IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 14, 2020, accepted October 19, 2020, date of publication October 26, 2020, date of current version November 6, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3033849

Computational Logistics for Container Terminal Logistics Hubs Based on Computational Lens and Computing Principles

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This work was supported in part by the Humanities and Social Science Programming Foundation, Ministry of Education, China, under Grant 19YJA630031, in part by the Natural Science Foundation of Fujian Province, China, under Grant 2017J01496, in part by the Scientific Research Foundation, Fujian University of Technology, under Grant GY-Z160125, and in part by the Traffic Science and Technology Project of Shandong Province, China, under Grant 2016B35.

ABSTRACT The volatile global shipping market puts forward the higher requirements to the container terminal logistics systems (CTLS) than ever, especially in terms of programming, planning, scheduling and decision. The computational logistics provide a systematic methodology to overcome the issues that differs from traditional approaches distinctly. This paper discusses the theoretical framework, important components and core concept of computational logistics, and then presents the container terminal logistics generalized computation design, implement, execution, analysis and evaluation hierarchy (LGC-DIE-AEH) by the integration of the computational lens and computing principles to explore the computational logistics in the field of CTLS. Subsequently, the execution performance of a quay crane farm at a regional container hub terminal in China is analyzed and evaluated by LGC-DIE-AEH. The crane performance evaluation core indicator framework (CPE-CIF) is proposed by the fusion of the design philosophy and underlying principles of computing architecture, operating system, and virtual machine by computational lens. The CPE-CIF help us to find out the advantages, disadvantages and improvement directions of quay crane farm operation. That illustrates and verifies the feasibility and credibility of LGC-DIE-AEH from the perspective of the practice of container terminal decision-making support at the tactical level.

INDEX TERMS Logistics, freight containers, scheduling, performance evaluation, computational efficiency, decision making, computational logistics, computational lens, computing principles.

I. INTRODUCTION

The container terminal is the core full duplex container transportation service hub nodes in the hierarchical and multistage logistics network all over the world. It implements and executes the positioning, mapping, transferring, routing, accessing and switching (PMT-RAS) of container logistics unit with the perspective of computational logistics that is a fundamentally different approach compared to any previous study [1]–[3]. The computational logistics is a programming, planning, scheduling and decision-making support methodology for complex logistics systems proposed by Bin Li on the 54th IEEE Conference on Decision and Control in 2015 preliminarily. The running of container terminal logistics systems (CTLS) has typical characteristics of hierarchy, dynamic, timeliness, nonlinearity, coupling and complexity (HDT-NCC). In addition, the global shipping market expects CTLS to be agile, efficient, robust and green [4]–[6]. All make the layout programming, process design, job planning, task scheduling, resource allocation and collaborative decision of CTLS, which is abbreviated as PDP-SAD, to be very intractable and a huge challenge whether in theory or in practice [7], [8].

The PDP-SAD at container terminals are all nondeterministic polynomial complete (NPC) for both of single resource management and integrated production scheduling. Moreover, the computational complexity of PDP-SAD continuously increases with the development of port and shipping industry [9], [10]. The PDP-SAD for container terminals has always been a hot and difficult topic in the field of operations

The associate editor coordinating the review of this manuscript and approving it for publication was Shih-Wei Lin.

research and control science. For one thing, the now available approach and solution to CTLS is usually for the specific terminal objects and service scenarios, and absence of generality, robustness, agility, portability and extendibility to a great extent. For another, the vigorous development of computer systems and the emergence of computational thinking not only supply the better computing power for the PDP-SAD of CTLS than ever, but also provide a possibility of finding a new path to obtain a research method different from previous that covers operational programming, intelligent optimization, system simulation etc. It is no other than computational logistics.

Over the past decade, we have done a lot of system modeling, algorithms design, mechanism transferring and case studies on CTLS by computational thinking [11], and some initial progress has been acquired based on the large amounts of computational experiments results, such as the elementary definition of computational logistics, the container terminal collection and distribution virtual machine architecture, and the hierarchical, parallel, heterogeneous and reconfigurable computation model of container terminal handling system [3], [12], [13]. Nevertheless, the methodological framework and fundamental principles of computational logistics for container terminal logistics hubs is still not described and explained systematically, especially for logistics generalized computation for container terminals (LGC-CT) pattern analysis and performance evaluation based on the actual production data at container terminals. Considering this, we expound and elaborate the methodology of computational logistics for container terminal logistics hubs based on computational lens and computing principles, and it is intended to provide an elementary theoretical framework and an engineering practical solution to the PDP-SAD of CTLS. It is also supposed to provide a valuable reference for the running of the other complex logistics hubs.

The reminder of this paper is organized as follows: Section 2 provides a literature review of the computational lens and great principles of computing that both are the cornerstone of computational logistics. Section 3 presents the customized theoretical framework of computational logistics for container terminal logistics hubs that covers LGC-CT, computability of LGC-CT, and container terminal-oriented logistics generalized computing theory (CTO-LGCT). The container terminal logistics generalized computation design, implement, execution, analysis and evaluation hierarchy (LGC-DIE-AEH) is proposed resumptively together with its core principles in Section 4. A real case study of CTLS including LGC-CT mechanism analysis and performance evaluation are reported detailedly in Section 5. Section 6 concludes the paper with some discussions and extensions.

II. COMPUTATIONAL LENS AND GREAT PRINCIPLES OF COMPUTING

The definition of computational logistics is made demonstrably by the transferring, integration and fusion the four of computational thinking, theory of computation, computational lens and great principles of computing, which are abbreviated to 4CTTLP. For one thing, the computational thinking involves solving problems, designing systems, and understanding human behavior, by drawing on the concepts fundamental to computer science, which is vigorously advocated by Wing [14], and establishes a fundamental methodology for the computational logistics whether for CTLS or the other complex logistics systems, there's been a lot of ink spilled on the computational thinking for CTLS in our previous study [3], [11]. For another, the theory of computation provides the rational tools for the computer engineering in practice, which mainly consist of automata, computability and computational complexity [15]. We also make a pilot study of CTLS with the theory of computation. For instance, we have defined the LGC-CT according to the nature of computation [12], and container terminal-oriented logistics generalized computational complexity (CTO-LGCC) based on the above computational complexity theory [16], which are the important milestones on computational logistics.

Nevertheless, the philosophy of computational logistics is more translated, implemented, executed and deployed based on the latter two during the application and practice. Both of computational lens and great principles of computing provide the explicit, concrete, mechanical, executable and exercisable instruments, means, principles, mechanisms, paradigms, patterns and algorithms for the computational logistics substantially. Then, we expatiate briefly the computational lens and great principles of computing, and address their function, position and application in computational logistics.

