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Container Terminal Oriented Logistics Generalized Computational Complexity

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ABSTRACT The planning and scheduling of container terminal logistics systems (CTLS) are the multi-objective and multiple strong constraints combinatorial optimization challenges under the uncertain environments, and those are provided with high goal orientation, dynamics, context-sensitivity, coupling, timeliness, and complexity. The increasingly sophisticated decision-making for CTLS is one of the most pressing problems for the programming and optimization method available. This paper discusses CTLS in terms of logistics generalized computation complexity based on computational thinking, great principles of computing, and computational lens, which three are abbreviated with 3CTGPL, and makes a definition of container terminal oriented logistics generalized computational complexity (CTO-LGCC) and container terminal logistics generalized computation comprehensive performance perspective (CTL-GCCPP) from the dimensions of time, space, communication, processor, and memory access. Both can analyze, generalize, migrate, translate, localize, modificate, and evaluate the above-complicated problems and lay solid foundations and establish a feedback improvement framework for the computational model and scheduling algorithms of the CTLS, which is an essential complement to the modeling and optimization methodology and solutions to CTLS with computational logistics. Finally, aimed at the logistics service cases for a large-scale container terminal, the simulation is designed and implemented for different scheduling algorithms, and the qualitative and quantitative comprehensive analysis is executed for the concomitant CTO-LGCC that demonstrates and verifies the feasibility and credibility of the CTO-LGCC and CTL-GCCPP from the viewpoint of the practice of container terminal decision-making support on the tactical level.

INDEX TERMS Logistics, scheduling, freight containers, computational modeling, computational complexity, decision making, numerical simulation, computational logistics, logistics generalized computation for container terminal.

I. INTRODUCTION

Container terminals are the core multimodal transportation hub nodes of the global supply chain network, and container terminal logistics systems (CTLS) are the logistics storing, routing and forwarding engines of the above logistics network. CTLS are the most representative example of complex logistics systems (CLS), and are the discrete event dynamic systems (DEDS) and distributed control systems (DCS) in dynamic and uncertainty circumstances as well. The characteristics of high nonlinearity, timeliness, uniqueness, coupling and complexity (NTUCC) on CTLS trigger a series of scheduling and decision problems directly. So, the job planning, task scheduling and resource allocation (JPTSRA) at container terminals have been the one of the most important research directions in the operation science, control theory, simulating optimization etc. [1]–[3].

The JPTSRA in CTLS must give full play to the operational potentials of the existing infrastructures and facilities cluster, and balance the interests of all parties in the alliance of harbor and shipping as well, under strict constraints and service contracts, and while satisfy the precondition of the production

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safety and green marketing. The current available research methods, such as operational programming, intelligent optimization and system simulation, have some inherent flaws. At the same time, the peculiarity of NTUCC become increasingly prominent than ever. Thereupon, we try to propose a new theoretical framework to explore, estimate and evaluate (3E) the container terminal oriented logistics generalized computational complexity (CTO-LGCC) with computational logistics, which can be regarded as a 3E compound compass of complex logistics service optimization (3ECC-CLSO).

Accordingly, the remainder of this paper is organized as follows. Relevant literature and our previous work are reviewed and summarized in Section 2. The container terminals oriented logistics computation generalization and unification are made a definition to establish a basis to the further discussion in Section 3. Section 4 presents the definition of CTO-LGCC and makes an analysis of its each subitem, subsequently the container terminal logistics generalized computation comprehensive performance perspective (CTL-GCCPP) with CTO-LGCC is proposed pertinently. A typical tactical job scheduling and resource allocation strategy is described and designed to illustrate the CTO-LGCC in Section 5. Computational experiments are conducted in Section 6 to demonstrate the application of CTO-LGCC and CTL-GCCPP, and then evaluate the feasibility, availability and effectiveness of the proposed scheduling algorithms. Conclusions and future research are given in the last section.

II. LITERATURE REVIEW AND OUR WORKS

A. SYSTEMATIC LITERATURE REVIEW

The positioning, mapping, transferring, routing, accessing and switching (PMTRAS) of container logistics unit construct the main themes and key issues of the logistics service at container terminals. The PMTRAS is discussed to focus on the working space and the handling and transferring equipment resources. The former mainly includes shipping accommodation, quayside berth and yard slot. The latter is primarily concerned with quay crane (QC), yard crane (YC) and internal yard trailer (IYT), container reach stacker (CRS), empty container fork lift (ECFL). Nevertheless, the planning and scheduling of the above any resource is of nondeterministic polynomial hard (NPH), and the joint planning and collaborative scheduling of them are even the more so.

A lot of work has been launched to probe into the JPTSRA of the foregoing space and facility, and some scholars have conducted a retrospective study on these key issues [4]–[10]. Some typical works, study characteristics and research trends can be summarized as follows.

1) SINGLE WORKING SPACE RESOURCE ALLOTMENT

The single working space resource allotment is the most discussed on CTLS because container terminals are nothing else than the warehousing hubs in the final analysis. Above all, the quayside berth is the most precious resources of container terminals, and the quayside is also the operational center of CTLS. Wang etc. solved discrete dynamic berth allocation problem by proposing a new meta-heuristic, which combined the nature-inspired Levy Flight random walk with local search, while considering tidal windows [11]. Ji etc. transformed the constrained single-objective continuous berth allocation problem (BAPC) model into unconstrained multiobjective BAPC model by converting the constraint violation as another objective, and the modified non-dominated sorting genetic algorithm was put forward to optimize the model [12]. Dulebenets proposed a novel evolutionary algorithm to assist with berth scheduling at marine container terminals, which applied a parameter control strategy and an adaptive mechanism with feedback [13]. Correcher etc. presented both a mixed integer linear programming formulation and a heuristic, which obtained optimal or near-optimal solutions to complex layouts of real terminals [14]. Dulebenets etc. also extended an existing berth allocation policy, where demands were diverted from a multi-user maritime container terminal to an external maritime container terminal at an additional cost [15].

In the next place, the JPTSRA of storage yard is the most complicated piece in the operation because the import, export containers and containers for transshipment all must be processed simultaneously. Moreover, the dynamic random uncertain elements are more abundant in storage yard than the working of quayside. The port yard storage optimization problem is akin to a packing problem in space and time, but where shapes packed and constraints are particular to port operations [16]. Alcalde etc. presented a method for forecasting the yard inventory of container terminals over an extended period, and addressed an integrated yard planning problem for determining the optimal storage space utilization by considering the yard congestion effect on terminal performance [17]. Boysen etc. treated and formalized an elementary optimization problem that was the parallel stack loading problem to intermediately store items without blocking, and the basic complexity proofs were provided [18]. A mixed storage strategy was proposed by Zeng etc. to improve the efficiency of yard operations, and the effects of the strategy on terminal operations were analyzed [19]. Zhen and Tan presented the multi-period yard template and a flexible yard template planning respectively [20], [21]. Boywitz introduced a new way to derive robust storage assignments, such that excessive retrieval effort was avoided despite due date uncertainty [22].

Finally, the central working objects of CTLS is the bay set in the shipping accommodation. Tierney etc. defined the hatch overstow problem to examine the complexity of the current state-of-the-art abstraction of container ship stowage planning problem (SSPP), and showed that this problem was NP-complete by a reduction from the set-covering problem, which meant that even abstract formulation of container ship stowage planning is intractable [23]. Zhang etc. investigated a multiobjective SSPP, which aimed to optimize the ship stability and the number of rehandles simultaneously [24]. Lee etc. come up with random sample model (RSM) and sequential sample model (SSM) for the analysis of SSPP, and showed how to achieve the optimal constraint ordering with respect to RSM and SSM respectively [25]. Monaco etc. addressed SSPP considering the objectives of the terminal management that were mainly related to the yard and transport operations [26]. Li etc. formulated the multi-port stowage planning problem for inland container liner shipping that hedged against container weight uncertainties, and three solution approaches were presented and compared for the large-scale experiments [27].

2) SINGLE FACILITY ASSIGNMENT AND SCHEDULING

The operation of CTLS are mainly involved with the multifarious facilities and equipments, however, the QC and YC both play a primordial role no matter what kind of handling technique is adopted. Naturally, the quay crane assignment and scheduling problem (QCASP), the yard crane scheduling problem (YCSP) are also the most-discussed topics.

For one thing, the QC is the most important key equipment of the whole CTLS, and it is the main facility for the quayside berth and the shipping accommodation. The recent studies are becoming increasingly interested in applying the practical working constraints into the QCAS. Chen etc. discussed the computational complexity of the unidirectional quay crane scheduling problem (QCSP), and a tighter mathematical formulation was studied [28]. Tang etc. described a new mathematical formulation for the QCSP and by addressing the structure of workload assignments that they developed an easier way to handle non-crossing constraints [29]. Chang etc. focused on the container loading and unloading problem with dynamic ship arrival times and proposed a scheduling method for quay cranes that was used for multiple vessels in a container terminal, based on a dynamic rolling-horizon strategy [30]. Zhang etc. extended the QCSP by taking into consideration the stability constraints, and a bicriteria evolutionary algorithm was raised to solve the problem [31]. Msakni etc. brought forward two exact methods to solve the QCSP where a task was defined as handling a single container and subject to different technical and practical constraints [32].

Moreover, the quay crane assignment and scheduling both are increasingly considered simultaneously. A formulation was developed for the QCASP, which accounted for crane positioning conditions and a genetic algorithm (GA) was developed to solve the QCASP by Diabat and Theodorou [33]. A Lagrangian relaxation was put forward by Fu etc. for the mathematical formulation in which practical considerations were incorporated in the model for the QCASP [34]. The number and the task dispatch of quay cranes were coupled, and a coupling model for the QCASP was proposed by Liang *et al.* [35]. Those make the models and algorithms to be practical.

For another, the YC is the most core operating equipment in the function of storage yard. He etc. addressed a YCSP with uncertainty of the task groups' arriving times and handling volumes, and a GA-based framework combined with three-stage algorithm was proposed to solve the problem [36]. Zheng etc. investigated two YC scheduling with storage and retrieval tasks in a container block, focused on minimizing the maximum tardiness of container task and establishing an integer linear programming model [37]. Galle etc. introduced a novel optimization problem resulting from the combination of two major existing problems arising at storage yards in container terminals that are YCSP and container relocation problem, and formulated this problem as an integer program which was solved by a heuristic local search scheme [38]. Kress etc. considered a scheduling problem for two gantry cranes moving on the same rails at a single storage block to minimize the makespan of seaside container processing while guaranteeing on-time processing of landside containers and considering non-crossing constraints among cranes [39].

