IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received May 12, 2022, accepted June 14, 2022, date of publication June 21, 2022, date of current version June 24, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3184728

Multiagent-Based Modeling and Simulation of a Coal Multimodal Transport System

YAN YANG[1,2], (Member, IEEE), QIANG ZHOU[1], AND KE CHEN[3], (Member, IEEE)

[1]School of Transportation and Logistics Engineering, Wuhan University of Technology, Wuhan, Hubei 430063, China
[2]Changzhou Institute of Technology, Changzhou, Jiangsu 213032, China
[3]Wuhan Accelink Technologies Co., Ltd., Hubei, China

Corresponding author: Yan Yang (yangyan2006@outlook.com)

ABSTRACT With the change in coal supply and demand, the dynamics of multiple transit nodes and the connection between different transportation modes make the Coal Multimodal Transportation System (CMTS) more complicated in the long-distance transportation of coal. Therefore, it is necessary to analyze the multimodal transportation nodes, build a coal multimodal transportation model, measure the network throughput through simulation experiments, and identify system bottlenecks. The CMTS is a complex nonlinear dynamic system with many participants with complex and uncertain links. Different transportation modes, operation links, and connection processes will affect system performance, and modeling and simulation technology effectively study complex dynamic systems. This paper takes the CMTS as the research object, uses agent-based modeling methods and Witness simulation software to analyze the composition and operation mechanism of CMTS, establishes the multiagent model of CMTS, and validates the model by a Witness simulation experiment of northern coal shipped to south. The simulation results indicate the capacity of the transport route and resource utilization of nodes in CMTS in case of different demand growth rates in the future. Based on the multiagent model and Witness simulation results, this paper provides practical support for constructing and applying the multimodal transport system model library and provides the basis for decision-making for the CMTS plan.

INDEX TERMS Coal multimodal transport system, multiagent-based modeling, multiagent system, Witness simulation software.

I. INTRODUCTION

At present, economic growth is slowing. Affected by factors such as energy structure adjustment and environmental protection needs, the development of the coal industry is faced with prominent contradictions such as excess capacity, the imbalance between supply and demand, and increasing pressure on environmental protection. The focus of this research is how to balance supply and demand and achieve efficient coal transportation. China's coal supply is mainly in the north and northwest of China, while consumption is in the south and east of China, which requires a complex coal transportation network covering a wide range. Primarily based on railways, coal transportation requires the combined use of vehicles of various transportation modes, such as roads and waterways, leading to complicated circulation links, low logistics operation efficiency, and long transportation lines in coal multimodal transportation. These problems have restricted the rapid development of coal transportation to a large extent.

The associate editor coordinating the review of this manuscript and approving it for publication was Chaitanya U. Kshirsagar.

The rational development and adequate coal multimodal transportation facilities can bring extremely competitive economic advantages. Scientific and meticulous planning of the transportation system of coal, a bulk natural resource, can also result in considerable benefits to the national economy. Therefore, using agent-based modeling and simulation methods of a complex system, analyzing the Coal Multimodal Transportation System (CMTS), building the CMTS model, designing example simulation experiments, identifying system bottlenecks based on the simulation results, and making recommendations for the CMTS operations are necessary and timely.

The CMTS is a dynamic complex nonlinear macro system involving many links, participants, and autonomous behavior; complex system modeling methods and simulation tools will enable the system's overall performance to be accurately evaluated. Its innovative applications will provide strategies for in-depth research within the system.

By combining the research literature on complex system modeling methods and multimodal transportation, this paper analyzes the hierarchical structure of the complex CMTS.

We use the multiagent-based modeling method to construct the multiagent model of the complex CMTS. Witness simulation software can help us verify the rationality and applicability of the multiagent-based modeling technique. By modeling and simulating CMTS and analyzing the simulation output results, the paper aims to identify the CMTS bottlenecks and provide planning suggestions and resolutions for government or operators, according to evaluation indicators.

II. LITERATURE REVIEW

We divide this section into two subsections. The first subsection reviews the literature on the modeling and simulation of complex systems, and the second reviews the literature on multimodal transport.

A. LITERATURE ON MODELING AND SIMULATION OF COMPLEX SYSTEMS

In recent years, many scholars have applied various modeling methods to complex systems and proposed solutions to problems.

As the scale of complex system problems under study proliferates, the model complexity of the multi-input components used to construct logical processes increases significantly. To better use, the parallelism of the multi-input component model, a vectorized component model framework, and a two-level mixed parallel method can support complex system simulation applications composed of multi-input component models [1]. However, existing modeling methods rely on overly simplistic assumptions, making it challenging to spot complexity in the system. A modeling approach is used for industrial systems to model different multiunit systems without restricting assumptions about the number of units or their properties by accessing discrete event simulations for modeling event queues [2].

As complex adaptive systems continue to grow in size and complexity and the need for system adaptability continues to increase, system modeling has become a significant problem. Parallel discrete event simulation became the logical choice process, linking complex system modeling and high-performance computing. Therefore, a hierarchical composite modeling framework, a three-layer architecture designed, can support the composition and integration of submodels [3]. The network agent-based modeling method can generate a dynamic spatial network structure and collaborative network and complex system theory to simulate forest space complex systems [4]. Subsystems of complex systems in a unified view, each with a set of input, output, and control variables, are integrated to model and simulate the operation of complex systems [5].

The graph-based modeling approach captures physical connections in complex optimization models through algebraic graph abstraction, capturing communication connections in computing architectures through computational graph abstraction [6]. To support the distributed sharing of computationally intensive simulation models and select the optimal service model to build for complex system simulation applications, scholars have proposed a service-oriented model encapsulation and chosen method [7]. The process encapsulates the model into a shared simulation service, supports the distributed scheduling of the model service in the network, helps the user search the model, and customizes the weight of the service quality indicator. The importance of computational modeling and simulation is highlighted by describing the application of computational modeling to teamwork and crowd behavior in different transportation hubs [8].

For human resource management complex systems, an agent-based approach to model it as a complex system in which alternative management strategies can be modeled through agent interactions while observing organizational performance [9]. Fuzzy mechanical modeling of complex systems helps us analyze a mixture of quantitative and mutually controllable qualitative modules [10]. Emergence acts as a critical feature of complex systems. Simulation is the only way to study the emergence of properties (at the macro-level) between groups of system components (at the micro-level).

Some scholars have used the port simulation software MicroPort to construct an improved multi-agent system to represent the interaction between various types of equipment and the decision-making process [11]. Some scholars have also proposed a distributed agent system for dynamic port planning and scheduling. The system consists of four agents: a port planning manager, a berth control agent, a shuttle agent allocation, and a yard storage agent. These agents communicate and cooperate to work out the berth allocation schedule and shuttle requirements [12].

However, designing multi-agent-based models for the operational management of complex dynamic systems is often a laborious and tedious task, requiring the definition of modeling methods to simplify the design process, for example, by defining a top-down approach including Specification, Concept, Implementation, and Validation - Validation in several steps [13]. Managing complex systems such as container terminals requires new ways of finding solutions. The methods for modeling the entities in a container terminal are presented, along with the simulation experiments conducted. A multiagent-based simulation approach evaluates container terminal management operations [14].

Then, scholars also proposed the modeling and simulation method for emergent behavior-discrete event system specification. They are adding up/down communication channels for modular and hierarchical modeling and simulating heterogeneous polyform systems [15]. The agent-based model is a computational model, a simulation of the interactive approach between the environment and the group of agents, and bottom-up modeling. Neural networks are top-down modeling preferred for relational learning and training sets to avoid detailed behavior categorization down to the device level. Both bottom-up agent-based and top-down neural network models have advantages and disadvantages [16].

There are many modeling methods for complex systems, such as Petri nets, system dynamics, neural networks, and agent-based modeling. Because agent-based modeling can reflect the multifaceted characteristics of complex systems, it has attracted researchers' attention and wide application. The literature on complex systems covers many areas, while research on complex multimodal systems is limited.

B. LITERATURE ON MULTIMODAL TRANSPORT

Multimodal transport involves using multiple modes of transport to carry goods from origin to destination. Traditional logistics models minimize transportation costs by properly defining service networks and transportation routes. Considering the multimodal transport problem of greenhouse gas emissions, we realize the need to build a model for this problem in a nonlinear integer programming formulation and then linearize it [17]. Optimizing the performance of a multimodal freight network involves fully balancing the interplay between cost, volume, departure and arrival times, and travel time. To study this interaction, an allocation model can efficiently determine traffic and costs in multimodal networks [18]. A weighted colored edge graph helps us choose the shortest path in a multimodal transport network, where colors represent modes of transportation. The shortest paths are selected using a partial order that compares the weights of each color, resulting in a Pareto set of shortest paths [19].

