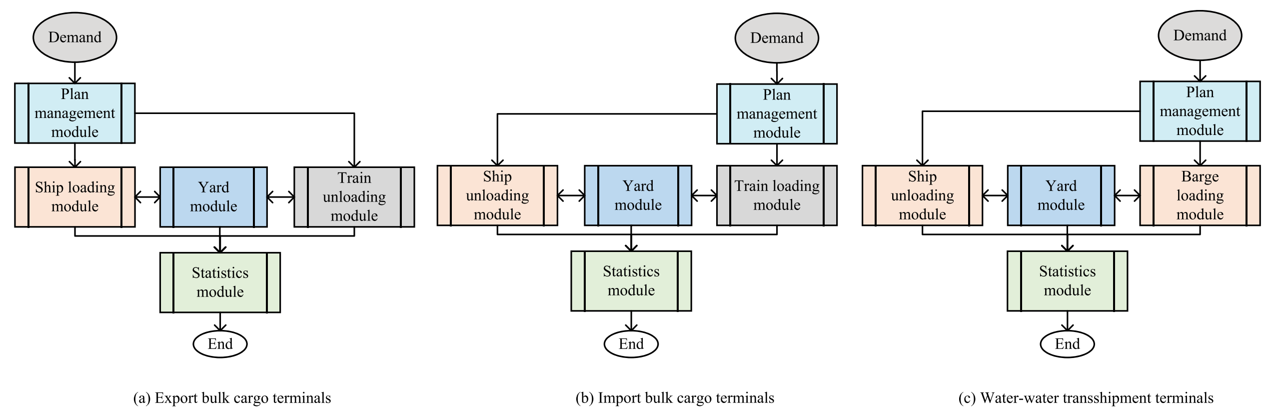

Figure 3. Flow chart of the demand-driven simulation model framework.

independently based on the demand of the demand side, and the arrival event of bulk cargo is generated based on the departure plan of the bulk cargo.

The flow chart of the demand-driven model framework is shown in Figure 3. In this case, the simulation models of the three types of bulk terminals are all driven by customer needs. The export terminal is shown in Figure 3(a). Figure 3(b) shows the situation of an import terminal. Figure 3(c) shows the framework process of the water-water transshipment terminal.

term and specific terminal production process, the arrival of dry bulk cargo is based on the production plan of the supplier, while the departure of dry bulk cargo is based on the arrival plan of the dry bulk cargo.

Figure 4 shows the corresponding simulation model framework flow chart. One of its characteristics is that the model is driven by the supplier's supply plan. As shown in Figure 4(a), the supply plan of the export terminal is the trigger point of the model. Figure 4(b,c) are the framework flowcharts of import terminals and water-water transshipment terminals, respectively.

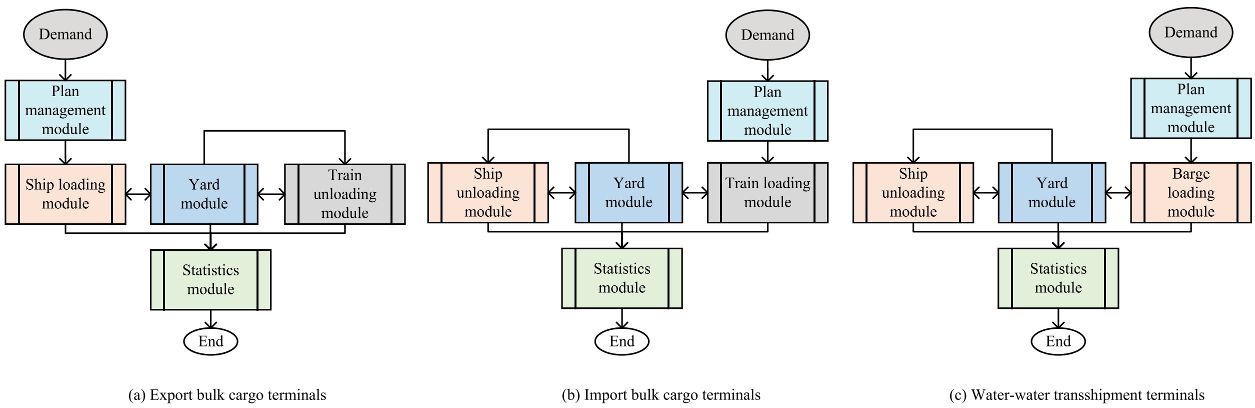

Figure 5. Flow chart of the yard and demand-driven simulation model framework.

driven model, the dry bulk terminal can also be regarded as a transit station for cargo transshipment. Unlike the demand-driven model, the supplier under this mode occupies a strong position in the supply chain, and the bulk cargo arrival plan formulated by it is the main basis for the operation of the terminal. Of course, the supplier will also consider the demand of the demand side when formulating the supply plan, but this consideration is more long-term or macroscopic, such as the annual demand plan. In the short-

4.3.2.3. Yard and demand-driven mode. In the yard and demand-driven operation mode, a dry bulk terminal is similar to a warehouse storage system. From the perspective of replenishment, the arrival of dry bulk cargo is yard-driven. The departure of dry bulk cargo is an independent event. That is, the demander of bulk cargo independently arranges vehicles or ships to transport the bulk cargo according to its own needs, and the time and amount of demand generated are determined by the demander. The arrival of dry bulk