A. COMPUTATIONAL LENS

The computational lens is proposed by Richard Karp in 2007 [17], [18], who is the Turing award winner in 1985 and a Fellow of the National Academy of Science and National Academy of Engineering. Richard Karp lays the foundation of NPC problem, especially for the large-scale combinatorial optimization problems. The PDP-SAD in CTLS is just about the large-scale combinatorial optimization problems and NPC problems with the complicated operating constraints and multiple optimization objectives. Accordingly, the computational lens provides an essential and abstract device for the running of CTLS.

Specifically, the computational lens focuses on the intrinsic and unified interconnections between the world of computation and the world of science, which is a metaphor for building the abstract bridge between the computational science and other sciences [18]. It is designed to put computational science at the heart of scientific research rather than be only an automation tool for other kinds of science studies just like it is always been. The thought has a curious coincidence with computational thinking, but it is more specific, vivid, maneuverable and executable compared to the latter.

Xu *et al.* presented that the computational lens and computational thinking lead to the emergence of a new computer science that is more universal and fundamental than the previous one in 2011, and the computer science is experiencing fundamental transformations, from its scope, objects of study, basic metrics, main abstractions, fundamental principles, to its relationship to other sciences and to the human society [19]–[21]. It happens that there is a similar case. Vasant *et al.* clearly pointed out that the scientific progress in many disciplines is increasingly enabled by the ability to examine the natural phenomena through the computational lens using algorithmic or information processing abstractions [22].

B. GREAT PRINCIPLES OF COMPUTING

The great principles of computing (GPC) is proposed systematically by the professor of Peter J. Denning, the former chairman of ACM [23], [24]. GPC is the collection of computing mechanics and the principles framework as a matter of fact. GPC is just computation, communication, coordination, automation, recollection, evaluation and design [25], and it is in-depth, broad, extensive, comprehensive and cosmic that covers all aspects of computation including organization, architecture, model, scheduling, algorithm, system, design, implementation, execution, deployment and debugging.

The GPC is a statement collection that guide, constrain and optimize how we manipulate and control matter and energy to perform agile, efficient and robust computations. The main body of the computational principle has two origins. One is the laws, processes, and methods of reproducible causality in computational science. The other is computational code of conduct [25]. The primary purpose of GPC is to achieve good design paradigm, scheduling scheme and operating performance by promoting understanding, reducing coupling, minimizing complexity, and achieving portability and extensibility. The original intention of GPC complements the idea of computational lens, and fully meets the requirements and expectations of CTLS. Naturally, the GPC has something important to offer for the programming, design, decision and evaluation of CTLS.

More importantly, Peter J. Denning have been devoted himself to accomplish a great cause. This is exactly that the computation is a natural science, and the conclusion can be recognized by academia and industry [26]–[29]. In addition, Peter J. Denning has also been trying to clarify the similarities and differences between computational principles and computational thinking [30]–[32]. All lays a solid foundation and guidance for the extension and application of GPC in complex logistics systems.

C. CORNERSTONE OF COMPUTATIONAL LOGISTICS

The concept, thought, theory, fundamental, principle, mechanism and algorithm of computation all provide the comprehensive analysis perspective and transferring customized framework of multidisciplinary, cross-disciplinary and interdisciplinary synthetic philosophy to solve complicated issues and overcome the operational complexity in CTLS. Furthermore, the evolution and development of the ideas of computation increase the clarity, dimensionality and profile of CTLS under computational lens. Though there are some content overlap and conflict between computational thinking and GPC to a certain extent as well [31], [32]. However, the combination and kernel of 4CTTLP are providing an insight and philosophy into the essences and characteristics of computations and applying the theory, principles and capacity of computation in different fields. The four pillars of computational logistics and their mutual relations can be illustrated by Fig. 1 roughly. Together, the four establish a theoretical foundations and conceptual architecture for the abstraction, automation, analysis and algorithms of the given complex logistics systems by procedure-oriented unification, computation-oriented abstraction, algorithm-oriented automation and problem-oriented explorations.

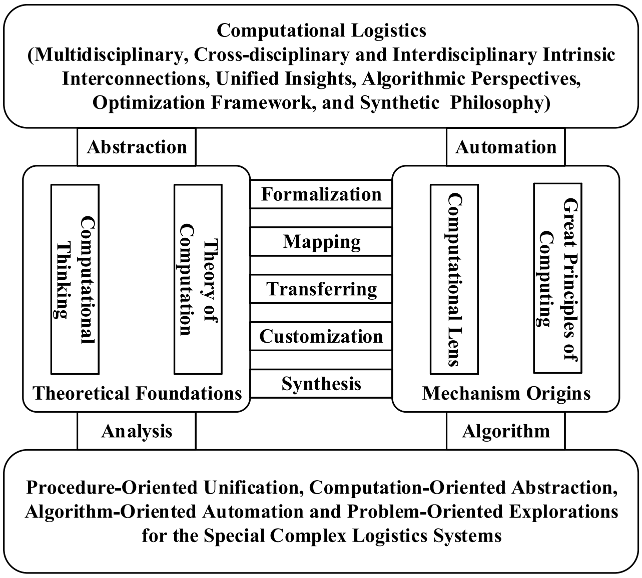


FIGURE 1. Four pillars of computational logistics.

Both of computational lens and GPC occupy a very important position in the methodology of computational logistics, especially for design, implementation, execution and evaluation. For one thing, the computational lens provides a metaphor mechanism between the world of computation and the world of the sciences [18]. For another, Peter J. Denning thinks that we tried to categorize computing as engineering, science, or math is fruitless, and the computation is just a paradigm [27]–[29]. In addition, the computing is now a natural science, and the computing is as fundamental as the physical, life and social sciences [30], [31]. Namely, the computational lens and GPC both are the more of abstraction metaphor, automation transferring, design paradigm and evaluation compass. Of course, in the origins and nature of computational lens and GPC, both are almost impossible to be expressed in mathematical formulas. Consequently, the refinement generalization, transferring, unification, integration and fusion of problem-oriented computation (RGT-UIF-PoC) is the kernel of the theory, solution, practice and application of computational logistics.

III. COMPUTATIONAL LOGISTICS FOR CONTAINER TERMINAL LOGISTICS HUBS

A. LOGISTICS GENERALIZED COMPUTATION FOR CONTAINER TERMINALS

The RGT-UIF-PoC occupies a very important position in the conceptual framework and fundamental principles of computational logistics. The LGC-CT is the direct manifestation and specific embodiment of CTLS oriented RGT-UIF-PoC with computational logistics. Naturally, the LGC-CT plays a significant role in the conceptual framework, research methodology and engineering proposals with computational logistics [12], [13].