A modal shift from road transport to an inland waterway or rail transport can reduce greenhouse gas emissions. Therefore, to combine trucks and inland waterway transport instead of a single truck to transport household waste from a collection center to a waste treatment [20]. Focusing on the problem of multimodal cargo transportation under uncertain conditions, a generalized interval fuzzy mixed integer programming model helps us determine the optimal transportation mode and transportation through each route [21].Based on the principles of system optimization, we need to construct a multimodal evacuation model that considers multiple traffic modes and their interactions and captures appropriate traffic dynamics, including congestion effects, the cooperative behavior of evacuees, and the transportation system's capacity [22].

Based on the virtual transportation network, considering the influence of various factors in dynamic alliance and the minimum cost and time as the basic optimization model, scholars combined the impact of active associations on the cost of multimodal transport to form a fuzzy cost model [23]. Considering carbon emissions in the study of multimodal transport and establishing a multimodal transport route selection model in a low-carbon environment has received increasing attention [24].

A significant bottleneck in port regionalization through multimodal transport chains is the expensive and time-consuming inland transport. Therefore, considering shipper preferences, proposing a pricing model to describe a competitive market in seaports [25]. The Witness simulation software proposes a dynamic calculation method of multimodal transport line parameters. The multiobjective multimodal transport efficiency evaluation framework is combined with relationship analysis and an entropy weight fuzzy analytic hierarchy process to evaluate the route performance under various multimodal transport schemes [26].

A simulation tool incorporating the model was developed to study the impact of waterway disruptions on interconnected multimodal transport systems [27]. To improve the efficiency of multimodal transport and reduce the cost of multimodal transport, some scholars studied the synergy evaluation of multimodal container transport based on the backpropagation neural network algorithm [28] and a new integrated framework of a fuzzy risk assessment model, data envelope analysis, and multicriteria decision methods for route selection [29].

The above literature review shows that the research theme focuses on the two significant aspects of multimodal transport route selection and cost optimization, considering the shortest route, carbon emissions, dynamic alliances, and many other factors. The research methods mainly include nonlinear integer programming and fuzzy mixed-integer programming models, backpropagation neural network algorithms, etc. Using the agent-based modeling method that reflects the multiple characteristics of the multimodal transportation system, there is limited literature on the overall modeling of the complex multimodal transportation system, which can analyze the system bottlenecks and the internal node transfer.

III. MULTIAGENT-BASED MODELING OF THE CMTS

We divided this section into six subsections. Based on agent-based modeling, we analyzed mapping between the CMTS and the multiagent system and proposed the multiagent modeling process of the CMTS. Then, we constructed the CMTS hierarchical model according to the process, agent classification, and function definition. The communication mechanism and interaction model between multiagents are established.

A. MAPPING BETWEEN MULTIAGENT SYSTEMS AND THE CMTS

An agent is an independent entity with precise boundaries and specific goals, autonomous behavior, and perception and communication capabilities [30]. Both agent-based and multiagent system simulations can be viewed as evolutions of cellular automata. This means that the model consists of interacting agents in a simulated environment so that agents may correspond to cities, vehicles, sensors, traffic signals, etc. One of the reasons for the popularity of agents and multiagent systems is the advancement of computers, which are more distributed, open, large, and heterogeneous. Managing interactions between autonomous entities with increasing interdependencies has been one of the most significant drivers of multiagent systems [31]. Most authors generally agree that a multiagent system consists of agents that communicate and collaborate [32].

The CMTS is complex, and it is theoretically feasible to introduce the multiagent modeling method into the simulation and optimization research of multimodal coal transport. Analyze the mapping relationship between the CMTS and

TABLE 1. Correspondence between the CMTS and multiagent system.

Coal Multimodal Transportation System	Multiagent System
It Consists of multiple entities with different functions.	It consists of multiple agents with different roles.
Each entity has its own goals and tasks.	Each agent has its own goals, resources, and tasks.
Coal transport tasks can be subdivided into individual or collaborative tasks.	Agents can assign tasks or coordinate with other agents to complete complex tasks.
The intermodal transportation system needs to coordinate logistics, information, and capital.	Agents coordinate through communication and interaction in the system.
Each entity in the system has autonomy, and the entities negotiate to complete the decision.	Agents are autonomous, can react to the environment, and take active actions to interact with other agents.
Diversity of transportation structure, which can combine various transportation modes.	Flexible system with different control and connection structures

the multiagent system to see if there is an internal connection between the two, which is helpful in building a multiagent model of the CMTS. The corresponding relationship is explained in Table1.

B. MULTIAGENT MODELING PROCESS

After discussing the adaptability of multiagent modeling above, according to the characteristics of the CMTS, the multiagent model framework of the CMTS is designed to realize the independence of functions and the practicability of the system. Using multiagent modeling and simulation technology to study CMTS, it is necessary to standardize the modeling process first to facilitate model development and reuse.

The system needs to be divided into layers from the top-down when designing the process. The divided layers can meet the system requirements and, at the same time, reflect the system's operation mode to a clear and precise target. To reduce the complexity of simulation modeling and realize the purpose of rapid construction of the agent model. The specific process of multiagent modeling is shown in figure1.

Multiagent-based modeling flowchart for a coal multimodal transportation system

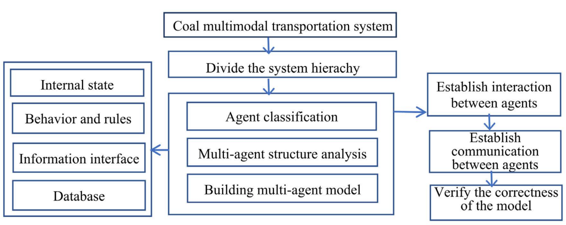


FIGURE 1. Multiagent-based modeling flowchart for a coal multimodal transportation system.

C. HIERARCHICAL MODEL OF THE CMTS

Based on the actual operation of the coal multimodal transport system, combined with system science and agent-based modeling methods, the CMTS is deeply analyzed. The transportation process of coal from the source of the supply to the consumption place involves the management and operation of coal mining enterprises, transportation departments, port companies, and consumers. The participating entities are independent of each other and have substantial autonomy. Based on the understanding and analysis of the above activities, starting from the top layer of the CMTS, the composition elements of the system are gradually refined and analyzed.

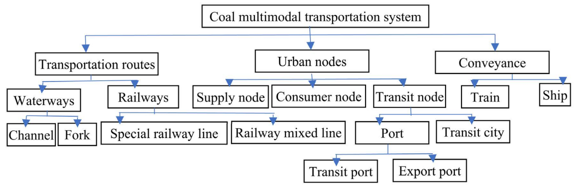


FIGURE 2. A hierarchical model of CMTS.

The established CMTS hierarchical model is shown in figure2. The hierarchical model determines the system problem study level. The division of system levels is helpful to realize the division of system entities and the definition of agent functions.

D. TYPES AND FUNCTIONS OF AGENTS IN THE CMTS

According to the coal multimodal transport hierarchy and operation mechanism, the CMTS is decomposed into a multiagent system composed of planning-decision-making and business execution layers. All kinds of agents are divided according to levels in the design, undertake different tasks, and realize various functions in the system.

The planning and decision-making layers are responsible for issuing instructions to guide the system activities. The modules of the execution layer are related to each other to complete the internal organizational activities of the system. Therefore, according to different task processes, the functional agents of the CMTS are divided, and the results are shown in Table2.

E. MULTIAGENT COMMUNICATION MECHANISM

Agent communication language is a vital component in a multiagent system to enable agents to communicate and exchange messages and knowledge. However, no universally agreed-upon agent communication language is widely adopted. Knowledge query and manipulation language (KQML) is the most commonly used agent communication language [33].

KQML is typical for multiagent communication. Its communications can be divided into the content, message, and communication layers. Taking the transportation scheduling agent and the terminal node agent as examples, KQML describes the message form of the transportation scheduling agent inquiring about the available unloading berths to the terminal node agent. The specific content is as follows:

{ask-one
:sender: Transportation Agent//message sender
:receiver: Port Agent//receiver of the message
:language: KIF//language of the content layer
:ontology: NYSE-TICKS//vocabulary comparison table
:content(Number unloadberth?number) //content of the message
}

TABLE 2. Classification of Agents in the CMTS.