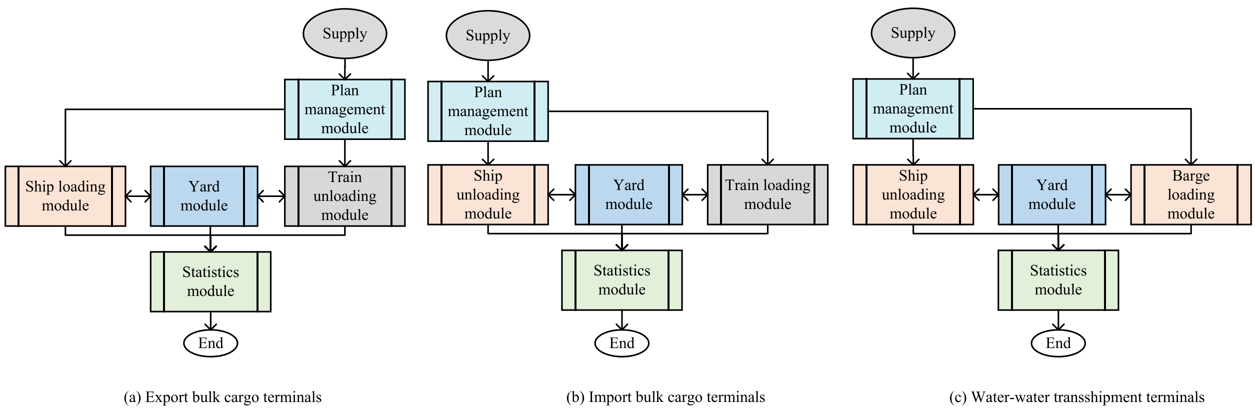

Figure 4. Flow chart of the supply-driven simulation model framework.

cargo is determined by the inventory of the terminal yard. To ensure the stability of the dry bulk supply, the bulk inventory on the yard must be maintained at a reasonable level. When the actual inventory in the yard is lower than the safety inventory, the bulk supplier must replenish the bulk in time. The driving source of terminal operation in this mode includes two aspects: the storage yard and customer needs.

Figure 5 is the corresponding simulation model framework flow chart. Under this framework, the dry bulk terminal must have a module driven by the yard, which is its main feature. Figure 5(a) is the export terminals, and the simulation model established by Zhu et al. (2018) uses this model framework. The frameworks of the imported terminal and the water-water transshipment terminal are shown in Figure 5 (b,c).

4.3.2.4. Yard and supply-driven mode. In the yard and supply-driven model, the dry bulk terminal can also be regarded as a warehouse storage system. However, unlike the yard and demand-driven model, the departure of dry bulk cargo is driven by the yard, while the arrival of dry bulk cargo is an independent event generated based on the supplier. That is, the bulk supplier occupies a dominant position in the supply chain, and it will sign a long-term supply agreement with the bulk demander and the terminal to meet the total demand of the demander within a longer period. However, in a relatively short period of time, the supplier will independently generate a bulk cargo arrival plan based on its own production plan. The departure of dry bulk cargo is determined according to the inventory of the terminal yard or the storage time. In this model, the terminal yard and bulk cargo suppliers are both driving sources of terminal operations.

Figure 6 shows the flow chart of the simulation model framework in the yard and supply-driven modes. There must be a module in the framework that is driven by the yard. The difference is that the other trigger of the framework is the dry bulk supplier rather than the demander. The frame of the export terminal in this mode is shown in Figure 6(a). Figure 6 (b,c) show the situation of an import terminal and a water-water transshipment terminal, respectively.

4.3.2.5. Demand and supply-driven mode. In the demand- and supply-driven model, the demand side and supply side of dry bulk terminals are equal. Both parties complete the loading, unloading and transportation of dry bulk cargo according to their own production plans. The terminal only serves as a transfer station in the

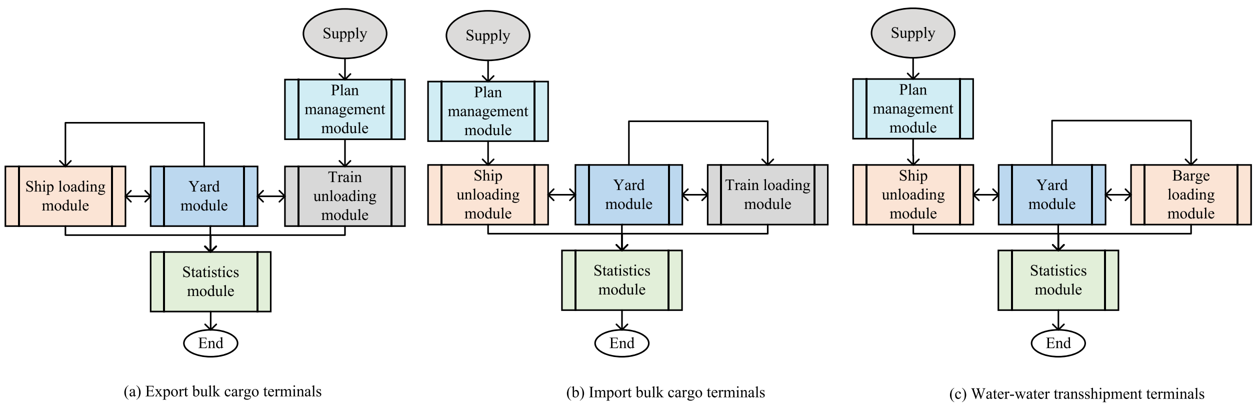

Figure 6. Flow chart of the yard and supply-driven simulation model framework.