From a narrow sense, the essence of computation is the transformation process of a string of symbols according to the certain transformational rules. In a broad sense, the computation is a transformation of the physical states of the given object oriented based on the special conversion rules. Container transportation has put into practice and kept on a continuing development for over sixty years all over the world, and it has established and formed a complete set of international operational framework, architecture and standards which ensures that all the components of working together cohesively and connects all the aspects of container logistics seamlessly. That lays a good foundation for the application of computational logistics in CTLS because the operation of computer system is based on a set of international standards too. The special containers and the nonstandard ones usually make up only a very small proportion of the whole container throughput, and then the two cases are not considered for the time being. In fact, the very global standards of container transportation make LGC-CT to be worth exploring and exploiting in depth, and have the desirable value and promising prospect whether in theory or in engineering.

In this premise, we have made a definition of logistics generalized computation alphabet (LGCA) as a basis for discussion of LGC-CT [16]. The LGCA mainly includes 32 generalized symbols, and those stand for the three-dimensional physical computed objects in CTLS that are no other than all kinds of common container transportation units. In LGCA, the twenty-foot general purpose container, forty-foot general purpose container, forty-five-foot general purpose container, forty-foot high cube container and forty-five-foot high cube container account for the vast majority of container throughout at any terminal, and those are particularly representative of the above container types in sequence. The five kinds of containers can be formulated by the subset of LGCA that is just about {A, G, S, M, Y} as the literature of [16] describes. LGCA are the basic serviced elements for the operation of the global container logistics networks, and the container terminal is the logistics generalized computational backbone hub node of container logistics networks too. Those are the concrete embodiment of the data thinking and network thinking within the conceptual framework of computational logistics essentially.

B. INTEGRATION AND FUSION BRIDGE OF ABSTRACTION, AUTOMATION AND ANALYSIS

Whether computational lens or GPC both are expected to reach and build a multidisciplinary, interdisciplinary and cross-disciplinary computational consensus based on computer and control science and engineering, and it can highlight an insight into the nature of computations that is just about process rather than only tool or means. As a matter of fact, the abstraction premises and application foundations of computational logistics are exactly the excavation, penetration, extension, expansion, exploration and exploitation of the conception of computation, and it is very philosophy and quintessence of RGT-UIF-PoC as well.

The LGC-CT is a problem-oriented integration and fusion bridge for the abstraction, automation and analysis, which is referred as 3A, between computational logistics and the cyber-physical systems of CTLS. LGC-CT fills in and cross the gap between the physical multi-level, multi-stage, multi-queue and multi-buffer logistics service process and cyber hierarchical and structured symbol set computing procedure, which both have been defined in detail in our works [16]. It is an important theoretical prerequisite and 3A investigation basis for the in-depth exploration because that makes the GPC to be also appropriate for the operation of CTLS under the computational lens naturally. Namely, CTLS becomes a new and important critical computing domain whose conception is also raised by Peter J. Denning together with the great principles' framework [25]. What is more, the new critical computing domain exists in the physical world rather than the information fields. It verifies, validates, accredits and applies GPC in the complex logistics hub under the computational lens, and that also encourages us to take a closer look at the nature of computing conversely.

This point is crucial, and of enormous consequences. It is equivalent to make the physical world and the cyber space to work in the same architectures, principles, mechanisms and modes by the RGT-UIF-PoC philosophy which provides a new solution to digital twin with the unified 3A modeling. For one thing, LGC-CT reaches the elementary success in the unification between the physical world and cyber space by the computation-oriented 3A in the critical computing domain of container terminal logistics. For another, LGC-CT helps us to win an essential inter-disciplinary perspective of computation by the integration and fusion of container terminal logistics operational framework and computer system running architecture. Both make LGC-CT to be the cornerstone and foundation of container terminal logistics oriented computational logistics 3A.

C. COMPUTABILITY OF LOGISTICS GENERALIZED COMPUTATION FOR CONTAINER TERMINALS

Based on the above definition, discussion and analysis, we talk more about the problem-oriented computability of logistics generalized computation for container terminals (PC-LGC-CT), and it is an important component of

RGT-UIF-PoC philosophy as well just as it plays an important role in classical computational theory.

Taking the import container as an example to illustrate PC-LGC-CT, the collection and distribution process of the import container is extracted, mapped and transferred with computational lens, and the function of f(x) is defined to compute the real time stacking position of the given container on the terminal yard. The set of container ships arriving at the port by liner form including their cabin space and affiliated containers can be considered as the domain of definition D in a certain period. Similarly, the three-dimensional space of terminal storage yard is the value domain R, which is the container slot multidimensional matrixes in practice. The collection and distribution mode, the plane layout of quay side and storage yard, handling technology, infrastructure and equipment configuration, and the key attributes of containers that are just about LGCA, which include size, empty or full, sailing date, shipper and so on, are the constraints of the above function of f(x). According to the definition of computability in the theory of computation in computer science, f(x) is obviously computable and must be so otherwise the container terminal does not work at all. Essentially, the f(x) is the mapping, shifting and transferring function between D and R, especially for the given running time window.

The above case is described for the import container. To the running procedure of the export one, the opposite is true. A similar definition for the function of g(x) and its constraints can be made by exchanging the domain and the range. Moreover, a similar definition for the function of t(x) and its constraints can be given for the container for transshipment by the combination of f(x) and g(x). Most obviously, the t(x) must be solved in stages. Moreover, its domain of definition is the combination of D and R in the f(x), and then the range of t(x) is equivalent to g(x).

Therefore, the PDP-SAD of LGC-CT is theoretically suitable for solving by the classical theory of computation. This is an important foundation for the further discussion on computational logistics for CTLS, and it also shows that the GPC may be applicable to CTLS from another aspect.

In fact, we have refined, transferred, customized and modified the computational complexity theory, which is a core component of the classic theory of computation, into CTLS to propose the CTO-LGCC to be a compound compass of complex logistics service optimization. The definition of PC-LGC-CT is another critical and theoretical foundation of RGT-UIF-PoC philosophy. Meanwhile, the PC-LGC-CT is the critical infrastructure for the generalization of GPC.

D. CONTAINER TERMINAL ORIENTED LOGISTICS GENERALIZED COMPUTING THEORY

Similar to CTO-LGCC, the PC-LGC-CT is supposed to model, evaluate, guide, tune and improve the running of CTLS, especially from the perspective of problem-oriented exploration with 3A. The PC-LGC-CT and CTO-LGCC, together with LGC-CT, construct the kernel of container terminal-oriented logistics generalized computing theory (CTO-LGCT).