Layers	Types	Functions
Decision-making layer	Plan and schedule agent	Manage the overall system situation and undertake three functions of collaboration management, task management, and resource management
planning layer	Order management agent	Place an order based on the node's stock status.
	Operation plan agent	The operation plan guides the supply, transfer, and consumer node's loading and unloading operations according to the order demand and inventory situation.
	Transport schedule agent	Determine the transportation plan according to the task requirements and road conditions, and negotiate and communicate with other agents.
Executive layer	Supply node agent	Supply coal and cache it in the storage center of the module, load the coal into trucks according to demand, and then transport it to each node through the road network.
	Transit node agent	Extract the destination information of the train, make judgments and intelligently select the route.
	Coal terminal agent	Describe the logistics transshipment capacity of terminal nodes with yard capacity, shore or land loading and unloading average productivity or statistical distribution, responsible for coal transshipment and storage activities.
	Consumer node agent	Judging inventory and choosing whether to issue orders to source points, unload trains coming in from the upstream road network, and consume coal at a specific rate.
	Ship management agent	Allocate the ships to the corresponding ports according to the needs; the starting port will load the coal to the destination port; the destination port will unload the boat and return the ship to the anchorage at the starting port.
	Train management agent	Allocate the trains to the corresponding source points according to the demand. The source points will load the coal to the destination. After the coal is unloaded, the train will return to the source point and wait for the next loading.

The meaning of this message is that the sender of the message, the transport scheduling agent, asks the message receiver, the terminal node agent, the number of available unloading berths, and the terminal node agent needs to answer, where ask is a predicate.

F. MULTIAGENT INTERACTION MODEL OF THE CMTS

The interaction model between coal multimodal transport agents is constructed based on completing agent task decomposition and scheduling and establishing a communication mechanism between multiple agents. The interaction model between coal multimodal transport agents is built, as shown in figure3.

The related cooperative behavior of planning and scheduling agents in figure3 is an example to explain the interaction between interactive agents. The agent is responsible for the formulation and adjustment, coordination, and control of the comprehensive information plan, formulates corresponding plans according to the order information, decomposes them into various subtasks, including operation plans, transportation scheduling plans, and order plans, and configures multiple facilities and equipment. Each agent responds to the assignment and task arrangement and reports the job status to the planning and scheduling agent. The data statistics agent is displayed visually, and the statistical data are fed back in real time so that the planning and scheduling agent can monitor and manage the system.

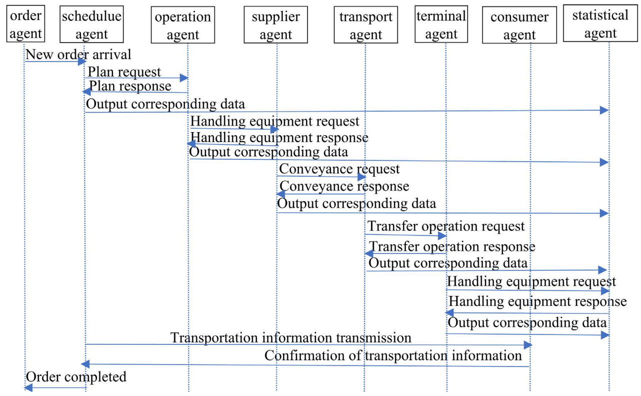


FIGURE 3. The multiagent interaction model of the CMTS.

IV. THE REALIZATION OF THE SIMULATION MODEL OF THE CMTS

The agent has constructed the hierarchical model of CMTS, the overall structure model of the multiagent, and the multiagent interaction model and analyzed the functions of each agent and the interactive communication mechanism. This section will implement the multilayer model of the CMTS based on Witness simulation software.

A. WITNESS SIMULATION PLATFORM

In this paper, Witness simulation software is used as the development platform of the multiagent. Witness simulation software primarily simulates discrete event systems, dealing with most logistics problems such as transportation, dock planning, and automatic production lines. It adopts the programming method of object-oriented modeling and can handle the interaction of large and complex networks, so it has strong achievability.

Witness software supports modeling based on multiple agents, describes the attributes of each agent through a pie chart, histogram, line chart, and output parameters, and realizes the interaction between the agents through the communication interface.

B. THE OVERALL STRUCTURE OF THE MULTIAGENT MODEL OF THE CMTS

Based on Witness, the realization form of the multiagent model of CMTS is divided into the agent development model and the realization of the human-computer interaction interface. The human-computer interaction interface is realized by using visual basics for applications to write the console program. According to different functions, different elements, variables, and parts are used to learn the development of agents and the encapsulation of modules. The overall structure of the multiagent model of CMTS based on Witness is shown in figure4.

Most of the current agent-oriented modeling languages were developed by people with primarily academic backgrounds. On the one hand, this fact generally assures the creation of theoretically sound solutions. On the other hand, it results in insufficient testing and a lack of proof of their

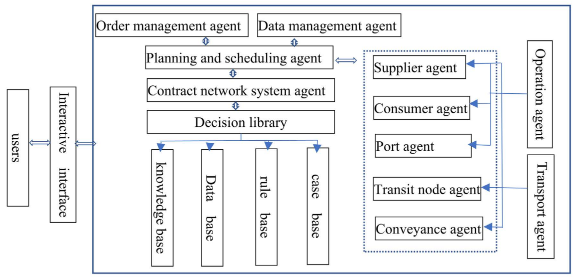


FIGURE 4. The overall structure of the multiagent model of CMTS based on Witness.

applicability in real-world modeling problems [34]. This paper realizes the application of the multiagent system modeling method in the real-world system: China's large-scale and long-distance CMTS, coal shipped from the North to the South, which solves practical problems.

C. THE SIMULATION OF THE EXAMPLE OF NORTHERN COAL SHIPPED TO THE SOUTH MULTIMODAL TRANSPORT SYSTEM

The multimodal transportation systems for coal from northern China to southern China (in brief, northern coal shipped to the south) are mainly composed of the primary source of coal (with cities as the nodes), the main coal consumption sites (main cities), the transit sites (main ports and railway stations), and the transportation routes (roads, railways, waterways).

The structure of the multiagent model for CMTS is generated through the connection between each node agent put into the Witness platform. The specific method is to judge the link relationship through the information of the output interface of the node agent and then automatically connect to generate the road network structure to realize the development of the CMTS's design.

The simulation of the northern coal shipped to the southern transportation network system is shown in figure5.

The left side of the figure5 is the element tree of the simulation model, and the right side is the coal transportation network in China. The background of the picture is a map of some provinces in China. A blue curve meandering from west to east in figure5 represents the Yangtze River, and the blue areas are the East China Sea and the South China Sea, respectively. Eight red and twelve green nodes can be seen on the land, representing coal supply and consumption places. Eight orange nodes represent the transshipment places. Five dark blue nodes represent the coal terminals of the main export ports in the north of China, and the five blue nodes represent the coal terminals of the main input ports in the south of China, a total of ten coal terminals. Small squares in figure 5 represent yards, and black represents coal.

As shown in figure5, the statistics of the constituent nodes of the northern coal shipped to the southern transportation network are shown in Table3.

Therefore, based on Table3 and the analysis of multiagent modeling above, the types and quantities of agents included

TABLE 3. Kinds and quantity of agent in the case.

Kinds of node agents	Name of node agents
Supply nodes	Baotou, Datong, Shenzhou, Yulin, Taiyuan, Jiaozuo, Yanzhou, Huaibei
Transit nodes	Hefei, Hangzhou, Ningbo, Xiamen, Fuzhou, Guangzhou, Chongqing, Nanchang
Coal terminals	Qinhuangdao, Tangshan, Huanghua, Tianjin, Lianyungang, Shanghai, Nanjing, Ningbo, Fuzhou, Guangzhou
Consumer nodes	Zhuhai, Changsha, Wuhan, Jinan, Rizhao, Xuzhou, Zhengzhou, Cangzhou, Shijiazhuang, Xian, Beijing, Qianan

TABLE 4. Kind and quantity of agents for the northern coal shipped to the southern system.