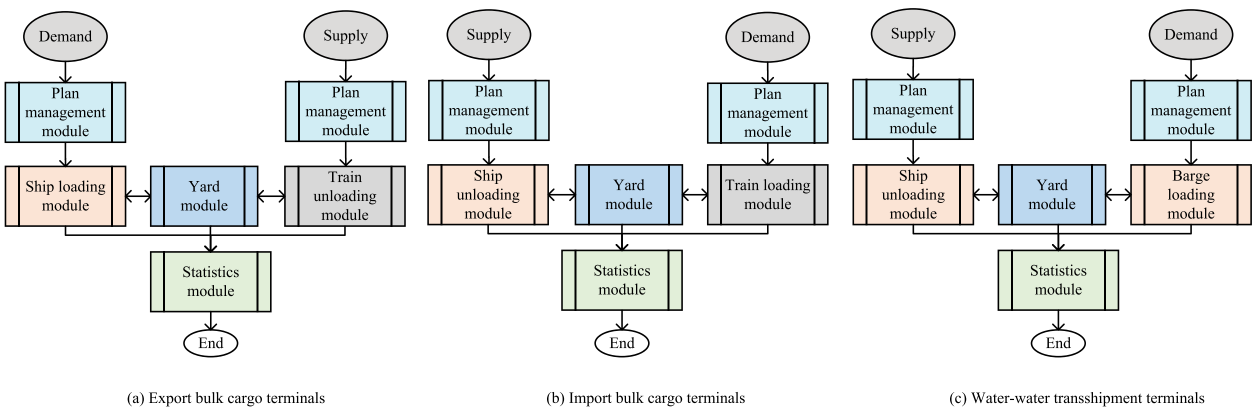

Figure 7. Flow chart of the demand- and supply-driven simulation framework.

dry bulk supply chain. Ship arrival events are generated based on customer demand, and train arrival events are generated based on the supplier's supply plan. The two are independent of each other. In this mode, it may happen that the supply side's transportation tools, such as ships or trains, cannot unload the ship or the truck due to insufficient space in the yard and must wait at the terminal. It may also happen that the demand-side transportation tools cannot be loaded on ships or trucks due to insufficient inventory in the terminal yard, and they are forced to wait at the terminal.

The demand and supply-driven simulation model framework is shown in Figure 7. The characteristic of the model framework in this mode is that the model has two independent driving points. The model framework of the export terminal is triggered by the demander and the supplier, as shown in Figure 7(a). The model frameworks of import terminals and transshipment terminals are also driven by the demand plan and supply plan, respectively, as shown in Figure 7(b,c).

5. Case study

5.1. Terminal description

A large coal export port located in northern China consists of five independently operated terminals. This section takes the third coal terminal as an example for analysis. The coal export terminal is composed of a train unloading area, storage yard area and ship loading area. The unloading area consists of facilities and equipment such as the train arrival line, the train dumper room, and the receiving belt conveyor. It uses two three-waggon tipples for unloading operations, with a rated dumping efficiency of 4800 t/h. The unloaded coal is transported to the storage yard through the receiving belt conveyor. The yard area consists of 4 strip yards with a total storage capacity of 1.7 million tons. There are 3 berths and 3 ship loaders in the loading area. The grades of these berths are 100,000 DWT (Dead Weight Tonnage), 35,000 DWT, and 35,000 DWT. The rated working capacity of the outgoing line consisting of the reclaimer,

Table 1. Parameters of facilities and equipment of the terminal.

Terminal area	Facilities and equipment	Technical specifications	Quantity
Train unloading area	Train dumper	4800 t/h	2
	Receiving belt conveyor	Q = 4800 t/h, B = 1.8 m	-
Yard area	Yard capacity	Storage capacity of 1.7 million tons	4 strip yards
	Stacker	4800 t/h, B = 1.8 m	2
	Reclaimer	6000 t/h, B = 2.0 m	3
Ship loading area	Shipping belt conveyor	6000 t/h, B = 2.0 m	-
	Mobile ship loader	6000 t/h	3
	Berth	One 10,0000DWT berth, two 35000DWT berths	3