3) COLLABORATIVE ALLOCATION OF MULTIPLE WORKING SPACES

As previously mentioned, the joint planning of berth and yard allocation is a special focus currently. A joint planning problem for berth and yard allocation in transshipment terminals was addressed by Tao etc., and a multi-cluster stacking strategy was presented to split each transshipment flow into a number of container clusters and then stack each cluster in different yard blocks [40]. A schedule template design problem was considered simultaneously with another two tactical level decision problems that are berth template design and yard template design, and this highly integrated problem was formulated as a set covering model by Jin *et al.* [41]. Liu etc. investigated the joint optimization of the tactical berth allocation and the tactical yard assignment at seaports, and proposed a comprehensive bi-objective mathematical model [42]. Ma etc. studied an integrated berth allocation and yard planning problem with discontinuities berth layout, and a novel multi-continuous berth layout approach and a mixed integer linear programming were proposed to deal with this new problem [43].

4) JOINT SCHEDULING OF MULTIPLE FACILITIES

As we noted earlier, the QC, YC and IYT three are the most important and critical equipments at container terminals. The collaborative scheduling between the two or among the three are the key focus of related research by the light of nature. Ji etc. established a mathematical model to integrate the loading sequence and the rehandling strategy considering stowage plan for ships and yards, and an improved genetic algorithm, the lower-bound and t-test for multi-quay crane operations were discussed [44]. A mixed-integer programming model was formulated for an integrated optimization problem on quay crane and yard truck scheduling by Zhen *et al.* [45]. Vahdani etc. also aimed to integrate the assignment of quay cranes in container terminals and internal truck sharing assignment among them, and a bi-objective optimization model was developed [46].

5) INTEGRATED SCHEDULING OF SPACES AND FACILTIES

As the operation of CTLS is not only involved with the working space, but also tied to the logistics equipments, some research is launched to the integrated scheduling of spaces and facilities. Karam etc. presented a new functional integration approach for the following problems: berth allocation, quay crane assignment and specific quay crane assignment [47]. Salhi etc. also put forward an integrated optimization model that combined the above three distinct problems, and an implementation of the genetic algorithm was considered [48]. Niue etc. focused on and integrate two scheduling problems in container terminal: yard truck scheduling problem and storage allocation problem (YTS–SAP), and a swarm intelligence technique was developed for problem solution [49]. In addition, the vehicle dispatching was integrated with yard crane scheduling and storage selection, and a three tree-based adaptive searching approaches were put forward [50].

As can be seen from the above literatures, whether the single resource allocation or the multistage integrated scheduling for CTLS both were the thorny problem of NP-Complete. Furthermore, the JPTSRA of CTLS is provided with the high NTUCC. All make the decision at container terminals to be especially tricky, and it is urgent to find a new method to meet the challenge. Within the conceptual framework of computational logistics, the top priority is to define 3ECC-CLSO to establish the evaluation reference frame and guide decision optimization at container terminals.

B. COMPUTATIONAL LOGISTICS ORIGINATED FROM CONTAINER TERMINAL LOGISTICS SYSTEMS

Just saying this, the existing research methods for CTLS are mainly operational programming, system simulation, intelligent optimization and simulation-based optimization. It is considered that the essence and connotation of the above approaches and the logistics process at container terminals both can be identical and unified, which is exactly computation according to computational thinking.

So we proposed a definition of computational logistics within the conceptual framework of computational thinking preliminarily on the IEEE 54th Annual Conference on Decision and Control (CDC 2015) in December 2015 [51], and then elaborated the logistics generalized computation for container terminals (LGC-CT) which was a core concept in the following discussion, and its planning, scheduling, control and decision based on computational logistics [52]–[54]. Furthermore, we have launched the empirical research on the typical large-scale container terminal in China with computational logistics [55]. Computational logistics provides a new abstract perspective and quantitative approach to study the logistics operations scheduling and decision-making purposefully from the visual angle of the generalization, unification, integration and fusion of computation (GUIF-C). GUIF-C is a multidisciplinary, interdisciplinary and crossdisciplinary mode of thinking, and it is significantly different from the traditional operations research solutions as well.

The definition of computational logistics is based on the work accumulation of our research group for container terminals since 2006 [56], which is the typical representatives of complex logistics hubs. The ideological roots and theoretical basis come mainly from computational thinking, great principles of computing, and computational lens, which are abbreviated with 3CTGPL in the following. 3CTGPL contains abundant basic ideas, ultimate fountains, realization principles, execution mechanisms and assessment measures of computer science and engineering. 3CTGPL are proposed and advocated respectively by four eminent scholars, which are Papert [57], Wing [58], Denning [59] and Karp [60]. The interrelation between computational logistics and 3CTGPL can be demonstrated by Fig.1 concisely.

3CTGPL not only provides the ideologies of computational logistics, but also supply the adequate provisions, nutrition and materials that are just the computing principles. By combining the above ideologies and principles, we can acquire the computational lens for CLS to make abstraction, automation and analysis, which is called after 3A for short. As a matter of fact, the three of computational thinking, great principles of computing, and computational lens construct an ideology-principle-instrument evolutive and adaptive theory and practice framework. All are supposed to establish the problem-oriented 3A exploration architecture for CLS. The problem-oriented exploration is also a typical characteristic of computational logistics, which is just derived from computational thinking. Essentially, 3ECC-CLSO is an important and specific application for CTLS within the conceptual framework of 3CTGPL.

In fact, some previous research has conducted a discussion on logistics service at container terminals based on the fundamentals and principles of computational science and control engineering. For example, a dynamic discrete-time model of container flows in maritime terminals was proposed as a system of queues, and two feedback control strategies for the allocation of the available resources were described by Alessandri *et al.* [61], [62]. Moreover, predictive control was also investigated as a paradigm for the allocation of handling resources to transfer containers inside intermodal terminals by Alessandri *et al.* [63]. In addition, the Petri Net models and multi-agent system (MAS) both were also applied to container terminals decision problems too [64]–[66]. These works have played a good role in exploring the introduction of 3CTGPL in container terminal logistics service scheduling and decision-making and laid an initial foundation for the definition and application of computational logistics.

Properly speaking, the nature of the works are just about the application and practice of computational logistics, which only do not put forward the concept of computational logistics explicitly. However, it is very these works that illustrate the connotation and practice of computational logistics from scratch. Computational logistics is not just the direct application of information technology for CLS [67],

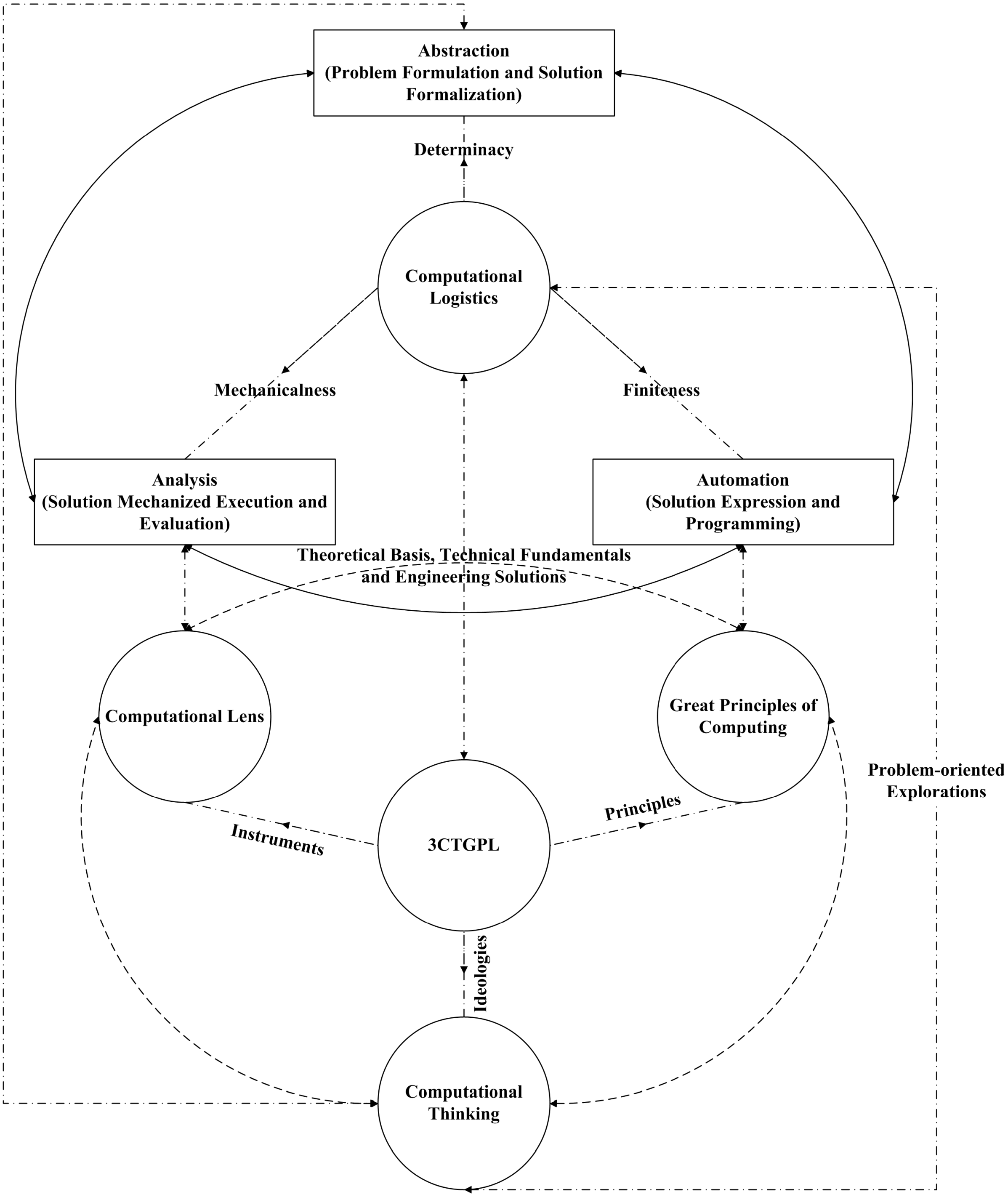

FIGURE 1. Computational logistics and 3CTGPL.

but is the generalization, migration, localization and modification (GMLM) of thinking, principle, framework, mechanism, strategy and algorithm in computational science. Furthermore, computational logistics is not a castle in the air because the above quintessence has been fully discussed and demonstrated whether in theory or in practice. What we need to do is designing and implementing the GMLM of these paradigms in logistics service scenarios, dimensionality, and problem spaces. As a typical representative of complex logistics system, now we focus on the application of computational logistics to CTLS. The 3ECC-CLSO is an important foundation work for the demonstration and discussion of CTLS with computational logistics.

III. CONTAINER TERMINALS ORIENTED LOGISTICS COMPUTATION GENERALIZATION AND UNIFICATION

In our previous studies, the concept of computation has been extended and developed from information space to physical world based on the nature of computation in the light of CTLS [68]. The traditional theory of computation must be also carried out the expansion and extension for cyber-physical systems (CPS), especially for CTLS. In this section, we are going to explore the container terminals oriented logistics computation generalization and unification in detail, and it is supposed to establish the most fundamental basis for the discussion of CTO-LGCC.