Kinds of agent	Number of agents
Plan and schedule agent	1
Order management agent	1
Operation plan agent	1
Transport schedule agent	1
Supply node agent	8
Transit node agent	8
Coal terminal agent	10
Consumer node agent	12
Ship management agent	1
Train management agent	1
Statistical agent	1

in the multiagent model of the north coal shipped to the south multimodal transportation system are shown in Table4.

D. DESCRIPTION OF ATTRIBUTION AND BEHAVIOR (ACTIONS) OF AGENTS IN A SIMULATION EXPERIMENT

Each agent has behaviors (actions). This paper selects four types of agents, namely, coal supply and consumption nodes, railway-waterway multimodal transport routes, and transit nodes, as examples to explain the behavior codes of agents, as shown in figure6.

The upper left of figure6 is the action code of the coal supply node (Baotou) agent, the upper right is the action code of the railway line agent, the lower left is the action code of the transshipment terminal agent, and the lower right is the action code of the transshipment city node (Hangzhou) agent.

There is a large amount of data describing the attributes of each agent. We take the facilities and production of coal supply points as an example, as shown in Table5.

E. MAIN STATISTICAL INDICATORS OF THE CMTS PERFORMANCE ANALYSIS AND EVALUATION

The overall efficiency of the coal intermodal transportation system is determined by the performance indicators of system nodes and transportation routes, and these indicators are related to each other and reflect the system bottleneck. The significant indicators selected in this paper are ship waiting time, the average utilization rate of berths, port throughput, the throughput of major coal transportation routes, the daily average occupancy rate of the yard, etc. The leading statistical indicators of the simulation test output are shown in figure7.

Figure7 is a screenshot of the real-time display of statistical indicators during a coal multimodal transport instance simulation experiment on the Witness platform. The left side

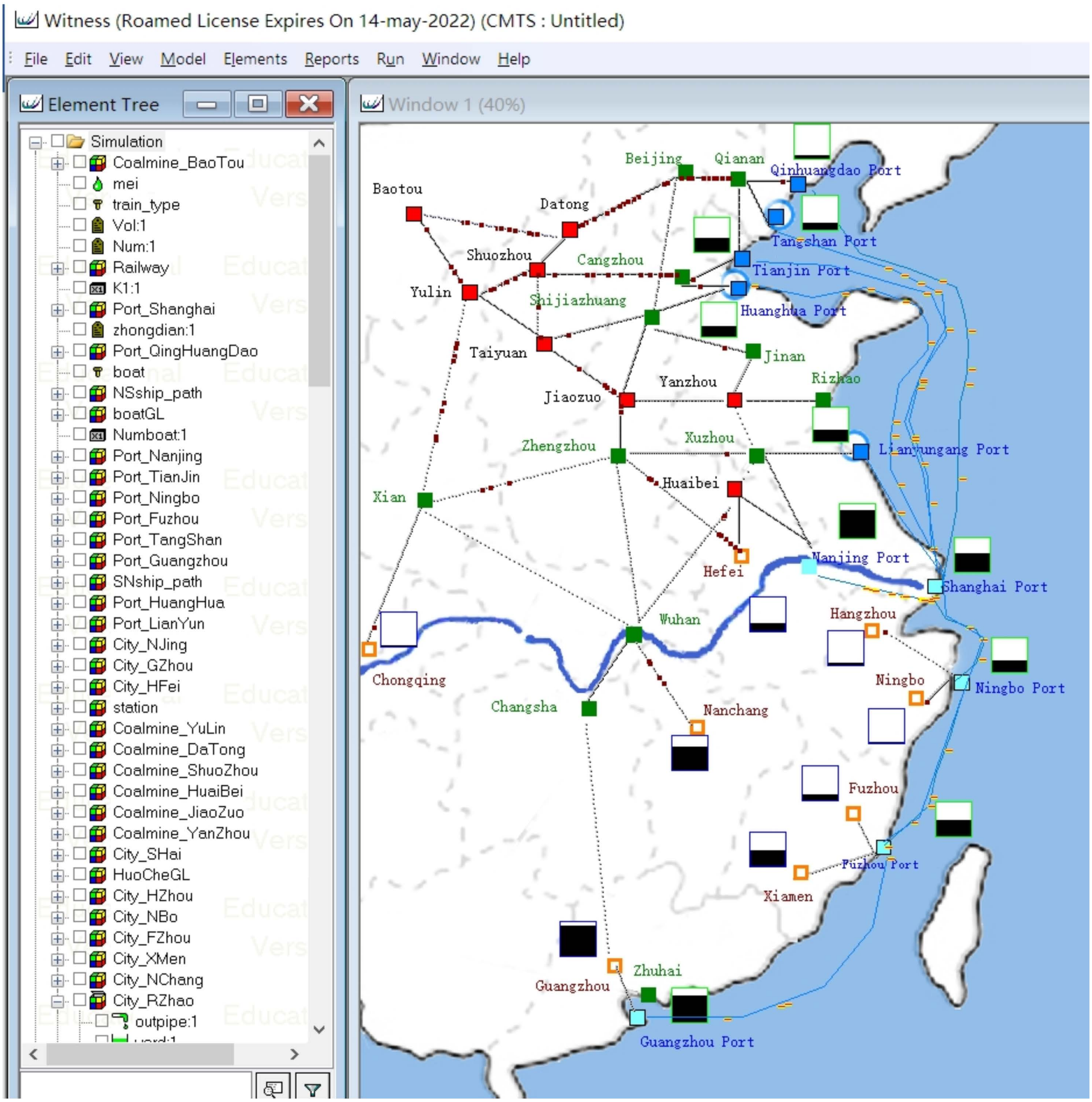


FIGURE 5. The simulation interface of north coal shipped to the south transportation network system.

of the figure is the element tree of the simulation experiment index statistics, and the right side of the figure is the real-time change and statistical display of the four key indicators in the coal intermodal transportation system. During the simulation experiment, the real-time changes in the ship waiting time, berth utilization, throughput, and outward transportation volume of coal source in the port are displayed in pie charts, bar charts, and statistical tables.

F. VERIFICATION OF THE MULTIAGENT MODEL OF THE CMTS BY EXAMPLE SIMULATION TEST

To check whether the output data are consistent with the actual value, the statistical parameters of the port throughput are selected to verify the model. The simulation time of the design model is 7,920 h, and the comparison between the simulated value and the actual value of the port throughput is shown in Table6.

From Table6, the positive and negative errors of the statistical parameters are not more than 5%, and the results verify the applicability and correctness of the model. Therefore, it is practical and sound to conduct simulation experiments of different scenarios with this model.

V. DISCUSSION

This section consists of 5 subsections. We discuss the characteristics and applications of the CMTS multi-agent model. At the same time, according to the output indicators of the example simulation experiment, we analyzed the influence