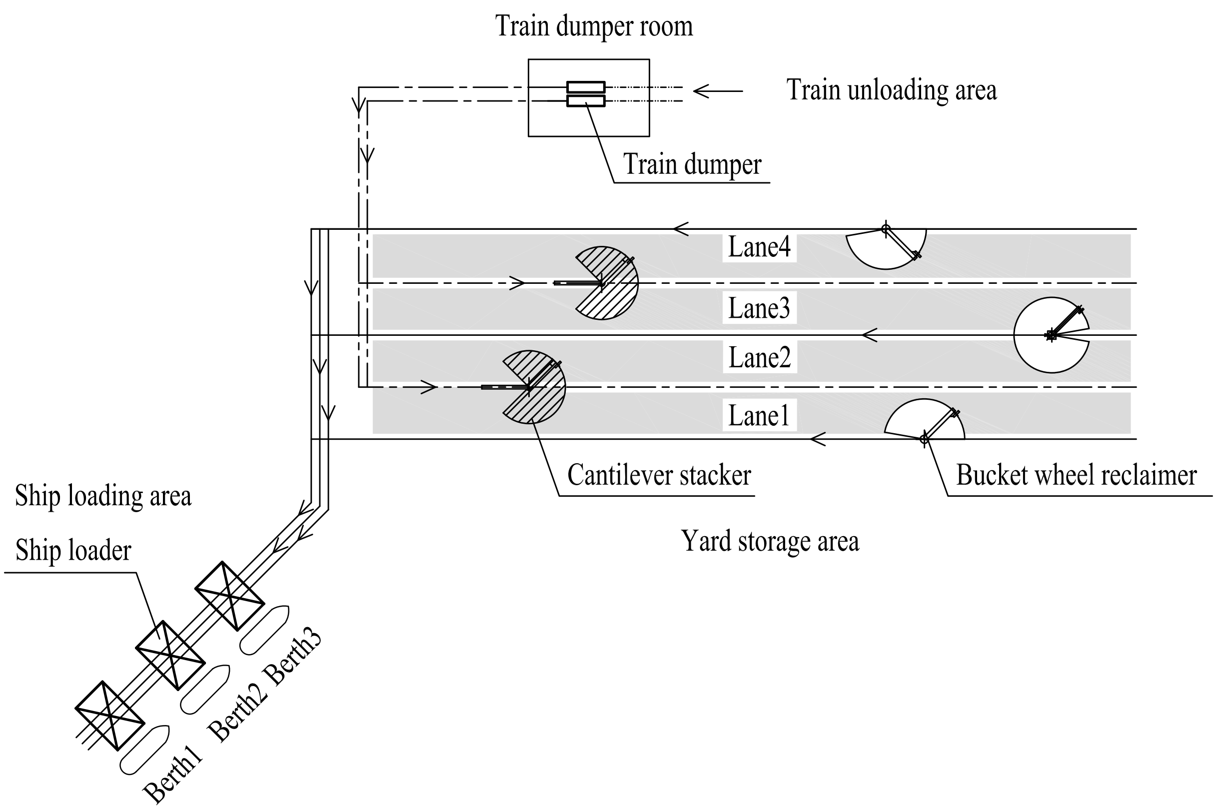

Figure 8. Layout of the terminal.

outgoing belt conveyor and ship loader is 6000 t/h. It should be noted that the actual operation efficiency of the terminal operation line is the rated operation efficiency multiplied by the efficiency coefficient. The detailed parameters of the terminal are shown in Table 1 below. Figure 8 shows the layout of the terminal.

5.2. Simulation model and verification

According to the production operation of the terminal, its production system can be subdivided into a plan management subsystem, train unloading subsystem, yard management subsystem, and ship loading subsystem. Therefore, it can be determined that the simulation model of this terminal is composed of a plan management module, train unloading module, yard module, ship loading module and statistics module. The terminal operation process obtained from the survey shows that the terminal is a yard and demand-driven mode, and the model framework should adopt the architecture shown in Figure 9. The customer needs to trigger the plan management module to form a ship arrival plan and then trigger the ship loading module. The train unloading module is triggered by the yard module. It formulates a train arrival plan based on the inventory of the yard and completes the replenishment of the yard. The train unloading module, the ship loading module and the yard module carry out data interaction and logistics connection to jointly complete the unloading and loading operations of coal. During the operation of these modules, the statistical module performs statistical analysis on relevant data.

Model modification modifies the established basic model according to the parameters of the facilities and equipment in each area of the terminal shown in Table 1, as well as their layout and logical relationship. For this coal terminal, its operating mode is yard- and demand-driven, so the output interface of the plan management module should be modified to connect to the ship loading module, and the attributes and variables of the temporary entity in the plan management module should be updated to ship-related information. In the train unloading module, the number of dumpers and their rated unloading efficiency, the rated conveying capacity of the receiving belt conveyor, etc. should be modified, and the layout and logical connection of these devices should be updated. The number and rated efficiency of stackers and reclaimers in the yard module and the rated efficiency of the yard belt conveyor also need to be updated. The division of storage yards and the storage capacity of each strip storage yard, as well as the layout and connection of equipment, also need to be updated. Similarly, update the number of berths, the number of ship loaders and rated working capacity in the ship loading module, as well as the logical relationship among berths, ship loaders and ship belt conveyers. Other input parameters in this model are shown in Table 2. Table 3 shows the actual statistics of ship loading.

This terminal is an operating terminal, and the model verification is a method of comparing the calculation results of the WITNESS simulation model with the terminal operating data. The model has a 30-day warm-up period. Figure 10 shows the relationship between the number of model runs and annual throughput. The figure shows that the annual average