The CTO-LGCT is the most immediate applications of computational logistics in the container terminal logistics hubs, and it is the comprehensive practice of RGT-UIF-PoC philosophy as well. It is supposed to establish a solid theoretical basis for the further application of computational logistics at the complex logistics hub for the standardized unit logistics. On the basis of the CTO-LGCT, the classic theory of computation and GPC can be migrated, transferred, integrated and customized purposefully and systematically from the information space to the physical world, moreover, the original theories, principles, mechanisms, patterns and algorithms in cyberspace and the counterpart in the physical world have influence on and promote each other. It makes us to explore and exploit the nature of computation with the unified viewing angle by the problem-oriented integration of disciplines and the mechanism fusion across information space and physical world, and provides a new insight into the nature and characteristics of computations.

IV. LOGISTICS GENERALIZED COMPUTATION ABSTRACTION AND AUTOMATION HIERARCHY

A. CONTAINER TERMINAL LOGISTICS ABSTRACTION AND AUTOMATION HIERARCHY

The computational logistics is the problem-oriented extension, exploration and exploitation of 4CTTLP for the logistics industry and supply chain management. The essence of computational thinking is abstraction and automation [14]. Based on the kernels of CTO-LGCT discussed above, we further deepen the application of the methodology of computational logistics for the critical computing domain of CTLS, and aim at acquiring the container terminal logistics abstraction and automation hierarchical structure. It is just about the container terminal LGC-DIE-AEH because the LGC-CT sits at the center of computational logistics for container terminals whether from the abstract formal modeling or the automatic execution mechanism.

The LGC-DIE-AEH is proposed formally by the fusion of computational lens and GPC, which is demonstrated by Fig. 2. It is quite explicit that the LGC-DIE-AEH is appropriate for making a specific analysis, evaluation and improvement for all the local control, synergic decision-making and integrated scheduling of LGC-CT. As a matter of fact, the LGC-DIE-AEH has important implications for the operation of other logistics hubs too. Now we establish and elaborate the LGC-DIE-AEH.

B. LOGISTICS GENERALIZED COMPUTATION CORE ATTRIBUTES FOR CONTAINER TERMINAL

In our previous studies, we have presented container terminal computational logistics conceptual framework and the container logistics computing architecture [11], [13], and those illustrate the notion and essence of computation in the critical computing domain of container terminal logistics

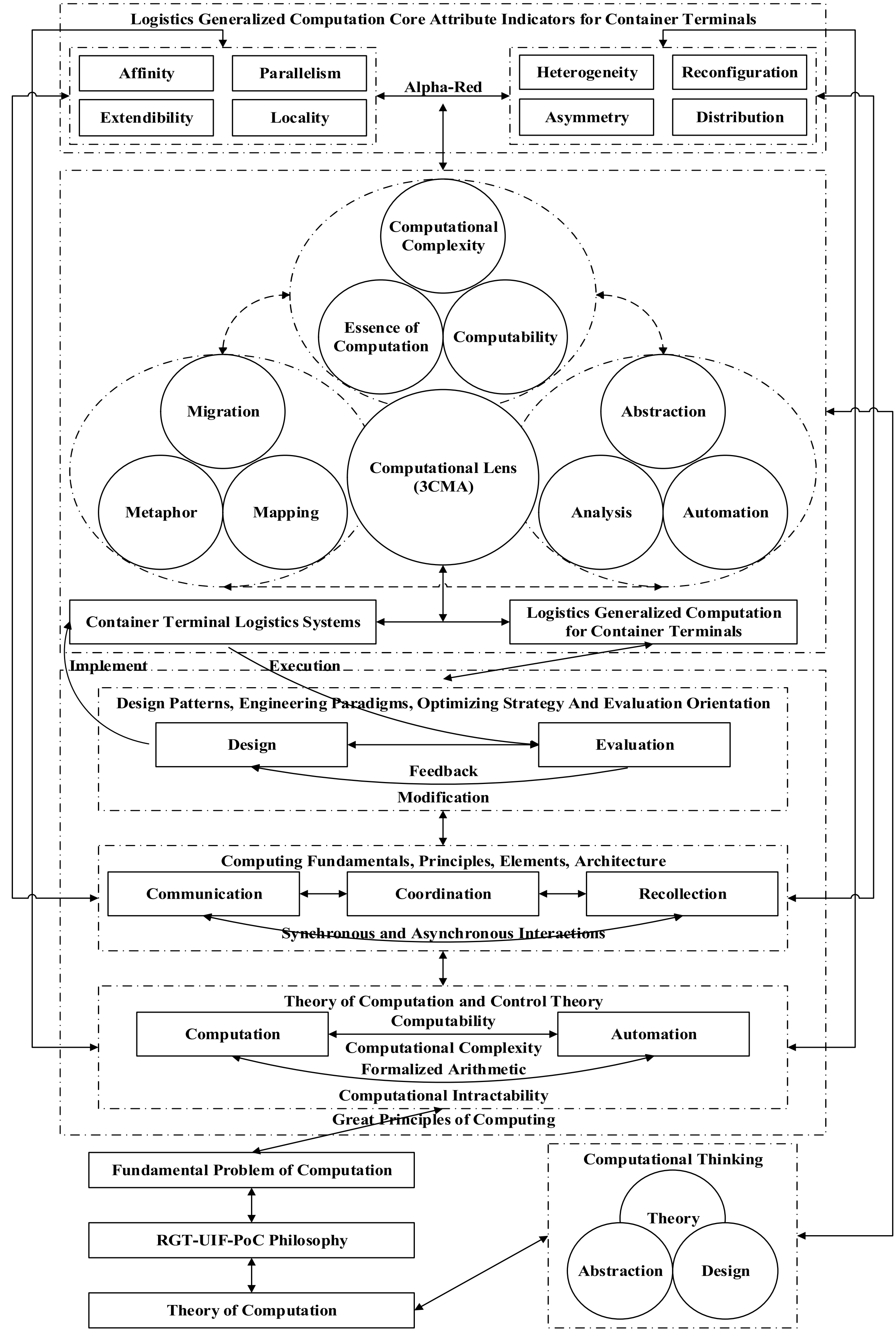


FIGURE 2. LGC-DIE-AEH preliminary sketch for container terminals.

from the perspective of hierarchical, parallel, heterogeneous and reconfigurable computation. Moreover, the similarities and differences among container terminals are also extracted, abstracted, analyzed, and then are taken into comprehensive consideration based on some factors, which are main composition and layout, handling technology, operation procedure, device configuration, collection and distribution modes, etc. Thus, the logistics generalized computation core attributes indicator (LGC-CAI) for container terminals are summarized and proposed systematically. LGC-CAI includes asymmetry, locality, parallelism, heterogeneity, affinity, reconfiguration, extendibility, distribution that are called after Alpha-Red.