A. ABSTRACTION AND GENERALIZATION OF COMPUTED OBJECTS

The abstraction and generalization of job objects bears the brunt of the above theoretical foundation. A range of container shipping standards, which have been developed for many years, lay a solid foundation for the container terminals oriented computational generalization. The transferring and switching container set between a given terminal to a designated vessel including the loading and unloading containers are considered as a three-dimensional generalized symbol string (GSS) with the multiple key attributes in the physical world. The primary general character in GSS can be defined and enumerated as follows. Those are the most basic processing element for LGC-CT.

The volume of international container transportation and throughput is usually measured by twenty-foot equivalent unit (TEU). Therefore, the container with the specification of TEU for general purpose can be regarded as the generalized symbol ’A’ during the process of container logistics services which occurs in the physical world. By analogy, we may enumerate the other generalized symbols in the container logistics service from the prospective of dimensions and purposes which both are the most important attributes of the generalized symbol, and those are listed as Table 1.

TABLE 1. Generalized symbol table for CTLS.

Symbol	Dimensions	Purposes
A	standardized twenty-foot equivalent unit	dry container
B	standardized twenty-foot equivalent unit	refrigerated container
C	standardized twenty-foot equivalent unit	dress hanger container
D	standardized twenty-foot equivalent unit	open top container
E	standardized twenty-foot equivalent unit	flat rack container
F	standardized twenty-foot equivalent unit	tank container
G	standardized forty-foot equivalent unit	dry container
H	standardized forty-foot equivalent unit	refrigerated container
I	standardized forty-foot equivalent unit	dress hanger container
J	standardized forty-foot equivalent unit	open top container
K	standardized forty-foot equivalent unit	flat rack container
L	standardized forty-foot equivalent unit	tank container
M	forty-foot equivalent unit high cube	dry container
N	forty-foot equivalent unit high cube	refrigerated container
O	forty-foot equivalent unit high cube	dress hanger container
P	forty-foot equivalent unit high cube	open top container
Q	forty-foot equivalent unit high cube	flat rack container
R	forty-foot equivalent unit high cube	tank container
S	standardized forty five-foot equivalent unit	dry container
T	standardized forty five-foot equivalent unit	refrigerated container
U	standardized forty five-foot equivalent unit	dress hanger container
V	standardized forty five-foot equivalent unit	open top container
W	standardized forty five-foot equivalent unit	flat rack container
X	standardized forty five-foot equivalent unit	tank container
Y	forty five-foot equivalent unit high cube	dry container
Z	forty five-foot equivalent unit high cube	refrigerated container
α	forty five-foot equivalent unit high cube	dress hanger container
β	forty five-foot equivalent unit high cube	open top container
γ	forty five-foot equivalent unit high cube	flat rack container
ε	forty five-foot equivalent unit high cube	tank container
ζ	non-standard	non-dangerous goods
H	non-standard	hazardous articles

The above 32 generalized symbols stand for the three-dimensional physical computed objects in CTLS, which encapsulates the vast majority of service targets. The generalized symbols that point to the multifarious containers have a sequence of key attributes that exert great influences on the executive process of LGC-CT, and those are also the important root and cause for the strong NTUCC on CTLS.

To be specific, the physical properties in the physical world of generalized symbols, which are not provided with by the coded character sequence in computers systems, can better reflect, discuss and probe into the nature of computation from a broader perspective and the higher dimensional problem space. Thus, some core attributes and their direct influences are listed concisely in Table 2.

The core attributes are embodied in a range of intercoupling decision variables, constraint conditions and objective functions, and have a great direct, indirect and coupled impact and chain reactions on the LGC-CT. Those bring great difficulties to the JPTSRA of CTLS, especially for the parallel control, heterogeneous cooperative and reconfigurable scheduling at container terminals.

TABLE 2. **Generalized symbol core attributes.**

Central Attribute Name	Attribute Value
Physical Dimensions	1. External Length 2. External Width 3. External Height 4. Is it flat rack container
Handling Specifications	1. Tare Weight 2. Max Gross Weight 3. Max Payload 4. Full/Empty
Logistics	1. Import/Export/ Transshipment 2. Loading Port 3. Unloading Port 4. Shipper 5. Freighter
Collection and Distribution Mode (Carrier)	1. Is it empty container reposition 2. Land/Water/Rail 3. Is it consolidating or devanning

B. INEVITABILITY OF TRADITIONAL COMPUTATIONAL COMPLEXITY EXTENSION

The central service targets of CTLS are the multifarious container ships, and those are the separated dynamic GSS buffer space essentially for the above generalized symbol set. From the operational perspective, container ships are the mobile, dynamic, stereoscopic, hierarchical, reconfigurable and structured GSS memory working spaces substantially. Meanwhile, container terminals are the stationary, stable, stereoscopic, hierarchical, reconfigurable and structured GSS memory working spaces. The PMTRAS of container function units between the liners and the terminals constitute the basic connotation and principle framework of LGC-CT. Thus, we obtain the intrinsic unification between LGC-CT and the classic computation from the visual angle of the nature of computation.

Nevertheless, in relation to traditional information computation, the targets of LGC-CT are the physical entity characters that have the more properties than the information characters, which have been enumerated in Table 2. This also leads to the differences of the working space and running rhythm between LGC-CT and information computation directly, and the differences introduce some new issues to help us to analyze, evaluate and explore the NTUCC as well. LGC-CT supplies the snapshot of computation in the specific scenario of container terminals

All indicate that CTO-LGCC is very similar to the classical computational complexity. However, CTO-LGCC also has its new intension, extension and expansion. Even some new computational complexity dimensionalities gradually emerge because the job objects and working space of CTLS have the more critical attributes apart from time and space. The additional key attributes are supposed to be embodied in the CTO-LGCC adequately. As a matter of fact, that makes us to get better acquainted with the causes of NTUCC and evaluate the performance of specific scheduling and decision architecture, framework, mechanism, strategy, algorithm and parameter (AFM-SAP) in the tactical level.

C. GENERALIZATION, MIGRATION, LOCALIZATION AND MODIFICATION OF COMPUTATIONAL COMPLEXITY THEORY

Through 3CTGPL, the operations of CTLS can be abstracted as the computation, storage and communication or an arbitrary combination of the three. Further from the perspective of LGC-CT abstraction framework, the running of CTLS are considered as the flexible decomposition, coupling and recombination of full-duplex heterogeneous and reconfigurable hybrid flow shop (FHR-HFS) and hierarchical memory cell allocation, defragmentation and recall (HMC-ADR). The combination of both constitute a multi-level, multi-stage, multi-buffer flexible LGC-CT job shop with multiple bounded blocking queues.

It is obvious that the JPTSRA of FHR-HFS and HMC-ADR both are the NPH problems. The classical computational complexity theory (CCCT) has proposed some useful and practical conclusions for people. One of them can be described as follows. The solution to a problem does not lie in the question itself, but in the change of the method. On the grounds of this point, we only revise the methodology for the JPTSRA of CTLS because the existing operational research, computer simulation, intelligent optimization and simulation-based optimization are all flawed in different degrees, especially in the aspect of the generality, robustness, agility, portability and extendibility (GRAPE), which is no other than the qualities expected by AFM-SAP for container terminals.

3CTGPL has provided a great principles framework and some philosophy fundamentals for the theory and solutions to computation, storage and communication. Those are maybe not the optimal solution, but it must be the high quality satisfactory one with the good quality of GRAPE. So, we introduce 3CTGPL to cope with NPH problem on the coupling of FHR-HFS and HMC-ADR, especially for CCCT. It is supposed to implement the GMLM of CCCT for CTLS to evaluate and guide the running of container terminals, and it is the very 3ECC-CLSO of CTLS. In fact, this is just the one of the starting points for defining computational logistics and tackling LGC-CT complexity.

IV. LOGISTICS GENERALIZED COMPUTATIONAL COMPLEXITY FOR CONTAINER TERMINALS

In the previous section, the definition of the relevant generalized character set and GSS is proposed clearly, and those have done a good foreshadowing. Now, we customize and revise the CTO-LGCC within the conceptual framework of computational logistics. Naturally, the connotation and content of CCCT are enriched and developed for CTLS. Obviously, the work is also GMLM of CCCT for the representative complex logistics hub.

Beyond all question, the bandwidth and processor are also the core resources except for time and space that both are the core dimensions in CCCT as well. The programming, allocation and control for the above four are the central focus of JPTSRA as well. From the perspective of computational logistics, CCCT can be applied in the conceptual framework of LGC-CT. That is not only the application of CCCT in operational programming in tactical level, but also the GMLM of CCCT in physical world. As a result, the notions of time, space, bandwidth, processor and their computational complexities for CTLS have some significant differences compared with the counterparts in the CCCT. The details are emphatically investigated as follows, which provides a comprehensive view of logistics generalized computing performance with the more efficiency dimensions.

A. LOGISTICS COMPUTATION TIME COMPLEXITY

In the field of computer science and engineering, the time complexity is the computational complexity that measures or estimates the time taken for running an algorithm. More specifically, the time complexity indicates the time required to perform a given algorithm for transforming the symbolic string [69]. Under the conceptual framework of LGC-CT, the time for symbolic string transformation has been given new meanings, which is called after logistics generalized computation time complexity (LGC-TC). Let's take the calling container ship for a certain terminal as an example to illustrate the LGC-TC. The container collection transferred between a terminal to a designated vessel including the loading and discharging containers are considered as a three-dimensional GSS. Thereupon, based on the above definition of the generalized symbols and strings, LGC-TC can be looked upon as the characteristic values of the turnround of given calling ship set in the physical world with a specific scheduling algorithm.

LGC-TC means that the characteristic values for the consumed time including the set-up time that is spent on the loading and unloading container collection attached to the given calling ship set achieving the container slot mapping, transformation and switching between ships' hold and storage yard by a specific scheduling algorithm. There is a basis and precondition for the discussion of LGC-TC that is the operation must meet the vessel stowage planning and storage space allocation one. Moreover, there are a lot of uncertain random dynamic factors in the operation of CTLS, so LGC-TC is a distribution function to a great extent. The key statistical indicators of LGC-TC are something that we're very concerned about.

The input parameters of the distribution function mainly include tide conditions, calling ship types, shipping schedule, real-time waiting ship queues, the amount and distribution of slots in vessels, loading and unloading volume, vessel stowage plan, berth layout, work load on quay side, berth allocation program, handling technology, stacking mode, device configuration, yard blocks distribution and storage space allocation planning, and so on. The definition of function is made according to the different operating AFM-SAP. In practice, the key statistical indicators are paid more attention to than the function, especially for carrier. Those largely reflect the service quality of the terminal.

How to define an appropriate function under the given environments is intended to obtain relatively low, controllable and steady LGC-TC. That is finding, designing, revising, implementing and tuning an AFM-SAP in nature. The definition and evaluation of LGC-TC is a very difficult thing, especially the continuous improvement the handling technology and stacking mode. However, it is essential to find the floor level and the worst case of LGC-TC to the specific AFM-SAP in the statistical sense. That is one of the central points for improving the logistics service efficiency of CTLS.