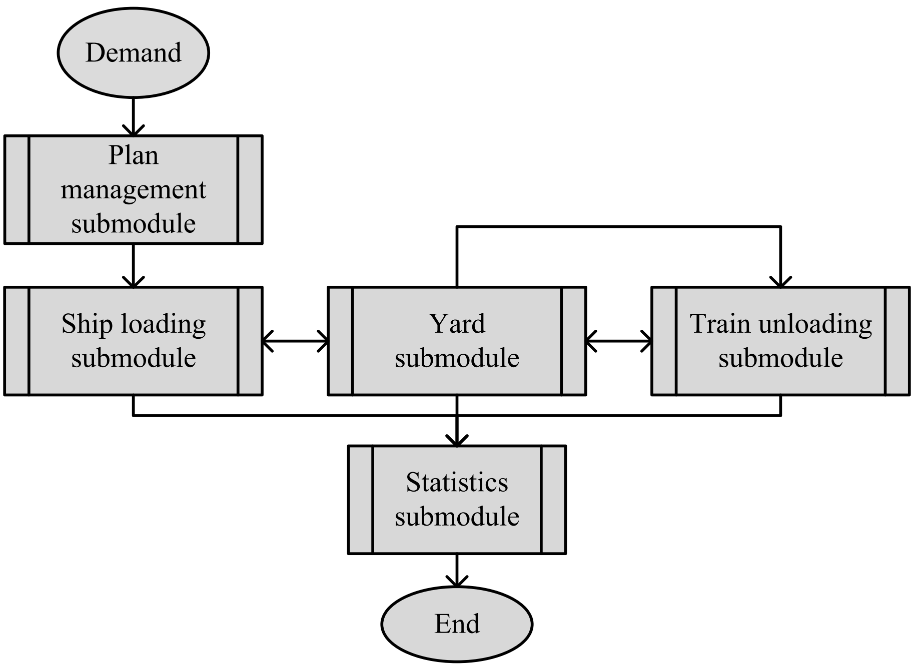

Figure 9. The model framework used in this model.

Table 2. Other input parameters in the model.

Input parameters	Parameter value
Ship arrival distribution	Negative exponential distribution
Ship berthing time (minutes)	Normal (60,5)
Ship unberthing time (minutes)	Normal (60,5)
Ship auxiliary operation time (minutes)	Normal (62.4,10)
Number of yard grids	1000 grids
Storage capacity of each grid	1700 tons
Number of coal customers	5 major customers, 6 general customers
The smallest batch of coal entering the yard	16,320 tons
Minimum storage period	6 days
Efficiency coefficient of the outgoing line	0.7
Efficiency coefficient of the incoming line	1

Table 3. Shipload information.

Coal customer varieties	Shipload distribution (Truncated normal distribution) TNORMAL(mean, standard deviation, min, max)
1	TNORMAL (35,428,15,144,17,795,75,942)
2	TNORMAL (31,387,14,844,15,915,74,593)
3	TNORMAL (28,548,11,487,10000,69,168)
4	TNORMAL (31,410,13,273,18,188,74,900)
5	TNORMAL (36,521,14,674,17,746,75,148)
6 ~ 11	TNORMAL (29,014,14,120,5067,84,028)

throughput is basically stable after 16 runs of the model. Therefore, the number of model runs is set to 16, each run for 330 days each time (excluding the time that cannot be operated due to weather and other reasons). The comparison between the experimental results and actual data is shown in Table 4. It can be seen from the table that the deviation between the output of the model and the actual data of the terminal is small. Therefore, it can be considered that the simulation model is close to the real system of the terminal, and this modular modelling method can be used to build the terminal model.

5.3. Experimental scene and simulation result

Since the coal export terminal studied is a yard- and demand-driven model, its seaside ship arrival plan is one of the main plans to drive the production and operation of the terminal. Ship load and ship density are two types of important information in the ship arrival plan. On the one hand, with the continuous improvement of water transport infrastructure such as

Table 4. Comparison of simulation results with actual data.

Performance Indicator	Actual data	Simulation result	Deviation (%)
Throughput (million tons)	46.77	46.37	0.85%
Number of ships served annually	1529	1510	1.24%
Average utilisation rate of dumper (%)	64.32%	63.97%	0.54%
Average utilisation rate of stacker (%)	67.31%	66.96%	0.52%
Average utilisation rate of reclaimer (%)	47.44%	47.29%	0.32%
Average utilisation rate of ship loader (%)	48.50%	48.46%	0.08%

The utilisation rate of the stacker and reclaimer in the table does not include the operation time of coal transfer in the storage yard.