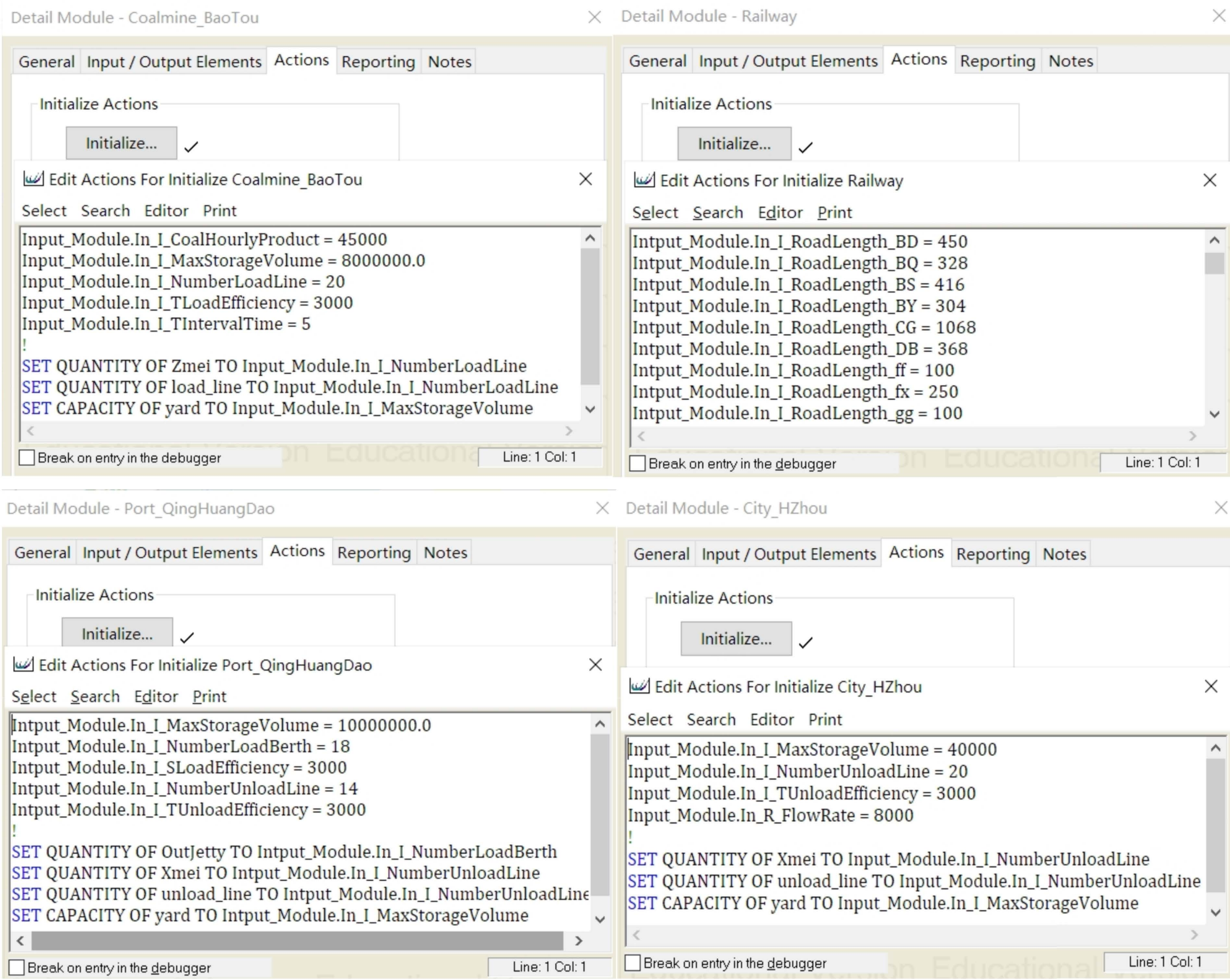


FIGURE 6. Code example of the behavior (actions) of agents in a simulation experiment.

TABLE 5. Comparison of simulation value and actual value of coal allocation at nodes.

Supply nodes	Annual production of coal (10,000 tons)	Planned storage time (days)	Maximum stockpile (10,000 tons)	Number of loading lines	Loading efficiency (T/h)
Baotou	35000	5	800	15	3000
Yulin	20000	3	600	10	3000
Datong	10000	3	500	8	3000
Shuozhou	5000	5	200	5	3000
Taiyuan	3500	3	200	5	3000
Huaibei	1000	3	80	3	3000
Jiaozuo	2000	3	80	5	3000
Yanzhou	1000	3	80	3	3000

of different demand growth rates in the CMTS on resource utilization and drew the simulation conclusion of the case of coal transportation from the north to the south.

A. CHARACTERISTICS OF THE MULTIAGENT MODEL OF THE CMTS

1) THE ADJUSTABILITY OF THE MULTIMODAL NODE AGENT IN THE MODEL

With the development of coal resources and the country's expansion plan for railways, the coal multimodal transport network is undergoing dynamic changes. The model can add or subtract model agents (consumption, terminal, and supply nodes) to study current and future coal transportation.

2) FLEXIBLE ALLOCATION OF TRANSPORT AGENTS IN THE MODEL

The model can configure agents of different means of transport to intermodal node cities. For example, the demand of a consumer city node mainly relies on water transportation. Nevertheless, railway transportation can be adopted when the water transportation capacity is insufficient or an emergency demand (such as a sudden increase in orders). The parameters that can be changed mainly include the number and size of ships issued by the port terminal and the number of trains to the city.

3) INTELLIGENT SELECTION OF MULTIMODAL TRANSPORT ROUTES

Given the problem that the capacity of some coal transportation lines is approaching saturation, the model sets the starting point and endpoint of the train and analyzes each railway station node. A route with a shorter distance is preferentially selected, and other methods are chosen when the capacity of

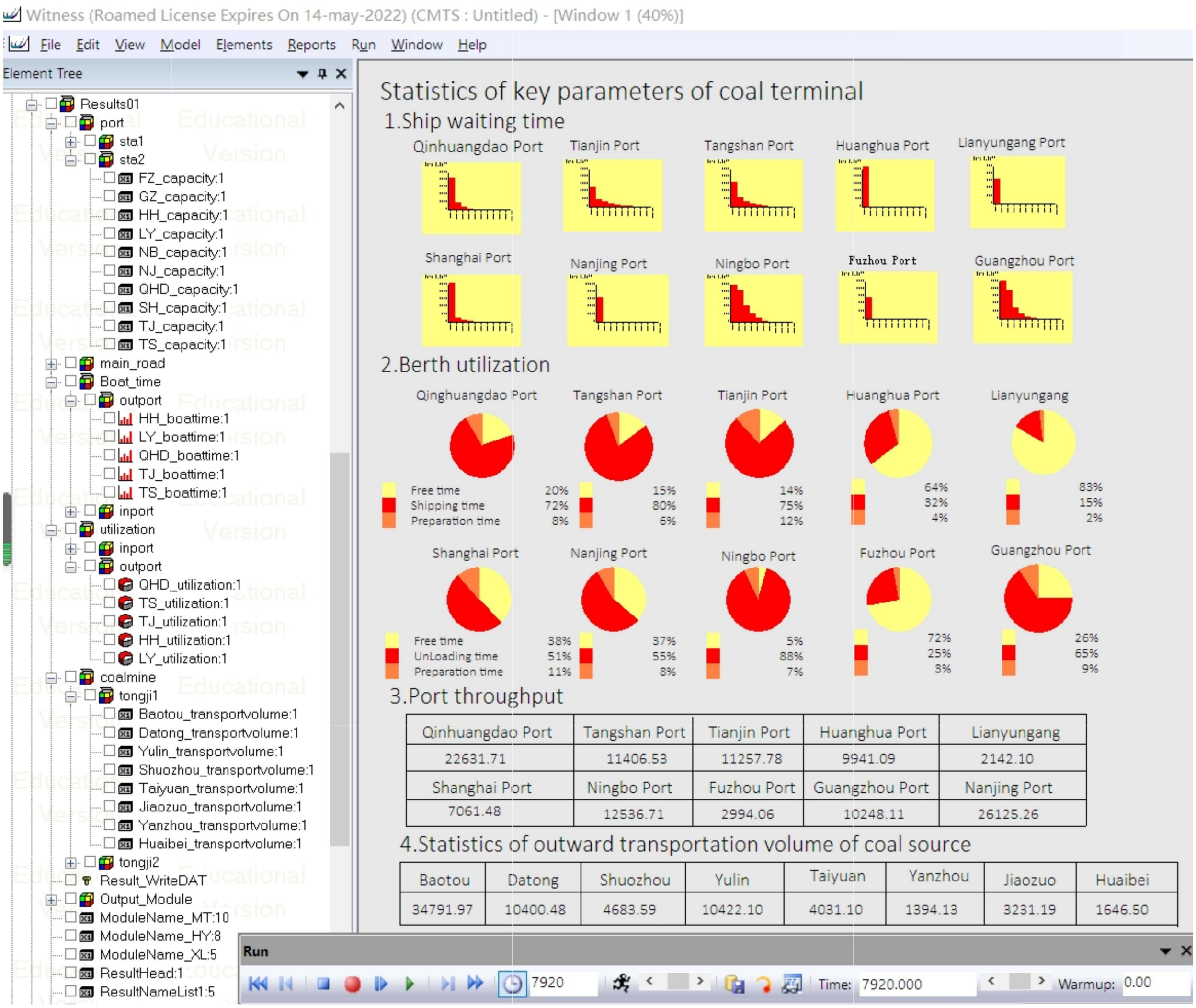


FIGURE 7. Main Statistical Indicators of Simulation Test Output Results.

the priority route is saturated. The model reduces the waiting time of the train and optimizes the transportation route.

4) EFFICIENCY OF MODELING AND SIMULATION EXPERIMENTS

According to different actual needs and the research objectives, we can model quickly and efficiently, design simulation experiments, and analyze the output results to solve practical problems.

Based on the characteristics of the model, we can conclude the practical application value of the multiagent model of CMTS.

B. APPLICATION OF THE MULTIAGENT MODEL OF THE CMTS

The suitability and practicability of multiagent modeling are verified based on the Witness CMTS simulation experiment of northern coal shipped to the southern system.