B. LOGISTICS COMPUTATION SPACE COMPLEXITY

In the domain of computer science and engineering, the space complexity of an algorithm or data structure is the maximum amount of space used at any one time, ignoring the space used by the input to the algorithm [69]. Space complexity of an algorithm is total space taken by the algorithm with respect to the input size.

Based on the computational logistics, we introduce the concept of space complexity into the evaluation and improvement of CTLS. According to the working characteristics and based on the specific scheduling algorithm, there are two implications in container terminal logistics generalized computation space complexity (LGC-SC) around the served objects from the different granularity, which are described below.

1) LOGISTICS COMPUTATION SPACE COMPLEXITY FOR VESSELS

Through the computational lens, the container ship is the very memory buffer register (MBR) in the global container shipping network. When a container ship calls a container terminal to achieve the loading and unloading import, export containers and container for transshipment, a receptacle is required by MBR to implement the cache feature. The receptacle is just about the quayside berth that is the fundamental foundation of implementing the GSS loading and switching in MBR.

Obviously, the receptacle must process the proper specifications for every calling vessel. The specifications define the position, length, width, depth and duration of the receptacle. The depth of a receptacle of is the first factor and core resources of the wharf apron, which has a direct impact on berth allocation decision. The position of a receptacle decides the initial position and end position. Consequently, both points determine the length of the receptacle, which usually includes the length of the ship and anchorage safe distances. The width of the receptacle is viewed as a direct index of QC configuration specifications as the QC must load and unload the outmost row containers. The specification of the receptacle is the logistics generalized computation space complexity for vessels (LGC-SCV), especially for the parameters of location, length and time span. Obviously, it is a clear determined array. To all appearances, LGC-SCV is closely related to the LGC-TC.

2) LOGISTICS COMPUTATION SPACE COMPLEXITY FOR CONTAINERS

From the operational level of granularity for containers transportation unit, the container collection transferred between a terminal to a designated liner including the loading and discharging containers are considered as a three-dimensional GSS, which is same with the definition in the LGC-TC. The planned and occupied slot collections on the ship hold and the storage yard respectively with the given prestowage plan and storage space allocation algorithm are abstracted as two virtual compact customized storage cell clusters (VCC-SCC). The specifications of VCC-SCC are no other than logistics generalized computation space complexity for containers (LGC-SCC).

Apparently, the coupling, constraints and complexity of container handling and transportation are much higher than the symbolic manipulating in computer systems. The contents of storage units in a computer's main memory can be accessed, extracted and stored exactly as often as is necessary. Most important of all, the access speed is independent of the location of the storage unit.

According to modeling and analysis of CTLS with computational logistics in our previous study, every calling container ship is regarded as an independent job. Once a container ship is moored to the appointed berth, it is going to be mapped as an independent process in container terminal operating systems (CTOS), which aims at indicating the given task.

Under the computational lens, the quay crane is the central processing unit (CPU) of CTLS, the berth and the MBR both constitute the cache of CPU. The cellular structure of container ship hold is just the data set structure of the cache. The data set structure can be abstracted as a five-dimensional heterogeneous memory array C (v, d, b, r, t), which denotes the slot collection attached to a given container ship. The meanings of the parameters are listed as follows.

v denotes which container ship is mooring berth to handle;

d indicates whether the slot is on the deck or under the deck;

b marks the number of bay in the ship's hold;

r indicates the row number in a particular bay on the ship;

t indicates the tier number in a particular bay on the ship;

Analogously, container terminal storage yard can be seen as the main memory of CTLS, and it may be abstracted as a five-dimensional heterogeneous memory array Y z, k, b, r, t as well, which represents all the slot collection on the storage yard. The meanings of the parameters are also listed as follows.

z denotes the yard zone attributes, such as import empty zone, export empty zone, import heavy zone, export heavy zone, dangerous goods container zone and so on.

k indicates the number of block on the yard;

b marks the number of bay in the block;

r indicates the row number in a particular bay in the block;

t indicates the tier number in a particular bay in the block;

Thereupon, container terminal logistics service is just the cell mapping and switching operation between the two multi-dimensional storage cell arrays essentially. It is obvious that the contents of the memory cell in the two multi-dimensional arrays can be accessed to store or fetch as required. However, the access speed is extremely relevant to storage location and types of containers whether in hold or on yard. Furthermore, the access operations are involved a series of associative instructions that are moving, shifting, relocation and handling and are executed by QC, YC, CRS and ECFL. The liner schedule, hull structure, yard layout, storage space allocation plan, ship stowage plan, collection and distribution sequences all have a great influence on the scheduling decision on the loading and unloading. In addition, it's worth mentioning that the above five dimensional vector definitions for ship hold and storage yard are only the abstraction bases and both can be further customized according to practical requirements.

3) HIERARCHICAL SPATIAL MEASUREMENTS

On the whole taking everything into consideration, LGC-SC is a function whose parameters embrace terminal layout, route planning, ship capacity assignment, short and medium workload, and the fitness of the function is the executive situations of the given liner schedule and the requirements for the collection and distribution for the specialized container unit set. Specifically speaking, the two subitems of LGC-SCV and LGC-SCC determine the fitness of the function together in a large part.

For one thing, LGC-SCV is just the quay side berth allocation plan for a certain calling vessel, which involves in four essential ingredients that are location, length, template window and facility profiles. LGC-SCV is supposed to respond to requests for berthing and guarantee the shipping schedule to be executed successfully.

For another, LGC-SCC is no other than the yard allocation plan for a certain calling vessel which includes key factors that are the blocks, bays, template window and facility profiles for full containers and empty ones respectively. LGC-SCC directly affects the turnaround of container ships, loading and unloading progress on wharf apron, stacking, marshaling, and relocation efficiency on storage yard, horizontal transferring route clash, and the collection and distribution period. Those are very important issues in theory and practice.

Similarly, how to define an appropriate function for the particular liners and terminals is intended to achieve agile, robust and controllable LGC-SC, LGC-SCV and LGC-SCC. That is searching and customizing resource allocation algorithm essentially. It is fundamental to acquire the floor level and the worst case of LGC-SCV or LGC-SCC to the specific AFM-SAP statistically. Both are crucial to improve the working performance of CTLS. Furthermore, the three of LGC-SCV, LGC-SCC and LGC-SC constitute hierarchical working spatial measurements for CTLS. So far, we have fulfilled the extension, expansion and evaluation of the traditional estimating dimensions in CCCT for CTLS.

C. LOGISTICS COMPUTATION COMMUNICATION COMPLEXITY

In the field of computer science and engineering, there are many communication models of distributed processing system (DPS), which are oriented to theoretical analysis or focused on engineering practice. The optimization goal of communication models is to reduce the total traffic of the system or the running time of the program communication. Consequently, within the above-mentioned conceptual framework of LGC-CT, logistics generalized computation communication complexity (LGC-CC) is defined as total horizontal transferring time of IYTs for a container ship loading and unloading operation with the yard trailer dispatching algorithm or path planning policy.

CTLS is typical DPS distinctly. Concretely, QCs, YCs, CRSs and ECHLs with the different specifications construct a container logistics parallel, heterogeneous and reconfigurable handling and switching network (PHR-HSN). Furthermore, PHR-HSN adopts the operating mechanisms for store and forward packet switching. The container is the very physical entity packet (PEP), and the relevant route and control information packet (RCP) is attached to PEP, and both form a generalized container data packet (CDP).

IYT is just the carrier of CDP in the PHR-HSN, and connects the distributed, parallel, heterogeneous and reconfigurable logistics computing units (LCU). In fact, IYT is the principal horizontal communication unit (HCU) to implement the loading, discharging, transferring, stacking, collection and distribution of CTLS.

The LCU among the PHR-HSN adopts the point-to-point messaging model, and apply the blocking and buffering mode. The inner yard trailer dispatching usually adopts the scheduling policy of static logistics service line or dynamic logistics service plane. Whether the IYT real-time scheduling and path planning is efficient, agile and robust or not will directly determine the effective release extent of logistics generalized computing capability and the level of traffic jams both in berths and yards.

The definition of LGC-CC is parallel to LGC-TC and LGC-SC, and then it is essential to find the floor level and the worst case of LGC-CC to the given AFM-SAP in the statistical sense. Moreover, for specific work loads, quay side and storage yard, based on the given IYT dispatching algorithm, we must obtain the upper and lower limits for queue length and waiting time of IYT under QC and YC in statistical significance, especially for the former. Consequently, the whole LGC-CC can be acquired.

D. LOGISTICS COMPUTATION PROCESSOR COMPLEXITY

The LGC-CT is launched and executed in the physical world, so the requirements, configuration, allotment and deployment of key LGC-CT resources for a container ship is one of the logistics computational complexity dimensions that need to be fully considered. In the FHR-HFS of LGC-CT, logistics generalized computation processor complexity (LGC-PC) for a specific algorithm is the weighted average of parallel processors dynamically configured at each job stage, especially in the case of multiple ships loading and unloading operations simultaneously, such as LGC-PC for QC and LGC-PC for YC. LGC-PC is comprehensive degree of parallelism of LGC-CT processing elements at a certain stage.

It would be specially mentioned that container terminal core resources planning and allocation should not only meet the requirements of ship handling operation but also ensure that the calling ship sailing schedule and the collection and distribution demand can be well executed and implemented. Under these constraint conditions, the function definition on the degree of parallelism and berthing time of calling vessels is one of the central focuses of resource allocation in CTLS.

The principal logistics computation processors (LCP) embrace QC, YC, CRS and ECFL. Those are just about the central resources for the collection and distribution of container terminals. Among them, QCs are the main handling computing engine (MHCE), and the YC, CRS and ECFL are the synergistic stack processing unit (SSPU), and the IYTs are the horizontal transferring execution unit (HTEU). The MHCE and SSPU both are just the LCU of PHR-HSN, and the HTEU is the very HCU of PHR-HSN. From the visual angle of LGC-PC, we define and discuss the evolution and development of LGC-CT meshed network for the specific job loads to a large extent.

Moreover, the nodes of LGC-CT are the primary logistics computing parallel elements. The parallel elements are usually provided with the heterogeneity whether in function or in specifications, moreover, they possess the characteristics of dynamic global flexibility and partial reconfiguration during the collection and distribution process. As a result, LGC-PC is typical of NPH.

LGC-PC is a theoretical analysis of physical machinery resource allocation and deployment for CTLS on the basis of the given handling technology and device configuration, and points out the functional relationship between facility assignment and LGC-TC. Because of the widespread phenomenon of trade off in the logistics operation, it is very necessary to find the upper and lower limits for certain facility assignment focusing on a calling ship or a container shipment route. The above function and threshold have important reference value for JPTSRA of CTLS under the compound resource constraints and the complicated operating environments.