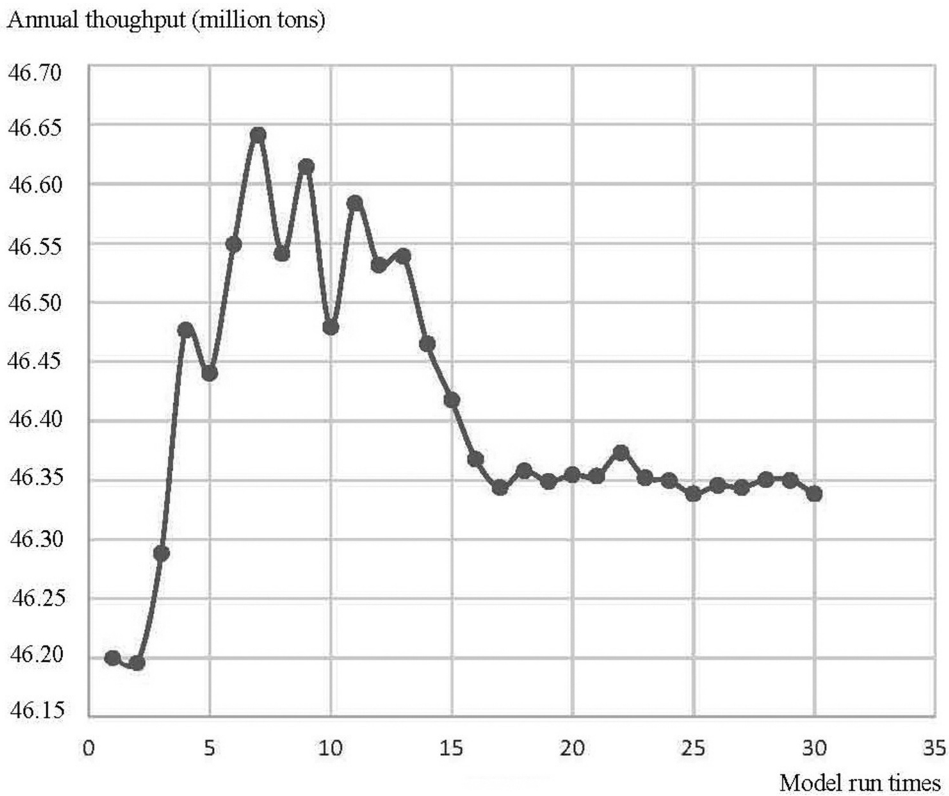

Figure 10. The relationship between the number of model runs and annual throughput.

terminals and waterways, the development trend of large-scale ships has become increasingly obvious. Larger ships will significantly reduce the transportation cost of dry bulk cargo and improve the overall competitiveness of the supply chain. Therefore, it is valuable to study the operation performance of the terminal under the background of a large-scale ship. On the other hand, with the development of the global economy and trade, the water transportation of dry bulk cargo will become increasingly prosperous, so it can be expected that the number of ships arriving at the terminal will gradually increase. For terminal operators, it is also a practical problem to study the performance of the terminal when the number of ships increases based on the existing facilities. Therefore, this section focuses on analysing the performance of the terminal's production operations under the conditions of increased ship loading and increased density of arriving ships.

5.3.1. Increased shipload

Based on the development trend of large-scale ships, this experiment analyses the operation of the terminal under the condition of increased ship loading. Based on the existing loading capacity of arriving ships at the terminal, we will test the changes in the throughput and equipment utilisation rate of the terminal when the shipload increases to 1.1 times, 1.2 times and 1.3 times. Table 5 shows the results of the test. The data in the table is the average of 16 runs.

(1) The increase in the loading of arriving ships will increase the annual throughput of the terminal. When the shipload increases to 1.1 times, the throughput will increase to 48.81 million tons; when it increases to 1.2 times, the throughput will increase to 50.20 million tons; and when it increases to 1.3 times, the throughput will increase to 50.63 million tons. This shows that with the increase in ship load, the increase in throughput decreases. After the ship load increased, many ships were forced to wait at anchorages for a long time because they did not meet the berthing conditions, resulting in a relatively declining number of ships serving each year. This decrease in the increase in throughput is the result of the combined effect of the increase in ship loading and the decrease in the number of ships in service each year.

(2) The change trend of the average utilisation rate of dumpers and stackers is consistent with the annual throughput. The utilisation rate of dumper #1 is between 79% and 82%, while the utilisation rate of dumper #2 is only 54%~59%. This is because the model prioritises using dumper #1 for coal unloading operations. The utilisation rates of stackers #1 and #2 were basically the same, both maintained between 69% and 74%. This is because both stackers serve two strip yards.

(3) The utilisation rate of the reclaimer increases with the increase in annual throughput, but the increase is decreasing. The utilisation rate of reclaimer #1 and reclaimer #3 is basically maintained between 39% and 44%, while the utilisation rate of reclaimer #2 is as high as 69% to 70%. The reason for the large difference in utilisation rate is that they serve different storage yards. Reclaimer #2 needs to serve the second and third strip yards at the same time, while reclaimers #1 and #3 only serve the first and fourth strip yards, respectively.

(4) With the increase in shiploads, the utilisation rate of ship loader #3 has increased significantly. When the loading capacity of the ship is increased by 1.1 times, the utilisation rate of ship loader #3 is 55.56%. When the load increased by 1.3, its utilisation rate reached 68.30%. This is because berth #3 is 100,000 DWT berth, and berths #1 and #2 are 35,000 DWT berth. When the shipload increases, large ships cannot berth at berths #1 and #2 and can only berth at berth #3, which leads to a rapid increase in the utilisation rate of ship loader #3. The table shows that the utilisation rate of ship loader #1 is higher than that of ship loader #2, and this phenomenon is related to the berthing sequence of ships. The model sets that small ships have priority to berth at #1berth. Only when berth #1 is not idle will the ship berth at berth #2.

Table 5. Simulation results when the shipload increases.

Terminal performance indicators	Shipload increased to 1.1 times	Shipload increased to 1.2 times	Shipload increased to 1.3 times
Throughput (million tons)	48.81	50.20	50.63
Number of ships	1474	1425	1365
Average shipload	33,121.50	35,233.26	37,100.25
1# dumper utilisation	79.71%	80.91%	81.33%
2# dumper utilisation	54.98%	57.66%	58.41%
Dumper utilisation	67.34%	69.28%	69.87%
1# stacker utilisation	69.99%	72.58%	73.79%
2# stacker utilisation	71.01%	72.49%	72.46%
Stacker utilisation	70.50%	72.53%	73.13%
1# reclaimer utilisation	39.99%	42.34%	43.85%
2# reclaimer utilisation	69.31%	69.53%	69.04%
3# reclaimer utilisation	39.99%	41.61%	41.87%
Reclaimer utilisation	49.77%	51.16%	51.59%
1# ship loader utilisation	60.33%	59.49%	57.91%
2# ship loader utilisation	36.87%	34.15%	31.75%
3# ship loader utilisation	55.56%	63.20%	68.30%
Ship loader utilisation	50.92%	52.28%	52.65%

Table 6. Test results when the ship's arrival density increases.