It is well known that the above eight computing attributes are very common in the field of computer organization, computer architecture, operating system, virtual machine, distributed, concurrent, parallel, and reconfigurable computing systems. The core production resources in CTLS whether for facility or for equipment, such as berth, yard, quay crane, yard crane, all possess the characteristics of Alpha-Red. The Alpha-Red provides a key perspective and insight into HDT-NCC of PDP-SAD at container terminals, and it gives some fundamental causes of HDT-NCC to a certain extent. What's more, Alpha-Red points out a clear, feasible and exercisable direction and scheme to improvement on the performance of CTLS. In case Alpha-Red is made the partial or full exploitation and exploration, the novel systematic theory and application solution to CTLS are supposed to propose correspondingly, and then the performance of CTLS can be promoted greatly. In fact, it is just about the original intention of computational logistics.

C. COMPUATIONAL LENS FOR CONTAINER TERMINAL

The LGC-DIE-AEH is designed for a continuously generalized feedback improving architecture for the 3A of LGC-CT. The LGC-DIE-AEH is established on the computational thinking and the theory of computation, and then the three of GPC, computational lens, LGC-CAI constitute the core architecture of LGC-DIE-AEH. It's necessary to define the running mechanism of computational lens in elaborating the principles, mechanisms and application of LGC-DIE-AEH.

The computational lens is the important mean and tool to observe the operational phenomenon and draw up conceptual perspective, and it covers three main components. Above all, the essence of computation, computability and computational complexity, which is aliased as 3C, are the most fundamental operating mechanism of computational lens. The above three can establish theoretical basis and make a problem-oriented sketch for the container terminal logistics hubs at the different decision level of strategic programming, tactical planning and executive scheduling. In the next place, the three of metaphor, migration and mapping, which is called 3M for short, is the kernel functions and common means of computational lens. Lastly, the three of abstraction, automation and analysis, which is abbreviated to 3A, is the main approaches of computational lens. The combination of 3C, 3M and 3A, which is named after 3CMA for short, construct the kernel of computational lens.

There is an internal iterative loop among 3C, 3M and 3A to design, implement, execute, evaluation and improve the working of CTLS by computational lens. On the one hand, the LGC-DIE-AEH is supposed to support the planning and scheduling decision by the agile, dynamic and iterative modeling, migration and modification. On the other hand, the LGC-DIE-AEH can guide the handling technology development, algorithm parameters tuning and performance synthetic evaluation flexibly and effectively. In reality, the LGC-DIE-AEH preliminary sketch is not only applicable to container terminals, but also propitious to support the planning and scheduling of the other complex logistics hubs, especially for the various levels of unit logistics hubs.

D. GREAT PRINCIPLES OF COMPUTING FOR CONTAINER TERMINAL

The GPC is not only appropriate for a wide variety of computer systems, but also provides important guiding significances and reference mechanisms for the running of CTLS. More broadly, the CTLS is the critical computing domain in the physical world under the thinking of RGT-UIF-PoC. It is a brand-new critical computing domain that is clearly different from the ones defined by Peter J. Denning The differences between CTLS and the other critical computing domains is huge, and the underlying reasons for the strong differences are multiple, interdependent and complex. The principal causes are listed as follows.

Above all, the operation of CTLS has the different and sophisticated constraint conditions. The biggest difference comes from the physical specifications and spatial constraints of the LGC-CT processing elements clusters and serviced object sets. The former covers diverse, heterogeneous, parallel and reconfigurable LGC-CT units, such as quay crane (QC), yard crane, container reach stacker and empty container handler. The latter mainly includes various containers and liners whose store-carrying capability is from 100 to 24000 twenty-foot equivalent unit (TEU). The huge variations in delivery capacity among liners make the LGC-CT processing element and memory cell for liners to be requirements diversification and individuation, especially for QCs and berths. This greatly deepens the HDT-NCC of PDP-SAD at container terminals.

Next, the running of CTLS is constrained and driven by different physical laws with respect to computer systems. The operation of LGC-CT processing element farm is mainly ruled by Newtonian law of dynamics. Whereas the performance ceiling of central processing unit (CPU) in computer systems is largely limited by the thermal design power and actual power consumption, which is primarily governed by electromagnetism. There are significant differences on the underlying physical principles of both.

Lastly, there really is a big difference between the running frequency of CTLS and the one of computer systems. The latter is usually 10^8 times more than the former. Nevertheless, the above two treatments are similar terms from the perspective of the nature of computation. The operation of CTLS presents a full and remarkable snapshot of the computation in the physical world.

The above causes make us have an opportunity, necessity and feasibility to redefine the container terminal oriented great principles of computing (CTO-GPC). The CTO-GPC is based on the above LGCA, PC-LGC-CT, and CTO-LGCC, and the specific definition is as follows. First of all, the computation in CTO-GPC is the very LGC-CT. Secondly, the communication in CTO-GPC means container routing, transferring and switching among the different LGC-CT transaction processing units. Thirdly, the coordination in CTO-GPC implies that CTLS performs hierarchical, parallel, heterogeneous and reconfigurable LGC-CT agilely, effectively and robustly by using the multiple dedicated processing units. Fourthly, the recollection in CTO-GPC denotes containers storage, stacking, shifting, retrieving, relocation attached to terminal storage hierarchy. Fifth, the automation in CTO-GPC signifies to discover, transfer and customize PDP-SAD frameworks, mechanisms, paradigms, algorithms and parameters for LGC-CT. Sixth, the evaluation in CTO-GPC intends to assess and predict the performance of CTLS, and guides the improvement on automatic implementation and execution of LGC-CT. Lastly, the design in CTO-GPC focuses to structure LGC-CT systems for reliability, dependability, agility and robustness.

It should be stressed here that the corresponding parts in LGC-DIE-AEH is no other than CTO-GPC. The combination of CTO-GPC and 3CMA comprises what is known as the kernel of computational logistics implementation and application. It provides the specific means and tools to apply and transfer the theory, principles and paradigms of computation into CTLS, even the other complex logistics domains. Meanwhile, the above combination provides an implementation and evaluation path and reference of RGT-UIF-PoC philosophy.

V. CASE STUDY

A. CONTAINER TERMINAL LOGISTICS GENERAILIZED COMPUTING SCENARIO

A representative and regional container terminal hub located on the China's South-East coastal areas is chosen to illustrate and expatiate on the computational logistics for CTLS with computational lens and GPC, especially for the interpretation, understanding, application and exploration on LGC-DIE-AEH.

There are five discrete berths are located along the marginal quay wharf apron, and the total length of berth set come up to 1650 meters. The single berth can accommodate the container liner with the water displacement of 50, 000 tons, and the terminal can accommodate the container ships with the water displacement of 150, 000 tons if allowing to cross the single berth because the prominent water depth conditions are available at the quayside. Meanwhile, there are ten quay cranes along the wharf apron with the four kinds of running specifications, and the specifications differences are distinct among QCs. This directly results in the QC subset being suitable for different types of liners.