The adaptability of the simulation model based on multiagent-based modeling can reflect various system problems through simulation tests in different scenarios. Specifically, the research can be carried out from the following aspects.

TABLE 6. Comparison of the simulation value and actual value of coal allocation at nodes.

Ports	The simulation value (10 kilo-tons)	The actual value (10 kilo-tons)	Relative error
Qinhuangdao	22829	23124	-1.3%
Tangshan	11314	11241	0.6%
Tianjin	11242	11394	-1.3%
Huanghua	10006	9739	2.7%
Lianyungang	2116	2157	-1.9%
Nanjing	26299	25267	4.1%
Shanghai	6908	6970	-0.9%
Ningbo	12555	12875	-2.5%
Fuzhou	2979	2982	-0.1%
Guangzhou	10319	10015	3.0%

1) DEALING WITH THE PROBLEM THAT THERE IS NO CHANGE INSIDE THE CMTS AND THERE ARE CHANGES OUTSIDE THE SYSTEM

Under the condition that the CMTS's composition and structure remain unchanged, by changing the environmental input of the system, the limit passing ability that each agent of CMTS can achieve is evaluated, and the internal resource utilization and bottleneck problems of the system are analyzed.

2) DEALING WITH THE PROBLEM THAT THERE IS NO CHANGE OUTSIDE THE CMTS AND THERE ARE CHANGES INSIDE THE SYSTEM

Under the condition that the external conditions remain unchanged, we change the composition of the CMTS to study the agent's influence on the CMTS and the improvement plan.

3) DEALING WITH THE PROBLEM THAT THERE ARE CHANGES OUTSIDE AND INSIDE THE CMTS

By changing the uncertain and complex factors inside and outside the CMTS, the influence mechanism of the single or combined changes of the elements on the efficiency of the CMTS system is studied, and the planning and design reference and decision-making basis are proposed.

C. ANALYSIS OF THE INFLUENCE OF THE COAL DEMAND GROWTH RATE ON THE NODE TRANSSHIPMENT AND LINE CAPACITY IN THE CMTS

Coal demand growth is 0%, 5%, 10%, 15%, 20%, and 25% as variable factors, and simulation experiments are carried out. The length of the simulation test is 330 days, that is, 7,920 hours, considering the influence of weather conditions and holidays. Each group of experiments was performed ten times, the results of the experiments were averaged, and the statistical parameters were counted.

There are many influencing factors of the coal multimodal transportation network. In the case of further growth in coal demand, we mainly analyze the outbound shipments of the supply nodes, the central railways' passing capacity, and the coal terminal's transfer capacity.

1) OUTBOUND SHIPMENTS OF THE SUPPLY POINTS

Figure8 shows the changing trend of the coal shipment volume from the supply points of the simulation test.

As shown in figure8, the coal transport volume from the source points generally increases with the increase in demand. Among the many supply sources, the two supply points, Baotou and Yanzhou, have experienced rapid growth in transportation volume. However, for the rest of the supply nodes, when the demand increases to a certain extent, the growth rate of coal shipments tends to be flat.

The Witness simulation results, the statistical analysis of the outgoing volume of coal supply points, and the forecast of future changes in coal outbound shipments according to the growing trend of coal demand provide a reference for adjusting the production plan at the supply point.

2) THE COAL TRANSPORT VOLUME OF THE MAIN RAILWAYS

Figure9 shows the changing trend of the coal transport volume of the main railways of the simulation test.

As shown in figure9, when the increase in demand is 15%, the coal throughput of the Shi-Tai railway line increases

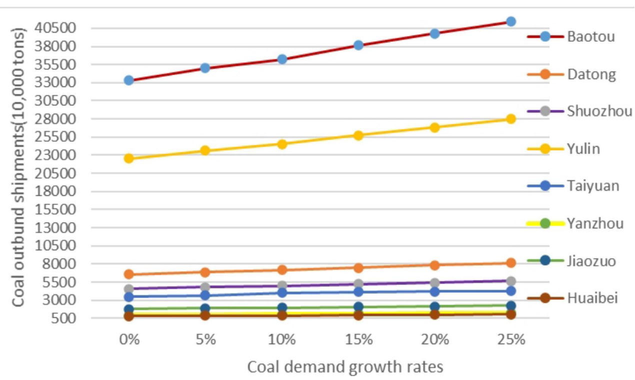


FIGURE 8. Line chart of outbound shipment of coal supply points under different demand growth rates.

to approximately 50 million tons and remains unchanged, indicating that the throughput limit of the Shi-Tai line has been reached. Therefore, the Shi-Tai railway line becomes the system bottleneck. With the increase in demand, the throughput of the other four railway lines has also increased steadily, especially the Da-Qin line, which has excellent potential.

3) THE TRANSFER CAPACITY OF THE COAL TERMINAL IN PORTS

As the demand growth rate changes, the throughput of the coal terminal also changes accordingly, and its predicted value is shown in figure10.

Figure10 shows that under increasing coal demand, the throughput of Nanjing and Qinhuangdao has always maintained a rapid upward trend, indicating that Nanjing and Qinhuangdao have strong transshipment capacity. When the demand growth rate is 0%-20%, the throughput of Tangshan Port changes relatively smoothly, and the growth trend is faster when it is 20%-25%. After the demand growth rate reached 15%, the port throughput change trend of Guangzhou and Ningbo Port slowed down.

D. DISCUSSION ON THE INFLUENCE OF DIFFERENT DEMAND GROWTH RATES ON RESOURCE UTILIZATION IN THE CMTS

1) AVERAGE DAILY OCCUPANCY RATE OF THE COAL YARD

In the case of different coal demand growth rates, the simulation output values of the average daily occupancy rate of each coal terminal's yard are shown in figure11.

Figure11 shows that with the change in the growth rate of coal demand, the average daily occupancy rate of storage yards in Nanjing and Shanghai is between 40% and 55%, which is capable of handling a larger amount of coal transfer. However, the occupancy rate of Ningbo and Guangzhou ports began to decline after the growth rate reached 10%, indicating that the ports cannot meet the needs of consumer cities, and it is necessary to increase the unloading capacity and add unloading berths.

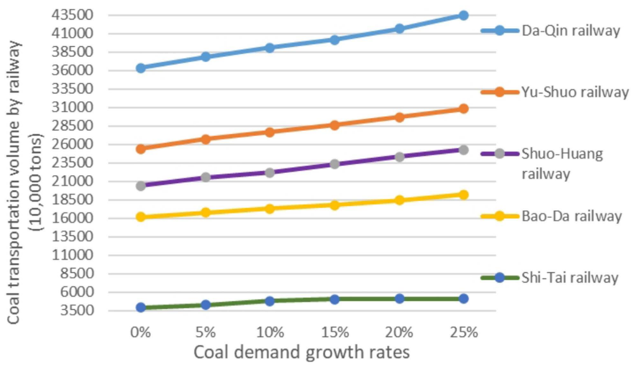


FIGURE 9. **Line chart of the coal transport volume of the main railways under different demand growth rates.**

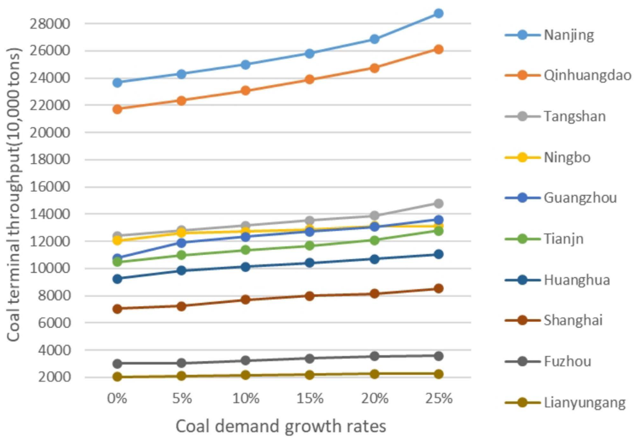


FIGURE 10. **Line chart of throughput of the coal terminal under different demand growth rates.**

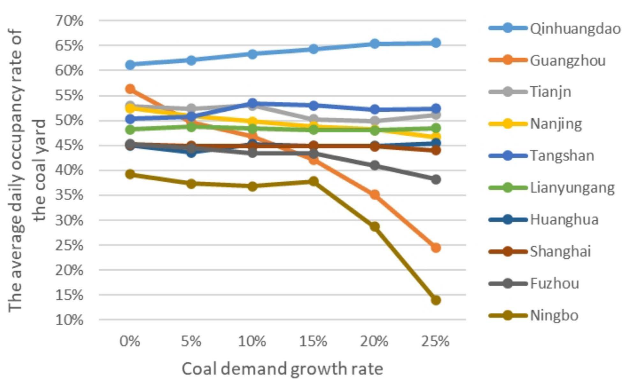


FIGURE 11. **Line chart of the average daily occupancy rate of the coal yard.**

2) BERTH UTILIZATION OF COAL TERMINALS

In the case of different coal demand growth rates, the simulation output values of the berth utilization rate of each coal terminal are shown in figure12.