E. LOGISTICS COMPUTATION MEMORY ACCESS COMPLEXITY

If CTLS are abstracted as the logistics generalized computation finite automata machine (LGC-FAM), the nuclear operations are focused on the positioning, mapping, accessing, shifting and switching of the storage units in the two heterogeneous memory arrays which are the just about container ship hold and the container terminal yard. The difficulty level of LGC-CT accessing two storages determines the ultimate efficiency of container switching between liners and terminals to a great extent, which is defined as logistics generalized computation memory access complexity (LGC-MAC).

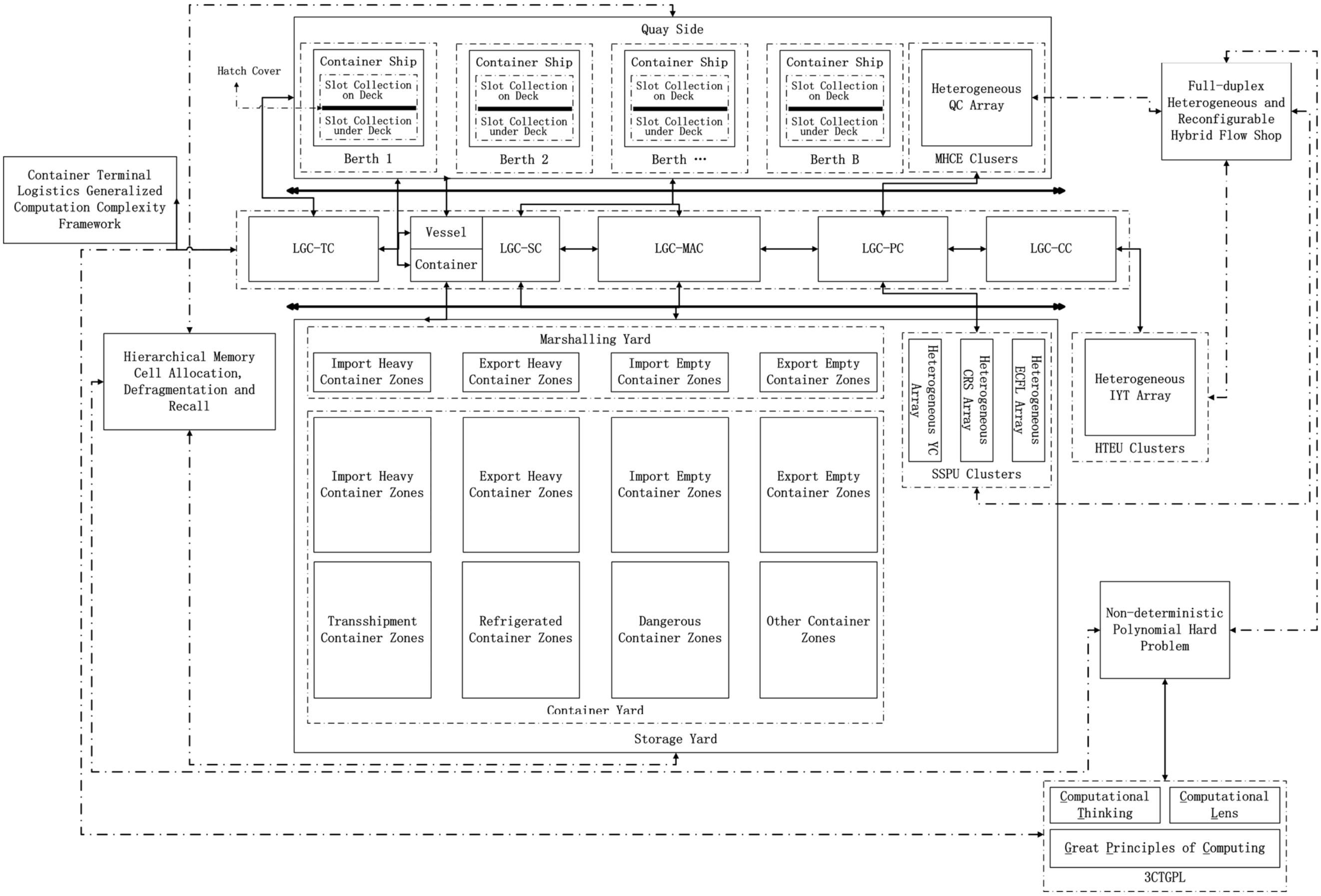

FIGURE 2. **Container terminal logistics generalized computation complexity framework.**

The most direct embodiment of LGC-MAC is the loading and discharging time of a calling ship. LGC-MAC is analogous to the dimensions described above, and is a distribution function as well. Likewise, we are concerned about the eigen value of LGC-MAC in statistical significance. LGC-MAC is the comprehensive manifestation of the four of LGC-TC, LGC-SC, LGC-CC and LGC-PC. The performance celling and lower limit of LGC-MAC are evaluated qualitatively and quantitatively by defining and combining the different scheduling strategies of LGC-TC, LGC-SC, LGC-CC and LGC-PC. With respect to LGC-TC, the LGC-MAC has a better chance of getting noticed by CTLS because it is the is intuitive, succinct and concentrated to express the quality and operation of terminal efficiency.

F. CONTAINER TERMINAL LOGISTICS GENERALIZED COMPUTATIONAL COMPLEXITY FRAMEWORK

The distinguishing features of handling and transportation procedures at container terminals are the root causes of their high NTUCC, which include hierarchy, dynamics, distributability, parallelism, locality, affinity, coupling, heterogeneity, reconfigurability, context-sensitive and goal- oriented. Those are all embodied in the profiles of CTO-LGCC, and have the powerful influences on the definition, design, implementation and evaluation of AFM-SAP.

Within the conceptual framework and fundamental principles of computational logistics, we get the logistics generalized computational abstraction for the operation of container terminals. Now, we make the definition of container terminal logistics generalized computation complexity framework (CTL-GCCF) based on the subdimensions described above, and it is the container terminal logistics generalized computation comprehensive performance perspective (CTL-GCCPP) by 3CTGPL as well, which is illustrated by Fig.2.

V. TACTICAL JOB SCHEDULING AND RESOURCE ALLOCATION STRATEGY DEFINITION

CTL-GCCF is intended to make definition, analysis and evaluation for the SFM-SAP, and then customize the special one for the given CTLS. Now, we work out a typical tactical job scheduling and resource allocation strategy (TJS-RAS) in accordance with 3CTGPL to demonstrate the CTL-GCCF preliminarily.

Firstly, the multilevel queue-scheduling hierarchical framework in COS is introduced and customized in TJS-RAS that is very long-medium-short term scheduling hierarchy (LMS-TSH). By contrast, migration and localization, the long-term scheduler is deciding which ships in the anchorage ground go into the berth allocation planning sequence. The medium-term scheduler is the berth load balancing to improve berth utilization and job throughput according to the hull form, ship route, berthing affinity and collection and distribution cycle. The short-term scheduler is the allocated number of QC and YC according to the LGC-CT context that has been defined in the previous study [54].

In the second place, the main thing to stress here is the queue disciplines in LMS-TSH. The queuing disciplines can be formulated from multiple dimensions. Obviously, the different algorithms are estimated, designed, developed and evaluated according to the characteristics of the specific dimensions. There are two typical dimensions: vessel and container. In addition, a mix of the multiple dimensions can make a new algorithm.

Thirdly, the berthing affinity is the soft and probabilistic one rather than the determinate. Those make the scheduling algorithm to be more flexible and customizable, which lead to GRAPE of TJS-RAS directly. In fact, on the one hand, the quay side berth set is separated into partitions. On the other hand, the calling hull form set is also divided into several subclasses. There is the berthing affinity between the berth partitions and the vessel subclasses, and then the berthing affinity lies in the specific ship types and given berth partitions. It is evident that the berthing affinity boundary is dynamic, fuzzy and adjustable. The berthing load threshold value, the berth allocation probability and the ship type affinity coefficient three are the main basic means of load regulation for berths. However, the parameters are so many that a lot of debugging is required for the given TJS-RAS with CTL-GCCF.

Finally, the job load of each berth is a synthetical indicator not just the current waiting jobs for it. The indicator incorporates the current running task, the waiting jobs and the number of tasks previously completed. Moreover, the load balancing of the berth is relative rather than absolute because the priority service of the certain ships and routes need to be considered with emphasis. The degree of balance and priority are changed and adjusted dynamically while the working circumstances permit.

According to the above definition, we make two berth allocation algorithms. One is hierarchical job scheduling based on waiting vessel queue length with berthing affinity and load balancing (HJB-WVQL-BALB), and the other is hierarchical job scheduling based on handling container queue length with berthing affinity and load balancing (HJB-HCQL-BALB). The former adopts the deterministic flexible berthing affinity, and the latter introduce the probabilistic flexible berthing affinity. It is evident that the latter has the better flexibility and customized scope than the former. Then, we discuss and demonstrate CTO-LGCC based on these two algorithms which are the typical definition of SFM-SAP for CTLS with computational logistics.

VI. COMPUTATIONAL EXPERIMENTS

A. CONTAINER TERMINAL SERVICE SCENARIO

A typical non-automated container terminal in China hub port is taken as the LGC-CT service scene to illustrate CTO-LGCC and CTL-GCCF. The traditional marginal quay is adopted by this terminal, and its water depth along the wharf apron is up to 18.5 meters. It covers ten berths, and their specifications can be described as follows. The length of each berth is 450 meters long, and the total shoreline length is 4500 meters, and all levels of container ships under 22000 TEUs are dockable by these berths which include the safe production interval. The wharf apron is equipped with 45 QCs that are of double 40-foot spreaders, and the heavy container yard operation area is furnished with 140 rubber tyred gantry cranes (RTGC) that is one of the most widely used YC in terminals of all sizes. The set of RTGC endows the working of storage yard with good flexibility and introduces greater complexity and more dependencies synchronously. In addition, the empty container yard working area is extra configured and deployed with 50 ECHLs as supplementary.

The port of the container terminal has established a good alliance with the numerous shipping companies around the world, and the ships are mostly large and medium-sized container trunk and feeder liners. Those vessels can be divided into twelve ship types whose critical attributes are showed in Table 3. There is no doubt that it is a large-scale container shipping hub and the water-water intermodal transportation holds the great proportion in practice.

Based on the above infrastructure, facility and business operation environments, the terminal design through capacity come up to 10 million TEU for every year. The calling ships includes the three main parts according to the practical data. To be specific, above all, the container liner, which follows particular routes during certain periods, which contain fixed intervals and named ports, is in accordance with the seven-order Erlang distribution. Next, the container ships that are transferred temporarily from other terminals within the same port, and their time interval between arrival and departure is in normal distribution. Lastly, the container ships are arranged temporarily from the adjacent ports within the same harbor and shipping alliance, and they meet the Poisson distribution at the time of arrival.