Terminal performance indicators	The number of ships increased to 1.1 times	The number of ships increased to 1.2 times	The number of ships increased to 1.3 times
Throughput (million tons)	48.40	49.80	51.19
Number of ships	1610	1694	1777
Average shipload	30,067.46	29,407.77	28,812.25
1# dumper utilisation	79.10%	79.78%	80.64%
2# dumper utilisation	54.59%	59.63%	60.59%
Dumper utilisation	66.84%	69.71%	70.62%
1# stacker utilisation	69.75%	71.84%	74.56%
2# stacker utilisation	70.19%	72.12%	73.29%
Stacker utilisation	69.97%	71.98%	73.93%
1# reclaimer utilisation	40.25%	43.01%	46.34%
2# reclaimer utilisation	67.85%	66.93%	66.09%
3# reclaimer utilisation	40.11%	42.60%	44.42%
Reclaimer utilisation	49.40%	50.85%	52.28%
1# ship loader utilisation	64.40%	66.04%	66.83%
2# ship loader utilisation	43.51%	46.77%	50.01%
3# ship loader utilisation	43.99%	43.69%	44.15%
Ship loader utilisation	50.64%	52.16%	53.66%

5.3.2. Increased ship arrival density

This experiment mainly analyses the terminal operations when the number of arriving ships increases. Based on the existing number of ships arriving at the terminal, we will analyse the changes in terminal throughput and equipment utilisation when the number of arriving ships increases to 1.1 times, 1.2 times and 1.3 times. Table 6 shows the results of the simulation test. The data in the table is the average of 16 runs.

(1) The annual throughput of the terminal will increase with the increase in the density of ships arriving at the terminal. The table shows that when the number of ships arriving at the terminal increases by 1.1 times, the annual throughput reaches 48.40 million tons; when the number of ships arriving at the terminal increases by 1.3 times, the annual throughput reaches 51.19 million tons. The number of ships served by the terminal will also rise from 1,610 to 1,777. It can be seen from the table that the average load of departing ships dropped from 30,067.46 tons to 28,812.25 tons. The reason for this phenomenon is due to the berthing rules of the ship in the model. Ships can berth only when the coal inventory in the yard is greater than the loading capacity of the ship, and the ship loading line and berth are free. With the increase in the number of arriving ships, many ships are waiting at anchorages. Since it is relatively easy for small ships to meet berthing conditions, it is easier to obtain qualifications for berthing and loading. Under the long-term screening of such berthing rules, some large ships were forced to wait at anchorages because they did not meet the berthing conditions, and the loading of departing ships decreased. In the operation of the terminal, this situation can be avoided by setting more flexible berthing rules. For example, when the waiting time of a large ship exceeds a certain set time, the ship automatically obtains the highest priority berthing qualification.

(2) The change trend of the utilisation rate of the dumper and stacker is basically consistent with the annual throughput. Since the number and rated efficiency of the dumper and stacker in the model are the same, their utilisation rates are not much different. The same situation also appears in the change trend of the utilisation rate of the reclaimer and the ship loader. The model assumes that there are no other operations, such as coal transfer or coal blending in the yard, so the operating time of the dumper and stacker, the operating time of the reclaimer and the ship loader are basically the same. During the operation of certain terminals, due to coal transfer and coal blending operations, the utilisation rate of the stacker may be greater than that of the dumper, and the utilisation rate of the reclaimer may be greater than that of the shiploader.

5.4. Comparative analysis of simulation experiment results

5.4.1. Terminal performance changes based on shipload

Zhu et al. (2020) studied the changes in the production performance of a coal export terminal when the load of ships changes. It is concluded that the annual throughput of the terminal will increase as the loading of arriving ships increases. However, as the load continues to increase, the increase in throughput will decrease. When the average loading capacity exceeds a certain value, the annual throughput of the terminal will decrease instead. The change trend of the utilisation rate of mechanical equipment and the throughput of the terminal is the same.

The simulation experiment results of this model also found this phenomenon. First, when the ship's loading capacity gradually increased from 1.1 times to 1.3 times, the throughput of the terminal continued to rise, but the rate of increase declined. It is foreseeable that as the load of ships continues to increase, after the terminal throughput rises to a certain value, there will also be a downward trend. As analysed above, the reason for this situation is that the berthing capacity of the terminal infrastructure has not been increased in tandem with the capacity of ships, and the number of berths that can serve large ships is limited. This has led to many large ships that do not meet the berthing conditions and are forced to wait, resulting in a relative decline in the total number of ships served by the terminal throughout the year. Second, the average utilisation rate of mechanical equipment is consistent with the change trend of throughput. That is, with the continuous increase in throughput, the average utilisation rate of dumpers, stackers, reclaimers, and ship loaders continues to rise, but their rise is also decreasing.