The calling liners are mainly domestic and foreign trade trunk lines, ocean routes and barge container ships among adjacent terminals. The terminal container annual throughput design capability is approximately 1.5 million TEUs.

B. CENTRAL HANDLING COMPUTATIONAL UNIT KEY PARAMETERS AND TASK ANALYSIS

Based on the computational logistics, it had made a point that the QC is no other than the central handling computational unit (CHCU) in the logistics generalized computation processing unit farm at container terminals in our previous studies [13]. Furthermore, the running of CHCU is really at the center of LGC-CT because it is the accessing, shifting and switching engine between water-land transshipment. In this case, the terminal adopts the coastwise wharf, and the ten QCs lined up at quayside. The ten QCs constitute a CHCU farm that possesses the parallelism, heterogeneity, reconfigurability and context sensitivity. As a result, the CHCU farm is for a multi-server, multi-queuing and multi-buffering LGC-CT with the heterogeneous shard memories that are the hatch, berth and wharf apron under the computational lens. Furthermore, the element in the CHCU farm can conduct dynamic flexible combination according to the calling liners. Thereupon, the CHCU farm operation can be considered as the random load test of CTLS that is frequently used in computer science, and we can make exploration and practice of LGC-CT by LGC-DIE-AEH.

The key running parameter of CHCU for configuration and deployment is shown in Table 1. It is worth mentioning that the quay crane identification number is abbreviated as QCID. The handling efficiency of CHCU is generally between 25 and 40 moves per hour, and the QC can load or discharge two twenty-feet equivalent units (1 TEU), or one forty-feet equivalent unit (2 TEU), or one forty-five-foot equivalent unit (2.25 TEU) at a time. The QC configuration is very common at container terminals in practice because the QC cluster must meet the loading and unloading requirements of a variety of ships, especially for the container hub port.

The key running parameter of CHCU directly determines the loading and discharging operation specifications of the liners that are the core service targets. It is clearly different from the situations in CPU for computer systems because the CPU makes no distinction at all among service objects that are all binary strings. Beyond all question, this greatly increases the difficulty of PDP-SAD. This is especially true when we consider multi-CHCU joint operations. Besides the liners that are the actually dynamic cache of LGC-CT by the CHCU, the specifications and technical parameters of containers are markedly different. It also exerts a powerful influence on the PDP-SAD of CHCU array.

We truncate LGC-CT log records executed by CHCUs for a recent full two years whose timesheet is more than

TABLE 1. Terminal quayside CHCU key running parameters.

QCID	Outreach (meter)	Max Lifting Height (meter)	Maximum lifting weight (tonne)	Maximum Handling Bays	Quayside Location Span (meter)
1	50	35	50	18	35 ~ 385
2	50	35	50	18	165 ~ 600
3	50	35	50	18	340 ~ 820
4	60	40	61	22	525 ~ 980
5	60	40	61	22	620 ~ 1108
6	60	40	61	22	695 ~ 1185
7	60	50	61	22	845 ~ 1295
8	65	42	65	24	970 ~ 1510
9	65	42	65	24	1175 ~ 1630
10	65	42	65	24	1180 ~ 1630

TABLE 2. Container liner calling terminal general profile.

Critical Features	Value Range	Median	Average	Mode	Standard Deviation	Variance
Calling Frequency	1-235	4	12.571	1	28.182	794.201
Handling Volume (Unit)	1-5036	221	345.34	128	390.766	152698.232
Handling Volume (TEU)	1-5062	282.500	463.966	246	554.954	307973.471
Berthing Time (Hours)	0.5833-46.9167	9.5833	10.548	8.500	5.681	32.272
Overall Running Time of QCs (Hours)	0.050-148.020	10.315	14.909	6.150	14.924	222.727
Delay Pending time of QCs (Hours)	0.000-11.970	0.200	0.906	0.000	1.236	1.528
Actual Handling Time of QCs (Hours)	0.050-142.080	9.505	14.003	5.620	14.339	205.605

10600 ones after data cleaning and ruling out some of the extremes. It is also considered as the basis of further discussion. Through the preliminary statistical analysis, the main features of LGC-CT log set can be summarized as follows.

During the two years, 406 different liners belonging to shipping companies in sizes made about 5104 voyages to the container terminal, the total time at berths for all the liners are 53836.830 hours during the two years. Meanwhile, the 1762604 container units are loaded and unloaded that is 2368081 TEUs in effect.

Correspondingly, the quay crane overall running time (QC-ORT) is 76095.758 hours during the two years, which is identified with CPU time by LGC-DIE-AEH. The QC-ORT consists of two parts: quay crane delay pending time (QC-DPT) and quay crane actual handling time (QC-AHT). The former is 4622.577 hours, and the latter is 71473.181 hours. Obviously, the smaller the former, the better. The best value for the QC-DPT is zero, however this is almost impossible in practice. The general profile of LGC-CT by the CHCU farm is displayed in Table 2. The above-mentioned provides a rough sketch for the computed core objects, which are just about the job set of the CHCU farm.

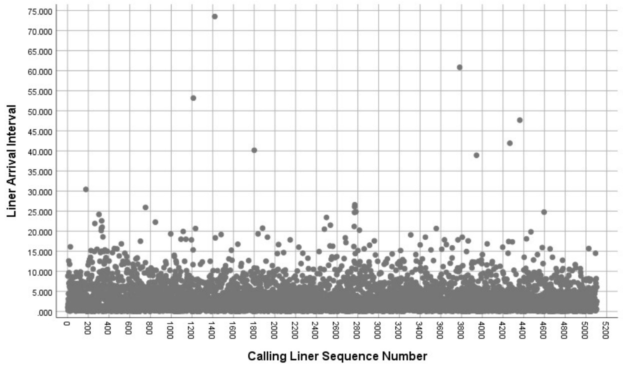
The arrival interval, departure interval and berthing time for the calling liners all are displayed in the Fig. 3. Obviously, the job sequences of the CHCU farm are high parallel and random whether from the arrival instant or for the berthing span. Through Table 2 and Fig. 3, it is easy to find that the specifications of visiting liner and the number of handling containers both have frequent fluctuations during the two years although the container logistics adopts liner transportation. It is clearly not conducive to the planning and scheduling decision of CTLS, but that is exactly one of the difficulties that the terminal operation must face.

On the whole, the above scenario indicates that the container terminal is running efficiently but not at full capacity in the two years, which has achieved almost 80% of the design capability of terminals. This is how most busy terminals operate all over the world, and the case study has good typicality and universality to demonstrate the exploration and application of LGC-DIE-AEH.