B. VV&A COMPUTATIONAL EXPERIMENTS

The computational experiment and data analysis are designed, implemented and executed based on AnyLogic 7.1.2 and SQL Server 2012. We conduct 25 computational experiments with the scheduling policy of random berth allocation with job balance (RBAJB) by the random seed from 1 to 25. RBAJB means that all levels of container ships are assigned all the berths with the equal opportunities, and the job of LGC-CT is treated and disposed without distinction. We can gain the following data with the experimental period of a year. For one thing, the vessel through capacity (VTC) of CTLS is 3358.88 ships annually, and the container through capacity (CTC) is 10101170.12 TEU yearly. For another, the average demurrage vessel is only 5.2 vessels for a year, and the average number of the waiting containers to be handled is only 18637.44TEU. Moreover, the unfinished vessels and containers have nothing to do with the logistics

TABLE 3. Critical properties for liners.

Ship Type Number	Hull Form	Capacity (TEU)	Handling Ratio	Berthing Affinity	Ship Contribution Percentage
1	port shuttle bus	500-1000	140%-190%	9, 10	10%
2	feed vessel I	1001-1799	130%-180%	8, 9, 10	8%
3	feed vessel II	1800-2499	120%-170%	8, 9, 10	8%
4	feed vessel III	2500-3200	110%-160%	8, 9, 10	8%
5	panamax type	3500-4499	30%-45%	6, 7, 8	9%
6	panamax extrme type	4500-5499	30%-45%	6, 7, 8	10%
7	post panamax type I	5500-5999	20%-40%	1, 2, 3, 4, 5	7%
8	post panamax type II	6000-7399	20%-40%	1, 2, 3, 4, 5	8%
9	post panamax type III	7400-10999	20%-35%	1, 2, 3, 4, 5	12%
10	post panamax type IV	11000-13999	20%-35%	1, 2, 3, 4, 5	10%
11	post panamax type V	14000-17999	20%-35%	1, 2, 5	8%
12	post panamax type VI	18000-22000	20%-35%	1, 2, 5	2%

TABLE 4. Load testing experimental result with RBAJB.

Group	CVADF	Average VTC	VTC Standard Deviations	VTC Range	Average CTC	Average No Service Vessels	No Service Vessels Standard Deviations	Average No Service Containers
1	2.35	16300.920	73.261	336	16426485.480	215.360	65.157	215134.920
2	2.36	16281.200	56.945	221	16400327.760	223.880	60.683	226367.400
3	2.37	16355.680	55.355	231	16487077.960	285.400	74.611	287707.600
4	2.38	16393.000	49.063	178	16521540.240	309.400	55.375	308762.040
5	2.39	16420.160	41.303	220	16558256.000	386.240	69.094	380846.320
6	2.40	16454.600	55.178	252	16564000.360	401.560	61.032	388716.000

TABLE 5. Load testing experimental result with HJB-WVQL-BALB.

Group	CVADF	Average VTC	VTC Standard Deviations	VTC Range	Average CTC	Average No Service Vessels	No Service Vessels Standard Deviations	Average No Service Containers
1	2.35	16460.560	93.879	373	16593937.120	24.160	8.783	25704.880
2	2.36	16484.600	68.678	290	16621391.960	29.240	15.012	31032.720
3	2.37	16566.720	61.234	267	16698795.400	43.880	22.924	23490.195
4	2.38	16589.440	59.401	241	16725184.280	69.720	42.286	68235.920
5	2.39	16589.160	42.435	154	16715437.400	146.840	59.197	57821.115
6	2.40	16616.840	54.621	228	16734776.680	198.080	65.221	176740.480

service capacity because they merely appear at the final phase of computational experiments.

Given the above, the computational model and its design implementation fully meets the annual design capacity of the container terminal, and it is well compliance with the various indexes of operation performances as well. Thereupon, it can be regarded as the basis for subsequent discussion.

C. LOGISTICS COMPUTATION LOAD TESTING

In practice, the actual VTC or CTC of CTLS both run circles around the carrying capacity as designed, especially for container hub ports. Meanwhile, container terminals make great efforts to maintain the existing routes and open new ones. Hence, we make a definition of calling vessel access density factor (CVADF), which means the reduction scaling of the interval of ships' arrival. Subsequently, we execute the load testing of the above CTLS according to different scheduling policies. Each group experiment with the diverse scheduling algorithms is executed for 25 times by the random seed from 1 to 25. The following is the main experimental results, and the characteristic values of VTC and CTC are showed in Table 4, Table 5 and Table 6 respectively.

According to the above data, we can discover that the system performance of HJB-WVQL-BALB and HJB-HCQL-BALB in load testing is far superior to that of RBAJB. If one year is regarded as the experimental period, the limitation of container throughput on CTLS is about 16750000 TEU. Among the above three allocation algorithms, HJB-HCQL-BALB has certain advantages in the aspect of load testing, and the CTC reaches up to 16758309.440 TEU averagely.

As the CVADF is increased from 2.35 to 2.40, the CTC keeps rising slightly while applying RBAJB, HJB-WVQL-BALB and HJB-HCQL-BALB. The latter two are is so far ahead of RBAJB in terms of CTC. While CVADF is 2.38, HJB-WVQL-BALB and HJB-HCQL-BALB both reach up to the peak in the precondition of the acceptable number of vessels in demurrage.

TABLE 6. Load testing experimental result with HJB-HCQL-BALB.

Group	CVADF	Average VTC	VTC Standard Deviations	VTC Range	Average CTC	Average No Service Vessels	No Service Vessels Standard Deviations	Average No Service Containers
1	2.35	16445.160	71.419	278	16544632.720	17.920	4.983	18898.680
2	2.36	16503.600	85.177	382	16643137.000	21.960	8.947	22102.040
3	2.37	16571.240	61.907	207	16692902.880	30.440	25.634	30632.320
4	2.38	16604.240	71.146	247	16711787.160	55.520	37.098	53405.920
5	2.39	16618.680	64.129	252	16747458.200	94.760	58.765	88021.800
6	2.40	16621.560	37.073	156	16758309.440	221.200	83.241	76895.877

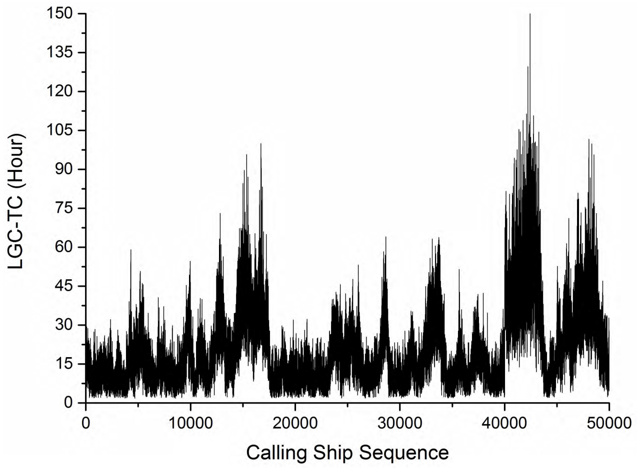

FIGURE 3. LGC-TC state sequence with HJB-WVQL-BALB and CVADF equals to 2.37.

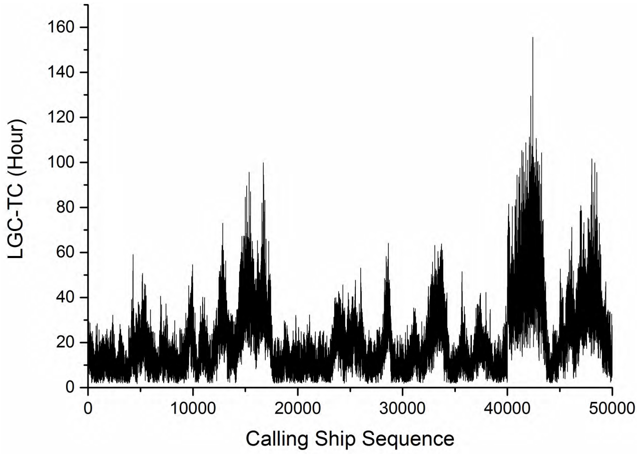

FIGURE 5. LGC-TC state sequence with HJB-WVQL-BALB and CVADF equals to 2.38.

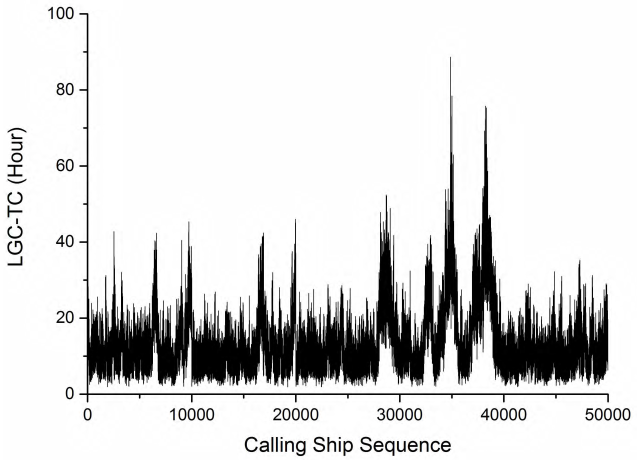

FIGURE 4. LGC-TC state sequence with HJB-HCQL-BALB and CVADF equals to 2.37.

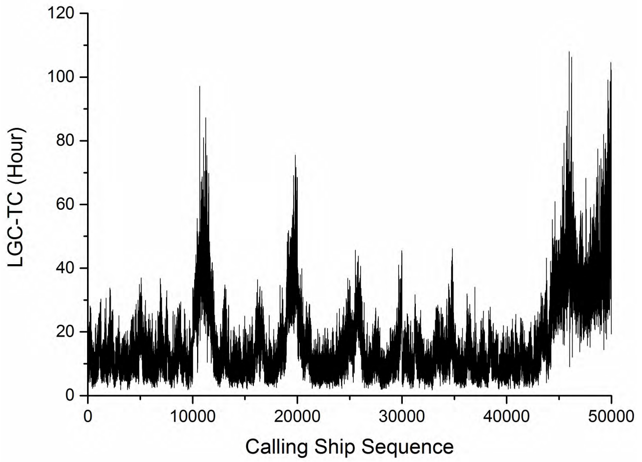

FIGURE 6. LGC-TC state sequence with HJB-HCQL-BALB and CVADF equals to 2.38.

D. LOGISTICS COMPUTATION TIME COMPLEXITY

In the light of the before-mentioned load testing, we select 2.37 and 2.38 as the typical value of CVADF to launch the discussion of LGC-TC. Thereupon, five experimental groups are picked for each CVADF and every algorithm respectively, whose overall performances approximate to the mean values closely. The 10000 container ships which accomplish stevedoring and leave the terminal are chose in middle- to late-stage of each simulation, and the vessel number of calling terminal is from 5001 to 15000 in the every experiment. That is to say, the LGC-TC of 50000 ships for each algorithm and each CVADF are used for statistical analysis. Those experimental results are showed in Fig. 3, Fig. 4, Fig. 5 and Fig. 6 accordingly.