As shown in figure12, with the growth of coal demand, the berth utilization rate of Tangshan and Huanghua terminals is between 30% and 50%, and there is space for further development. Combined with figure 10, although Tianjin Port has maintained a rapid growth trend in throughput, it has little potential for future development due to the high utilization rate of berths. In contrast, the throughput of Tangshan and

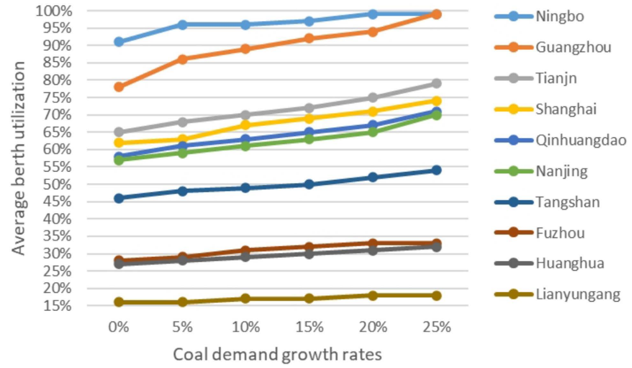


FIGURE 12. **Line chart of the berth utilization rate of each coal terminal.**

Huanghua ports is not large, and the occupancy rate of their storage yards is analyzed. Indicators all show that the two terminals can handle larger-scale coal demand. In the future development of CMTS, Tangshan and Huanghua Port have excellent growth potential.

E. THE CONCLUSION OF THE WITNESS SIMULATION TEST OF THE CASE OF THE NORTH COAL SHIPPED TO THE SOUTH

1) THE SHI-TAI RAILWAY TRANSPORTATION LINE IS THE MAIN CMTS BOTTLENECK

The Shi-Tai railway transportation line is often in a tight transportation capacity, and its limited transportation capacity is the main CMTS bottleneck. This result recommends carrying out coal railway construction and transportation planning. The Da-qin and Shuo-Huang railway lines have great potential for coal transportation. The transportation capacity of the railway line or transfer nodes connected to them should be increased to give full play to the coal transportation advantages of these two railway lines.

2) TANGSHAN PORT HAS EXCELLENT POTENTIAL FOR THE CMTS

The railway-water multimodal transportation of northern coal should be transported to Tangshan Port as much as possible. This result suggests strengthening the construction of the railway line connecting with Tangshan Port and giving full play to the coal transfer capacity of Tangshan Port.

3) BUILDING NEW COAL TERMINALS OR TRANSFERRING SOME COAL ADJACENT TO NINGBO AND GUANGZHOU PORTS

The berth utilization rate of Ningbo and Guangzhou coal terminals is relatively high, and the loading and unloading capacity is close to saturation. The two regions (Zhejiang and Guangdong Province) where Ningbo and Guangzhou are located account for a large proportion of coal demand. With the further growth of coal demand in the future, consideration should be given to building new coal terminals or transferring some coal to adjacent ports for loading and unloading to alleviate the current terminal pressure.

VI. CONCLUSION

A. CONCLUSIONS ON CMTS MODELING AND SIMULATION

We draw the following conclusions based on the CMTS multiagent model constructed in this paper and the example simulation test of north coal shipped to the south transportation on the Witness platform, combined with section V (Discussion).

Firstly, the agent-based modeling method is suitable for CMTS modeling. The constructed CMTS multiagent model is sound through the example simulation test on the Witness platform.

Secondly, the model can realize multiagent adjustment and configuration and automatically select the multimodal transportation route.

Thirdly, based on different research goals and the needs of solving problems, a multiagent model of the multimodal transport system can be efficiently built. The model has a wide range of application scenarios.

B. THE MAJOR CONTRIBUTIONS OF THIS PAPER

As the environment changes (such as increasing demand), many problems need to be solved urgently in the operation of CMTS, such as the identification of system bottlenecks and utilization and development of resources (such as the transfer capacity of nodes and lines in the transportation). This paper conducts research around these issues, and the study's main contributions are stated as follows.

First, by analyzing the mapping relationship between CMTS and multiagent systems, we confirm the applicability of multiagent modeling in CMTS and use the agent-based modeling method to propose a CMTS multiagent modeling process.

Second, by constructing the hierarchical model of CMTS, multiagent classification and function definition are realized. The communication mechanism between agents is created to complete the interaction model of CMTS multiagents.

Next, Witness software is used to simulate the case model of northern coal shipped to the south, and the test results verify the rationality and versatility of the CMTS multiagent model.

Finally, based on discussing the characteristics and applications of the multiagent model, we design a simulation experiment and analyze the transfer capacity of the multimodal node and the passage of the railway line by changing the growth rate of coal demand and according to the output results and statistical indicators of the simulation experiment. The system's bottleneck is identified, and suggestions for route planning and node development in CMTS operation are put forward.

C. THE INNOVATION OF THE THESIS

In this paper, based on analyzing the structure, characteristics, and links of CMTS, we use the multiagent theory to abstract the nodes participating in intermodal transportation into multiple interrelated agents with autonomous capabilities. The process of multimodal transport is realized through interaction between them, and then a multiagent-based coal multimodal transport model is constructed.

The innovations of this paper are as follows.

First, a method of applying multiagent theory to CMTS for modeling is proposed, the development process of the multiagent model of CMTS is designed, the function encapsulation of the agent is realized, and a multiagent-based model is constructed.

Second, an example simulation test on the Witness simulation software platform is designed. Based on the simulation output results, the transportation network throughput capacity is analyzed, the system bottleneck is identified, and suggestions are put forward to improve CMTS operational performance.

Third, we built a module library comprising multiagent models for multimodal transport systems to be portable.

The simulation model combining multiagent theory and CMTS provides a new research method for multimodal coal transport. When analyzing system problems at different levels, it is possible to quickly build a coal multimodal transport model by changing the combination of agents to achieve a quantitative system performance analysis. This work has important practical significance for analyzing the network structure and action mechanism of coal multimodal transport and provides specific theoretical meaning and engineering value.

ACKNOWLEDGMENT

This article comes from the Critical Laboratory Construction Project of the Ministry of Communications, "Research and Development of Multimodal Transport and Logistics Hub Simulation Model Library." The research group has a profound background in simulation modeling research on coal terminals and multimodal transport projects and is good at finding system bottlenecks and researching system optimization strategies.

REFERENCES

[1] F. Zhu, Y. Yao, W. Tang, and D. Chen, "A high performance framework for modeling and simulation of large-scale complex systems," *Future Gener. Comput. Syst.*, vol. 51, pp. 132–141, Oct. 2015.

[2] A. Alrabghi and A. Tiwari, "A novel approach for modelling complex maintenance systems using discrete event simulation," *Rel. Eng. Syst. Saf.*, vol. 154, pp. 160–170, Oct. 2016.

[3] F. Zhu, Y. Yao, W. Tang, and J. Tang, "A hierarchical composite framework of parallel discrete event simulation for modelling complex adaptive systems," *Simul. Model. Pract. Theory*, vol. 77, pp. 141–156, Sep. 2017.

[4] T. M. Anderson and S. Dragićević, "Network-agent based model for simulating the dynamic spatial network structure of complex ecological systems," *Ecol. Model.*, vol. 389, pp. 19–32, Dec. 2018.

[5] M. Antal, C. Pop, T. Petrican, A. V. Vesa, T. Cioara, I. Anghel, I. Salomie, and E. Niewiadomska-Szynkiewicz, "MoSiCS: Modeling, simulation and optimization of complex systems—A case study on energy efficient datacenters," *Simul. Model. Pract. Theory*, vol. 93, pp. 21–41, May 2019.