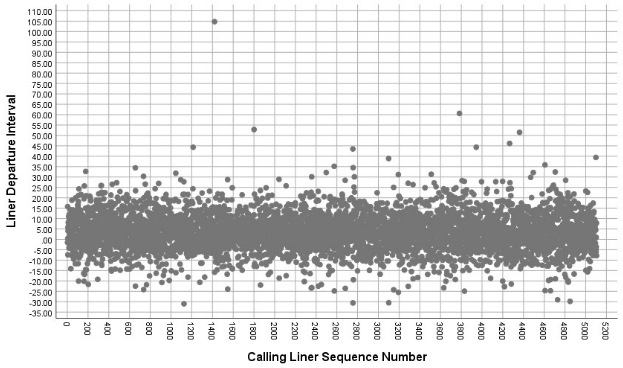
C. CENTRAL HANDLING COMPUTATIONAL UNIT FARM LGC-CT RUNNING EFFICIENCY

Under the computational lens, the QC is just the exactly as the CPU in computer systems both in terms of function and status. As a result, the abstraction, automation and analysis of the QC set plays a crucial role in the operation and execution of CTLS.

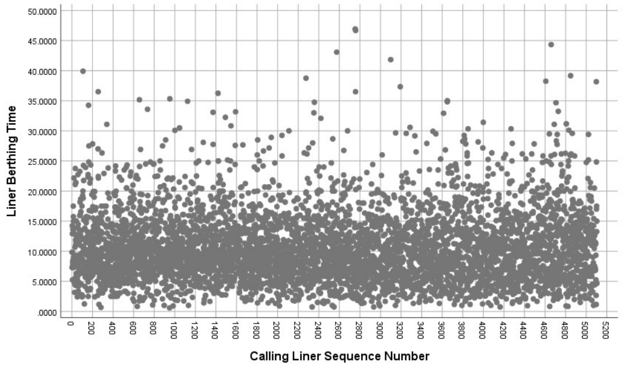
In the previous section, the QC has been abstracted as the CHCU, and all QCs deployed along the quayside constitute a CHCU farm. The automation of QCs is just about the design, deployment, implementation, execution and evaluation of LGC-CT by QCs. As a matter of fact, the running of QCs demonstrates the PC-LGC-CT to a great extent, and



(a) Arrival interval distribution of visiting liner



(b) Departure interval distribution of visiting liner



(c) Berthing time distribution of visiting liner

FIGURE 3. Calling liner berthing conditions.

it expatiates on the principle of computation in GPC whose focus is just computability in its original definition, for CTLS as well. In its broadest sense, the LGC-CT by QCs covers the allocation, binding, pending, accessing, shifting, handling, collaboration and release of the CHCUs according to the ship stowage plan, expected time of ship arrival, estimated time of ship departure, the real-time container arrangement conditions on yard, and so on.

Another thing to explain that the visiting liner is abstracted as the generalized program in CTLS by computational lens. One or more QCs constitute one or more loading and discharging lines for the execution of a generalized program. We can open up discussion on the performance of LGC-CT from the visual angle of liner and CHCU.

In this section, we expand the analysis of the CHCU farm for LGC-CT running efficiency from the seven key performance indicators of CHCUs. Those are quay crane handling container units (QC-HCU), quay crane handling TEUs (QC-HTU), QC-ORT, QC-DPT, QC-AHT, gross crane rate for container units (GCR-CU), gross crane rate for TEU (GCR-TEU). Those are showed from Table 3 to Table 9 seriatim. All the seven indicators provide a performance sketch of the CHCU farm. In addition, the berthing time of liners is bound up with the CHCU LGC-CT performance.

With the conceptual framework of LGC-DIE-AEH, the liner berthing time is equivalent to the program dwell time in computer science, which is a critical parameter of program execution. In fact, the seven of QC-HCU, QC-HTU, QC-ORT, QC-DPT, QC-AHT, GCR-CU, GCR-TEU are all abstracted and transferred from the design philosophy and underlying principle of computing architecture, operating system, and virtual machine by LGC-DIE-AEH. As a result, the above seven indicators, berthing time and QCID nine constitute the crane performance evaluation core indicator framework (CPE-CIF). Judging from the specific practices of LGC-DIE-AEH, the CPE-CIF dwells on the principle of evaluation in GPC, which is intended to measure whether the system behaves as expected in its original definition, for CTLS too. The data from Table 3 to Table 9 is very the LGC-CT oriented actual load test under the computational lens, which is of great significance for the performance prediction and decision management of the CHCU farm.

D. CENTRAL HANDLING COMPUTATIONAL UNIT FARM CLUSTER ANALYSIS

On the grounds of the above statistical analysis, it is concluded that there are a lot of parallel and reconfigurable LGC-CT behaviors in the process of the CHCU farm scheduling and execution. Thereupon, we conduct the K-means cluster analysis of LGC-CT log through the CPE-CIF to probe into the running mode of the CHCU farm.

In accordance with the specifications and heterogeneity of CHCUs that showed in Table 10, we set the number of clusters to be four. Consequently, the quantities of CHCU LGC-CT running records are 3717, 315, 1666 and 4985 items for the four clusters respectively. The final cluster centers of the LGC-CT by CHCUs are showed in Table 10.

The berthing time and the QC-ORT are the most core performance indicators of LGC-CT by LGC-DIE-AEH because the two correspond to program resident time and single CHCU occupancy time separately. The correlation between the berthing time and the QC-ORT is the synergy effect evaluation of LGC-CT and the generalized memory under computational lens to a great degree. In effect, it is also designed to explore the principle of communication in GPC, which means reliably moving information between locations in its original definition, for CTLS.

For the whole LGC-CT log, the Pearson correlation coefficient between the liner berthing time and single QC-ORT is 0.600, and it demonstrates that both are moderate correlation

TABLE 3. LGC-CT key indicators by quay crane handling container units.

QCID	Number of execution records	Handling Volume Minimum	Handling Volume Maximum	Total of Handling Volume	Average of Handling Volume	Standard Deviation of Handling Volume	Variance of Handling Volume
1001	994	2	626	108031	108.680	83.211	6924.052
1002	1256	1	801	142174	113.200	87.236	7610.052
1003	1325	1	1197	170670	128.810	103.128	10635.450
1004	1281	2	1086	207841	162.250	122.316	14961.225
1005	1133	1	1081	207755	183.370	134.318	18041.227
1006	1157	1	1397	210334	181.790	144.283	20817.644
1007	1050	2	1026	193176	183.980	139.536	19470.167
1008	973	5	1073	192162	197.490	149.635	22390.728
1009	813	2	1055	172064	211.640	166.267	27644.573
1010	701	2	1272	158397	225.960	177.065	31351.888

TABLE 4. LGC-CT key indicators by quay crane handling TEUs.