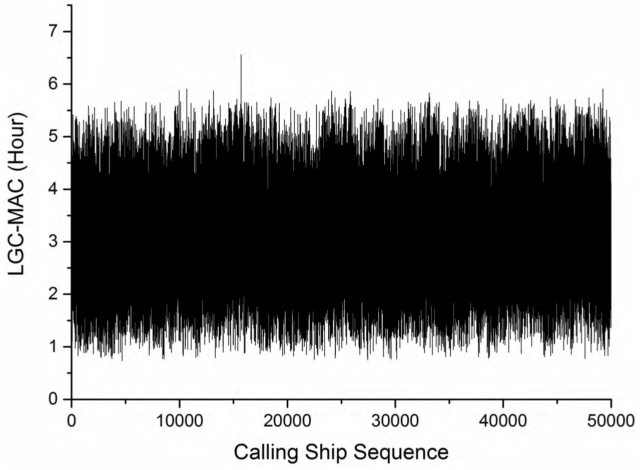

FIGURE 7. **LGC-MAC state sequence with HJB-WVQL-BALB and CVADF equals to 2.37.**

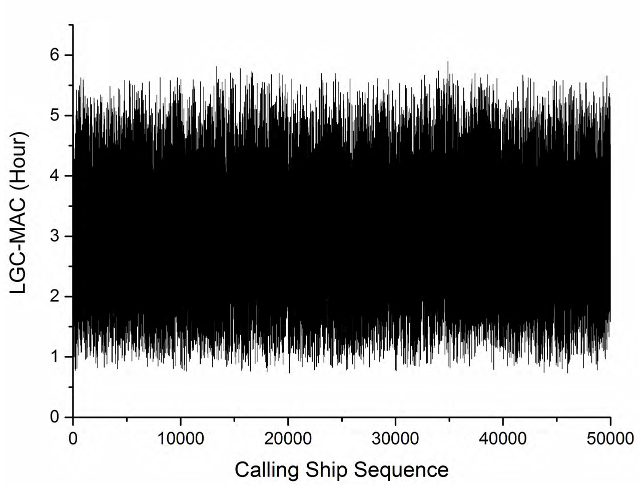

FIGURE 8. **LGC-MAC state sequence with HJB-HCQL-BALB and CVADF equals to 2.37.**

From the above characteristic curves, we can find that the LGC-TC is shaking violently on the condition that CTLS is operating at full capacity. Moreover, the predictability of LGC-TC is very limited. It means that the gap between the upper limit and the floor level is so large, especially for that CVADF is equal to 2.38. It is concluded that the CVADF should be less than 2.35 for the controllable LGC-TC, and the VTC and CTC are really meaningful.

In addition, it's worth noting that the ordinate scales are distinctly different among the four figures, and those also reflect the performance difference of scheduling algorithms from one side.

E. LOGISTICS COMPUTATION MEMORY ACCESS COMPLEXITY

For the above same calling ship set, the LGC-MAC of 50000 ships for each algorithm and each CVADF are used for statistical analysis too. The simulation results are showed in Fig. 7, Fig. 8, Fig. 9 and Fig. 10 separately. Meanwhile, all the key indicators of LGC-TC and LGC-MAC are listed in Table 7.

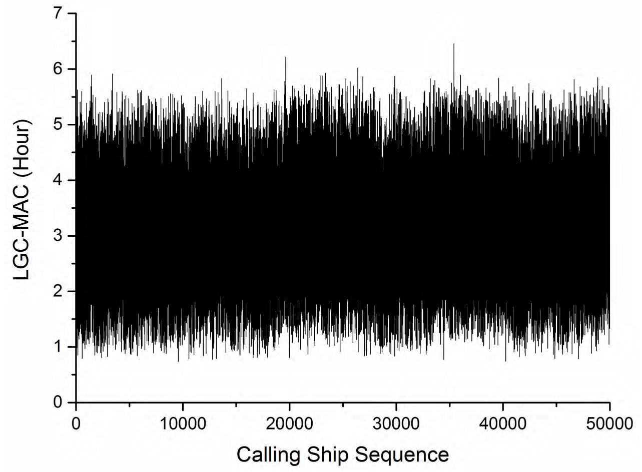

FIGURE 9. **LGC-MAC state sequence with HJB-WVQL-BALB and CVADF equals to 2.38.**

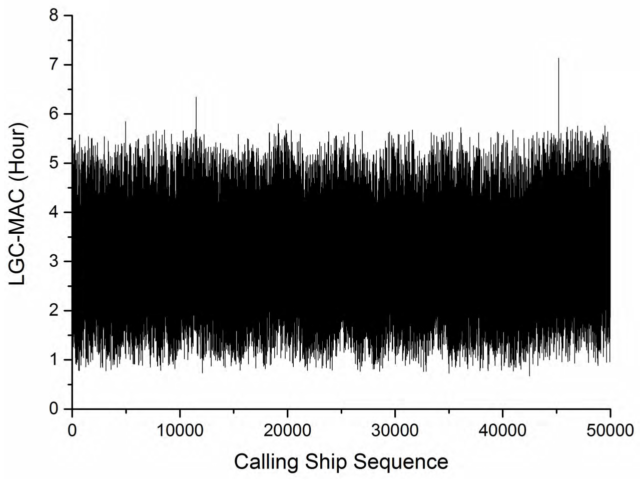

FIGURE 10. **LGC-MAC state sequence with HJB-HCQL-BALB and CVADF equals to 2.38.**

We can discover that the scheduling performance with HJB-HCQL-BALB is far superior to that of HJB-WVQL-BALB in terms of LGC-TC and LGC-MAC, especially in the aspect of LGC-TC. This point can be detected and verified explicitly from the various critical flag values. The LGC-TC of HJB-HCQL-BALB is not only low, but also has higher reliability in respect to the HJB-WVQL-BALB.

So far, we select the LGC-TC and LGC-MAC to demonstrate the application of CTO-LGCC and CTL-GCCPP, and evaluate the advantages and disadvantages of scheduling algorithms preliminarily. In fact, the LGC-TC and LGC-MAC are also the most important indicators concerned by carriers and terminals. Both can give valuable references for the scheduling decision on the tactical level.

Furthermore, any algorithm is bound to have its own peculiarities that are usually high correlative with the

TABLE 7. LGC-TC and LGC-MAC key indicators with HJB-WVQL-BALB and CVADF equals to 2.37.

Group	CVADF	Algorithm	Average LGC-TC	LGC-TC Standard Deviations	LGC-TC Median	LGC-TC Range	Average LGC-MAC	LGC-MAC Standard Deviations	LGC-MAC Median	LGC-MAC Range
1	2.37	HJB-WVQL-BALB	20.082	14.263	16.230	153.960	2.937	0.902	2.821	5.824
2	2.37	HJB-HCQL-BALB	12.992	7.802	11.053	86.772	2.871	0.890	2.752	5.165
3	2.38	HJB-WVQL-BALB	23.143	16.932	18.287	191.733	2.950	0.900	2.830	5.716
4	2.38	HJB-HCQL-BALB	16.461	11.849	12.609	106.258	2.901	0.897	2.778	6.461

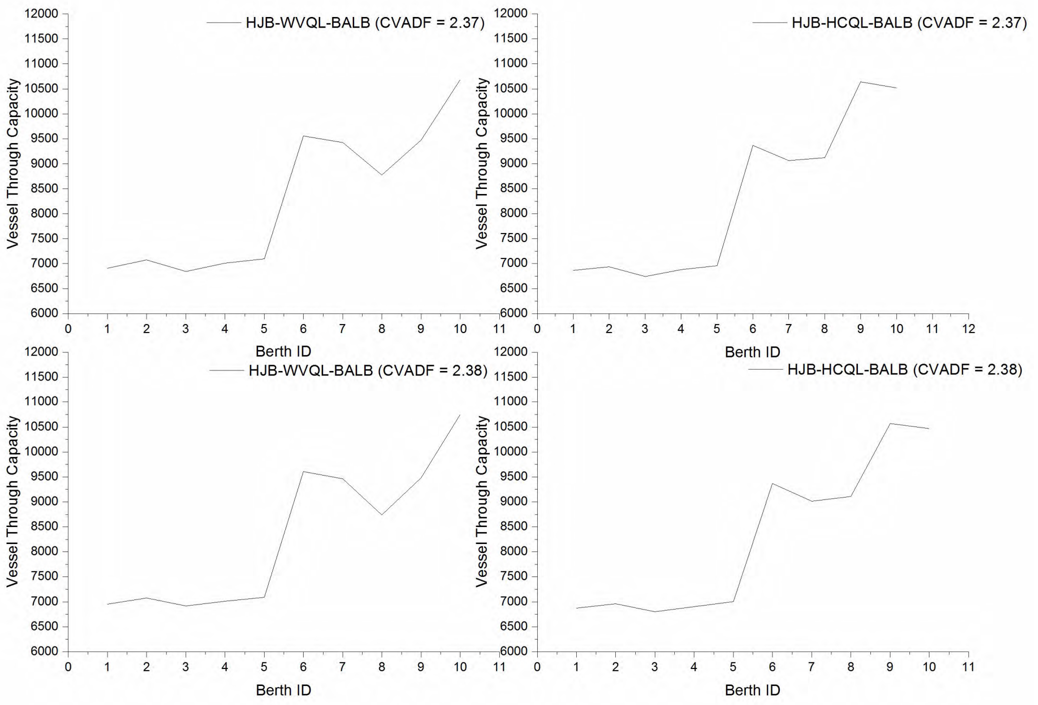

FIGURE 11. Load balancing statistics for single berth based on VTC with different tactics.

definition, designing, implementation and execution. Subsequently, the unique features of HJB-HCQL-BALB and HJB-WVQL-BALB are going to execute further evaluations to illustrate the availability and extendibility of CTO-LGCC that is a fundamental, flexible and extensible 3ECC-CLSO.

F. LOAD BALANCING ANALYSIS

The two scheduling algorithms of HJB-WVQL-BALB and HJB-HCQL-BALB integrate queuing discipline, berthing affinity and load balancing as a core part of decision strategies. We illustrate the load balancing situations with the same groups of experimental data from the dimensions of VTC and CTC, which is showed in Fig. 11 and Fig. 12.

It is found that the same scheduling algorithm has the highly similar load balancing performance curves under the different job loads whether from the visual angle of VTC or the one of CTC. It is important to note that the performance curves of VTC is exactly opposite that of CTC for the same algorithm regardless of the operating load.