[6] J. Jalving, Y. Cao, and V. M. Zavala, "Graph-based modeling and simulation of complex systems," *Comput. Chem. Eng.*, vol. 125, pp. 134–154, Jun. 2019.

[7] S. Xiong, F. Zhu, Y. Yao, W. Tang, and Y. Xiao, "Service-oriented model encapsulation and selection method for complex system simulation based on cloud architecture," *Entropy*, vol. 21, no. 9, p. 891, Sep. 2019.

[8] M. C. Davis, H. P. N. Hughes, A. McKay, M. A. Robinson, and C. N. van der Wal, ''Ergonomists as designers: Computational modelling and simulation of complex socio-technical systems,'' *Ergonomics*, vol. 63, no. 8, pp. 938–951, Aug. 2020.

[9] K. U. S. Somarathna, ''An agent-based approach for modeling and simulation of human resource management as a complex system: Management strategy evaluation,'' *Simul. Model. Pract. Theory*, vol. 104, Nov. 2020, Art. no. 102118.

[10] S. Spolaor, M. S. Nobile, G. Mauri, P. Cazzaniga, and D. Besozzi, ''Coupling mechanistic approaches and fuzzy logic to model and simulate complex systems,'' *IEEE Trans. Fuzzy Syst.*, vol. 28, no. 8, pp. 1748–1759, Aug. 2020.

[11] Z. Sun, L. H. Lee, E. P. Chew, and K. C. Tan, ''MicroPort: A general simulation platform for seaport container terminals,'' *Adv. Eng. Informat.*, vol. 26, no. 1, pp. 80–89, Jan. 2012.

[12] X. F. Yin, L. P. Khoo, and C.-H. Chen, ''A distributed agent system for port planning and scheduling,'' *Adv. Eng. Informat.*, vol. 25, no. 3, pp. 403–412, Aug. 2011.

[13] M. N. Abourraja, M. Oudani, M. Y. Samiri, D. Boudebous, A. El Fazziki, M. Najib, A. Bouain, and N. Rouky, ''A multi-agent based simulation model for rail–rail transshipment: An engineering approach for gantry crane scheduling,'' *IEEE Access*, vol. 5, pp. 13142–13156, 2017.

[14] L. Henesey, ''Multi-agent systems for container terminal management,'' Ph.D. dissertation, Blekinge Inst. Technol., Karlskrona, Sweden, 2006.

[15] D. Foguelman, P. Henning, A. Uhrmacher, and R. Castro, ''EB-DEVS: A formal framework for modeling and simulation of emergent behavior in dynamic complex systems,'' *J. Comput. Sci.*, vol. 53, Jul. 2021, Art. no. 101387.

[16] F. Y. Xu, X. Wang, L. L. Lai, and C. S. Lai, ''Agent-based modeling and neural network for residential customer demand response,'' in *Proc. IEEE Int. Conf. Syst., Man, Cybern.*, Oct. 2013, pp. 1312–1316.

[17] Y. Qu, T. Bektaş, and J. Bennell, ''Sustainability SI: Multimode multicommodity network design model for intermodal freight transportation with transfer and emission costs,'' *Netw. Spatial Econ.*, vol. 16, no. 1, pp. 303–329, Mar. 2016.

[18] F. Corman, F. Viti, and R. R. Negenborn, ''Equilibrium models in multimodal container transport systems,'' *Flexible Services Manuf. J.*, vol. 29, no. 1, pp. 125–153, Mar. 2017.

[19] A. Ensor and F. Lillo, ''Colored-edge graph approach for the modeling of multimodal transportation systems,'' *Asia–Pacific J. Oper. Res.*, vol. 33, no. 1, Feb. 2016, Art. no. 1650005.

[20] D. Inghels, W. Dullaert, and D. Vigo, ''A service network design model for multimodal municipal solid waste transport,'' *Eur. J. Oper. Res.*, vol. 254, no. 1, pp. 68–79, Oct. 2016.

[21] W. Tian and C. Cao, ''A generalized interval fuzzy mixed integer programming model for a multimodal transportation problem under uncertainty,'' *Eng. Optim.*, vol. 49, no. 3, pp. 481–498, Mar. 2017.

[22] X. Yang, X. Ban, and J. Mitchell, ''Modeling multimodal transportation network emergency evacuation considering evacuees' cooperative behavior,'' *Transp. Res. A, Policy Pract.*, vol. 114, pp. 380–397, Aug. 2018.

[23] W. Zhu, C. Gao, X. Zhang, and D. Li, ''Multimodal transport cost model bases on dynamic alliances,'' *J. Coastal Res.*, vol. 98, p. 414, Dec. 2019.

[24] H. Li and L. Su, ''Multimodal transport path optimization model and algorithm considering carbon emission multitask,'' *J. Supercomput.*, vol. 76, no. 12, pp. 9355–9373, Dec. 2020.

[25] C. Qu, Q. Zeng, K. X. Li, and K.-C. Lin, ''Modeling incentive strategies for landside integration in multimodal transport chains,'' *Transp. Res. A, Policy Pract.*, vol. 137, pp. 47–64, Jul. 2020.

[26] Q.-Z. Wang, J.-M. Chen, M.-L. Tseng, H.-M. Luan, and M. H. Ali, ''Modelling green multimodal transport route performance with witness simulation software,'' *J. Cleaner Prod.*, vol. 248, Mar. 2020, Art. no. 119245.

[27] J. Azucena, B. Alkhaleel, H. Liao, and H. Nachtmann, ''Hybrid simulation to support interdependence modeling of a multimodal transportation network,'' *Simul. Model. Pract. Theory*, vol. 107, Feb. 2021, Art. no. 102237.

[28] W. Zhu, H. Wang, and X. Zhang, ''Synergy evaluation model of container multimodal transport based on BP neural network,'' *Neural Comput. Appl.*, vol. 33, no. 9, pp. 4087–4095, May 2021.

[29] N. Koohathongsumrit and W. Meethom, ''An integrated approach of fuzzy risk assessment model and data envelopment analysis for route selection in multimodal transportation networks,'' *Expert Syst. Appl.*, vol. 171, Jun. 2021, Art. no. 114342.

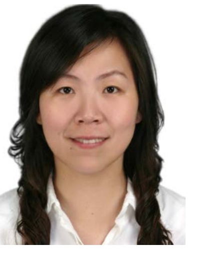
[30] V. Reis, ''Analysis of mode choice variables in short-distance intermodal freight transport using an agent-based model,'' *Transp. Res. A, Policy Pract.*, vol. 61, pp. 100–120, Mar. 2014.

[31] N. Monteiro, R. Rossetti, P. Campos, and Z. Kokkinogenis, ''A framework for a multimodal transportation network: An agent-based model approach,'' *Transp. Res. Proc.*, vol. 4, pp. 213–227, Jan. 2014.

[32] J.-B. Soyez, G. Morvan, R. Merzouki, and D. Dupont, ''Multilevel agent-based modeling of system of systems,'' *IEEE Syst. J.*, vol. 11, no. 4, pp. 2084–2095, Dec. 2017.

[33] G. K. Soon, C. K. On, P. Anthony, and A. R. Hamdan, ''A review on agent communication language,'' in *Computational Science and Technology*. Singapore: Springer,2019, pp. 481–491.

[34] R. Cervenka and I. Trencansky, ''Survey on agent-oriented modeling languages,'' in *The Agent Modeling Language—AML: A Comprehensive Approach to Modeling Multi-Agent Systems*. Basel, Switzerland: Springer, 2007, ch. 2, sec. 7, pp. 33–34.



YAN YANG (Member, IEEE) received the master's degree in engineering from the Wuhan University of Technology, in 2009, where she is currently pursuing the Ph.D. degree in transportation engineering. She has been teaching with the Changzhou Institute of Technology, since 2009. Her research interests include logistics transportation and supply chain management.

QIANG ZHOU received the Ph.D. degree in engineering from the Wuhan University of Technology, in 2002. Currently, he is a Professor and a Doctoral Supervisor with the School of Transportation and Logistics Engineering, Wuhan University of Technology. His research interests include production logistics system planning and modeling, simulation analysis of complex logistics transportation systems, and application and research of port logistics system digital twin technology.

KE CHEN (Member, IEEE) received the master's degree in engineering from the Wuhan University of Technology, in 2018. She is a Planning Engineer at Wuhan Accelink Technologies Company Ltd. Her research interests include production and transportation planning.