5.4.2. Terminal performance changes based on the density of arriving ships

The paper (Zhu et al., 2020) also studied the changes in the production performance of coal export terminals when the density of arriving ships changes. It found that as the time interval between ship arrivals decreases, the throughput of the terminal gradually increases, but the magnitude of the increase decreases. This simulation experiment also found the same phenomenon. As shown in Table 6, when the number of ships arriving at the terminal increases from 1.1 times to 1.3 times, the annual throughput of the terminal also increases. It is foreseeable that when the number of arriving ships continues to increase, the annual throughput of the terminal will not increase after reaching a certain peak. This is because despite the increase in the number of ships arriving at the terminal, the berths and mechanical equipment of the terminal have not changed. Therefore, once the service capacity of these facilities reaches the limit, there will be queuing and waiting of ships at the terminal, and the throughput will reach its maximum at this time. In fact, when the waiting time of ships is too long, it often means that the service level of the terminal has decreased, which will affect the enthusiasm of subsequent ships to arrive at the terminal.

5.4.3. Comparison of the impact of changes in shipload and ship density

Based on the existing infrastructure and operating rules of this coal export terminal, increasing the density of ship arrivals will make it relatively easier to increase the annual throughput of the terminal. Comparing Tables 5 and 6, it is found that under the current operating conditions of the terminal, when the loading capacity of ships increases by 30%, the annual throughput of the terminal increases by 8.26%; and when the number of ships arriving at the terminal increases by 30%, the annual throughput increases by 9.46%.

This phenomenon is caused by the berth level of this terminal. Berth #1 and Berth #2 of this terminal are small berths of 30000DWT, and Berth #3 is a large berth of 100000DWT. At present, the average load of ships docking at the terminal is approximately 30,000 tons. When the loading capacity of ships increases, large ships can only be berthed at berth #3, causing berth #3 to be busier than berths #1 and #2. Currently, due to the limitation of berth resources, it is relatively easier for large ships to wait in the anchorage. However, under the condition of increasing ship arrival density, the proportion of large ships in the total number of arrival ships has not changed. Currently, the busyness of the three berths changes in the same proportion. The utilisation rate of ship loader #3 also shows this phenomenon. Under these two test conditions, the average utilisation rate of the ship loader is between 50% and 54%. However, in the case of increased ship loading, the utilisation rate of ship loader #3 is between 55% and 69%. When increasing the ship arrival density, the utilisation rate of ship loader #3 is only 43%~45%.

5.4.4. Conclusion of the simulation experiment

Through the above analysis, it is found that the production performance of the coal export terminal is basically positively correlated with ship loading and ship arrival density. As a terminal operator, to cope with the possible increase in ship density and ship loading, measures can be taken from two aspects to improve the service capacity of the terminal. On the one hand, they can transform the terminal infrastructure and upgrade the berth level. By strengthening the hydraulic structures of berths #1 and #2 and improving their berthing capacity, the relative shortage of large berths in the future can be effectively alleviated. On the other hand, they can improve the berthing strategy of ships. Due to the different levels of the three berths, their berthing strategy has a certain impact on the waiting time of ships and the utilisation rate of berths. Terminal managers can adopt more flexible berthing strategies and seek a balance between terminal service levels and terminal annual throughput.

6. Conclusions and future research

To promote the application of system simulation methods in dry bulk terminals, this paper proposes a DEVS-based modular modelling method. Based on elaborating the modular modelling method based on DEVS, the module library for specialised dry bulk terminals is analysed, and five model frameworks are discussed. Taking a coal export terminal as an example, the application process of the modular modelling method based on DEVS is analysed, and the effectiveness of the method is verified. Overall, the following conclusions can be drawn through this study.

(1) The proposed modular modelling method for dry bulk terminals based on DEVS is feasible. This modelling method introduces the modular modelling ideas of DEVS into the field of dry bulk terminals and attempts to standardise the modelling process, which can help modellers quickly establish simulation models. It helps the system simulation method be applied in dry bulk terminals.

(2) The simulation module library and model frame library for dry bulk terminals established in this study are effective. The module library covers export, import and water-water transshipment terminals. The model framework library includes five main modes: demand-driven, supply-driven, yard and demand-driven, yard and supply-driven, and demand and supply-driven. This standardised module and model framework can be reused for modelling different types of dry bulk terminals, effectively reducing the modelling workload.

The modular modelling method based on DEVS proposed in the paper provides a better solution for dry bulk terminal modelling analysis. However, this study also has certain limitations. On the one hand, the operation rules and decision-making process entered in each module are relatively simple. No optimisation model is embedded in these modules. In fact, each production operation module of the terminal can embed some optimisation programs to obtain more efficient terminal performance. For example, berth allocation algorithms and crane operation scheduling can be embedded in the ship loading module and the ship unloading module to reduce ship waiting time and increase terminal throughput. The yard management module can be embedded in the yard allocation optimisation algorithm, the stacker-reclaimer scheduling algorithm, etc., to improve the operation efficiency of the yard and optimise the equipment utilisation efficiency. On the other hand, there are deficiencies in the comparative study of the DEVS model with other models.

Therefore, in the future research process, we will focus on embedding some production optimisation scheduling models into corresponding modules. By comparing and analysing the operating results of the model after the optimisation module is embedded with the actual performance of the terminal, it provides suggestions for the optimisation of the operating rules of each production link. On the other hand, we will study the difference in fidelity of simulation models based on different modelling methods. In addition, this research is aimed at dry bulk terminals, which can be extended to other types of terminals, such as container terminals, general cargo terminals, and liquid bulk terminals, in the future.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Benfei Zhu http://orcid.org/0000-0003-4731-7569

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