The main reason for the above phenomenon is to pursue the comprehensive balance of berth load, and it is one of the original intentions of HJB-WVQL-BALB and HJB-HCQL-BALB as well. That is aimed at obtaining the task load equilibrium in the premise of considering VTC and CTC synchronously. The piloting, berthing and departing time for container ships, the preparation time for QCs and IYTs, the opening, shifting, closing of hatch covers etc. are the most

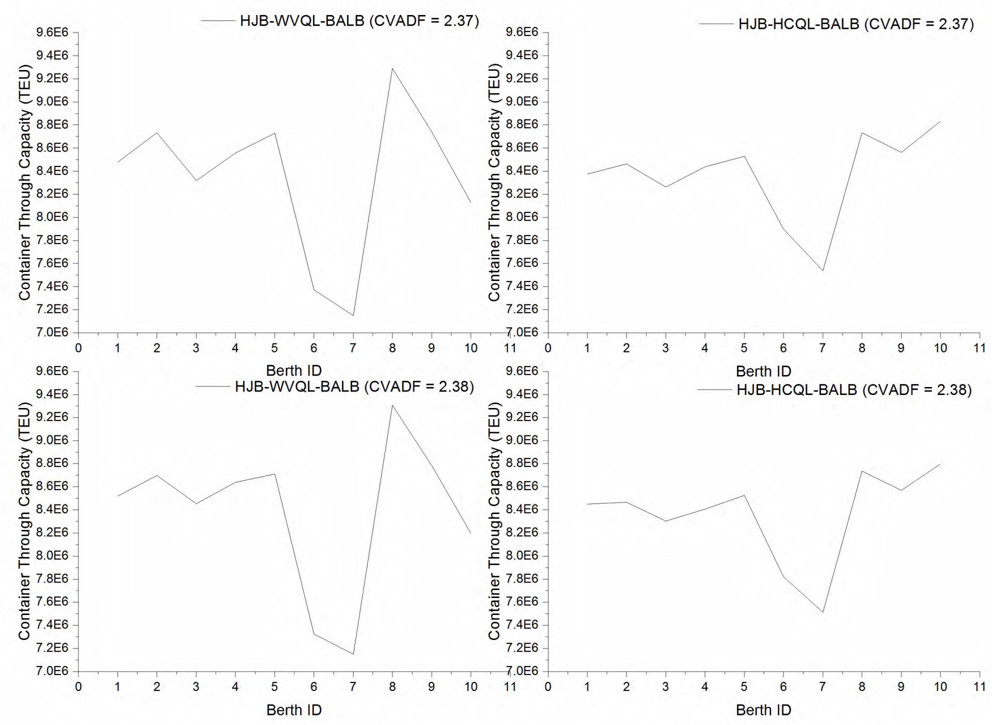

FIGURE 12. Load balancing statistics for single berth based on CTC with different tactics.

essential causes of the production status. Nevertheless, even in the above cognitive premise, HJB-HCQL-BALB still has the better manifestation in the aspect of load balancing than HJB-WVQL-BALB, which can be seen from the fluctuation in load curve, especially for CTC. Obviously, the characteristic curves of HJB-HCQL-BALB has the smoother and more stable amplitude than those of HJB-WVQL-BALB. In reality, it is a significant reason why HJB-HCQL-BALB is superior to HJB-WVQL-BALB.

G. SOFT BERTHING AFFINITY EVALUATION

Besides the loading balance, the soft berthing affinity is another core concept of algorithm design, which has been defined in Table 3. The regulation is not mandatory, and the degree of soft can either be formulated by the fixed coefficient or the given probability distribution. HJB-WVQL-BALB adopts the former, and the HJB-HCQL-BALB introduce the latter. Thereupon, we make a quantitative analysis of the flexibility and adaptability of the HJB-WVQL-BALB and HJB-HCQL-BALB based on the central service objects of LGC-CT, which are just about the post panamax type III, post panamax type IV, post panamax type V and post panamax type VI. The four kinds of liners occupy about a third of the calling ship set, which is the top-drawer service objects. Similarly, we execute the data analysis of the same experimental groups for the departure liners, and get the results that are showed in Fig. 13, Fig. 14, Fig. 15 and Fig. 16 discriminably according to the ship form. It is worth mentioning that the ordinate range is also distinctly different in the four diagrams.

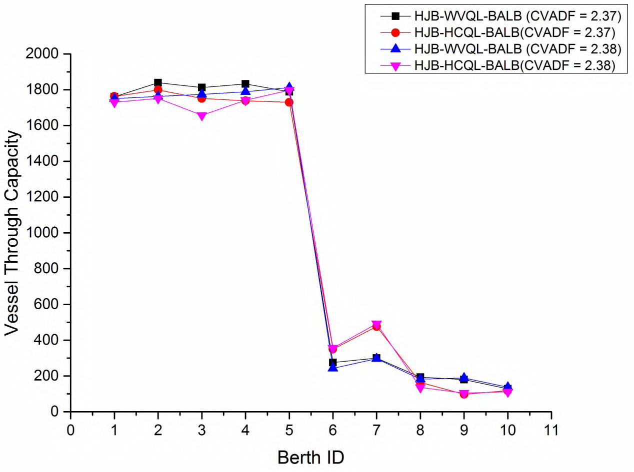

FIGURE 13. Flexibility and adaptability of berthing affinity algorithms for the post panamax type III.

In accordance with the Fig. 13, Fig. 14, Fig. 15 and Fig. 16, the four ship forms can be divided into two groups visibly. The former two types are the Group I, and the latter two are the Group II. From the perspective of berthing affinity behaviors, it is discovered that the calling ships of panamax type III and post panamax type IV have the analogical soft berthing affinity flexible and adaptive curve. A similar situation occurs in the post panamax type V and post panamax type VI. Furthermore, the HJB-WVQL-BALB has the better performance than the HJB-HCQL-BALB for the Group I on

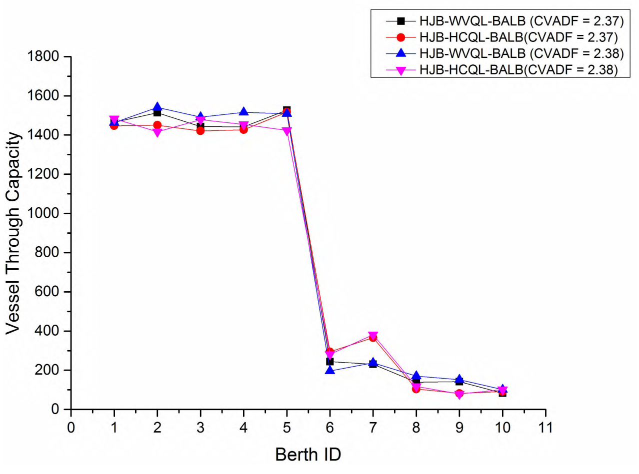

FIGURE 14. Flexibility and adaptability of berthing affinity algorithms for the post panamax type IV.

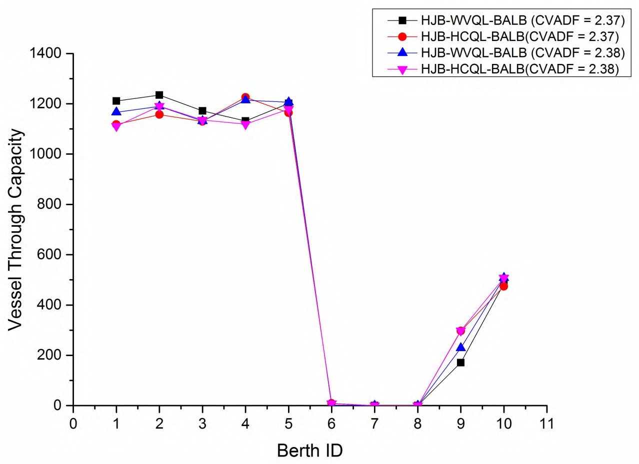

FIGURE 15. Flexibility and adaptability of berthing affinity algorithms for the post panamax type V.

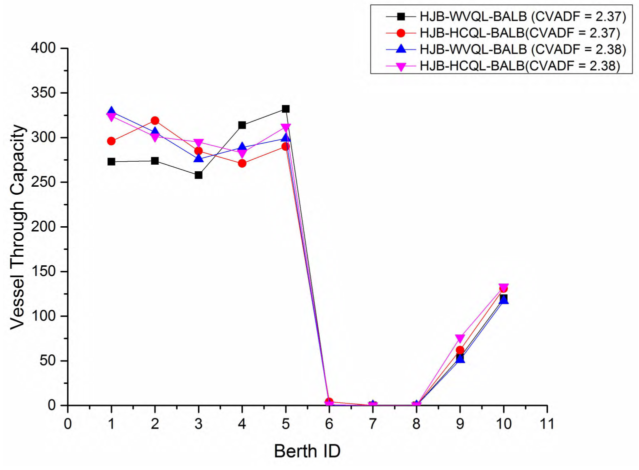

FIGURE 16. Flexibility and adaptability of berthing affinity algorithms for the post panamax type VI.

abidance by the rules of berthing affinity. As for Group II, HJB-WVQL-BALB performs slightly better than HJB-HCQL-BALB. Especially for the panamax type VI, HJB-WVQL-BALB and HJB-HCQL-BALB has its own merits. Moreover, whether HJB-WVQL-BALB or HJB-HCQL-BALB hardly occupies this berth of 6, 7 and 8 to guarantee the efficient operation of LGC-CT for other liners.

According to the application of CTO-LGCC to this case, it is concluded that CTL-LGCC is supposed to determine the upper limit of the given container terminal and evaluate advantages and disadvantages the algorithms from the common and unique dimensions. Furthermore, it can guide the parameter tuning of AFM-SAP. All can provide strong support for the decision making of CTLS at multiple levels whether in theory or practice.

VII. CONCLUSION AND FUTURE WORK

Through the above performance modeling and experimental analysis, we can come to the following conclusions. Above all, CTO-LGCC is a performance comprehensive evaluation and improvement framework for the specific scheduling principles, mechanism, tactics, algorithms and parameters, and provide a multilevel, multidimensional and multiobjective 3ECC-CLSO, which guides the GMLM of the given JPTSRA tactics, and then an important puzzle is achieved to construct the feedback decision-making support architecture based computational logistics. Secondly, CTO-LGCC can be applied both locally and globally, and it may be used for both single-objective optimization and multi-objective optimization as well. Thirdly, CTO-LGCC is a tailorable, scalable and evolvable 3ECC-CLSO, and is supposed to appropriate for the container terminals with the different design scale, handling technology and device configuration. Furthermore, the unique features of the given algorithm can be integrated into CTO-LGCC seamlessly, such as the berthing affinity and load balancing in HJB-WVQL-BALB and HJB-HCQL-BALB. Finally, in the future, the principles of dynamic control, performance appraising, and continual improvement of parallel computation, heterogeneous computing and reconfigurable computation are going to be integrated into CTO-LGCC purposefully, which is intended to match the development trend of automation and intelligence at container terminals.

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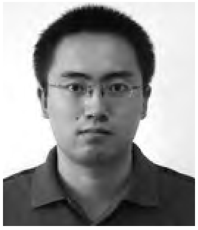

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