QCID	Number of execution records	Handling Volume Minimum	Handling Volume Maximum	Total of Handling Volume	Average of Handling Volume	Standard Deviation of Handling Volume	Variance of Handling Volume
1001	994	2.000	768.000	153936.250	154.865	111.531	12439.265
1002	1256	2.000	1068.000	201161.250	160.160	115.914	13436.005
1003	1325	1.000	1343.000	232632.500	175.572	129.739	16832.248
1004	1281	2.000	1187.000	275518.000	215.080	161.253	26002.518
1005	1133	2.000	1142.000	278394.000	245.714	182.883	33446.227
1006	1157	1.000	1443.000	285341.750	246.622	193.566	37467.981
1007	1050	2.000	1052.000	261614.750	249.157	193.046	37266.766
1008	973	7.000	1544.500	257404.500	264.547	214.944	46200.900
1009	813	2.000	1320.250	222864.500	274.126	224.671	50476.886
1010	701	2.000	1354.000	199213.500	284.185	222.280	49408.225

TABLE 5. LGC-CT key indicators by quay crane overall running time (hours).

QCID	Number of execution records	QC-ORT Minimum	QC-ORT Maximum	Total of QC-ORT	Average of QC-ORT	Standard Deviation of QC-ORT	Variance of QC-ORT
1001	994	0.040	27.780	5566.502	5.600	4.391	19.279
1002	1256	0.050	45.370	7401.091	5.893	4.457	19.865
1003	1325	0.050	43.960	8286.258	6.254	4.468	19.964
1004	1281	0.070	24.500	8732.147	6.817	4.484	20.104
1005	1133	0.050	33.350	8391.200	7.406	4.718	22.261
1006	1157	0.050	27.970	8366.110	7.231	4.726	22.336
1007	1050	0.100	27.860	7827.230	7.455	4.701	22.102
1008	973	0.200	33.930	8049.550	8.273	5.418	29.357
1009	813	0.030	34.300	7067.100	8.693	5.653	31.961
1010	701	0.080	36.100	6408.570	9.142	5.874	34.503

TABLE 6. LGC-CT key indicators by quay crane delay pending time (hours).

QCID	Number of execution records	QC-DPT Minimum	QC-DPT Maximum	Total of QC-DPT	Average of QC-DPT	Standard Deviation of QC-DPT	Variance of QC-DPT
1001	994	0.000	6.670	466.340	0.469	0.835	0.698
1002	1256	0.000	6.390	569.850	0.454	0.787	0.620
1003	1325	0.000	6.820	548.797	0.414	0.786	0.617
1004	1281	0.000	6.400	586.400	0.458	0.824	0.679
1005	1133	0.000	4.830	690.770	0.610	1.009	1.018
1006	1157	0.000	5.330	465.020	0.402	0.834	0.696
1007	1050	0.000	6.120	350.700	0.334	0.785	0.616
1008	973	0.000	6.130	447.590	0.460	0.942	0.887
1009	813	0.000	4.500	280.690	0.345	0.742	0.551
1010	701	0.000	4.800	216.750	0.309	0.663	0.439

that is showed in Fig. 4. It seems that the collaboration between berth allocation and quay scheduling is rational and acceptable. However, the Pearson correlation coefficient turn into 0.447, 0.845, 0.623, and 0.183 for the four cluster. The Pearson correlation coefficient of the cluster 1 and the cluster 4 is obviously going down separately, especially for

TABLE 7. LGC-CT key indicators by quay crane actual handling time (hours).

QCID	Number of execution records	QC-AHT Minimum	QC-AHT Maximum	Total of QC-AHT	Average of QC-AHT	Standard Deviation of QC-AHT	Variance of QC-AHT
1001	994	0.040	27.780	5100.162	5.131	4.141	17.146
1002	1256	0.050	45.370	6831.441	5.439	4.280	18.320
1003	1325	0.050	40.210	7737.591	5.840	4.317	18.639
1004	1281	0.070	23.110	8145.747	6.359	4.336	18.801
1005	1133	0.050	33.350	7700.430	6.797	4.474	20.019
1006	1157	0.050	26.740	7901.090	6.829	4.624	21.738
1007	1050	0.100	26.810	7476.530	7.121	4.615	21.300
1008	973	0.200	33.930	7601.960	7.813	5.233	27.386
1009	813	0.030	33.130	6786.410	8.347	5.542	30.714
1010	701	0.080	35.100	6191.820	8.833	5.791	33.540

TABLE 8. LGC-CT key indicators by gross crane rate for container units.

QCID	Number of execution records	GCR_CU Minimum	GCR_CU Maximum	Median of GCR_CU	Average of GCR_CU	Standard Deviation of GCR_CU	Variance of GCR_CU
1001	994	5.000	66.670	22.221	23.445	8.674	75.240
1002	1256	3.790	80.000	21.865	23.086	8.935	79.838
1003	1325	4.970	64.350	22.180	23.382	8.429	71.043
1004	1281	6.667	76.810	25.160	26.230	8.765	76.827
1005	1133	5.450	80.000	26.030	27.310	9.516	90.559
1006	1157	4.640	66.846	25.570	26.742	9.295	86.399
1007	1050	5.106	87.070	24.960	26.329	9.455	89.393
1008	973	4.425	81.080	25.000	26.107	9.195	84.543
1009	813	5.810	83.330	24.360	25.647	9.221	85.029
1010	701	3.160	70.080	24.600	25.640	9.177	84.209

TABLE 9. LGC-CT key indicators by gross crane rate for TEU.

QCID	Number of execution records	GCR_TEU Minimum	GCR_TEU Maximum	Median of GCR_TEU	Average of GCR_TEU	Standard Deviation of GCR_TEU	Variance of GCR_TEU
1001	994	5.370	90.280	32.705	34.733	14.349	205.907
1002	1256	6.400	88.500	31.230	33.558	14.158	200.446
1003	1325	5.450	90.910	30.770	32.955	13.357	178.421
1004	1281	8.130	90.280	33.410	35.056	12.511	156.526
1005	1133	6.270	88.340	35.130	36.680	13.199	174.204
1006	1157	5.740	86.090	34.880	36.210	12.941	167.468
1007	1050	6.670	89.540	33.175	34.890	12.559	157.727
1008	973	4.425	84.810	32.190	34.131	12.466	155.407
1009	813	6.730	83.330	30.410	32.422	11.552	133.458
1010	701	6.320	81.400	30.840	32.329	11.090	122.978

TABLE 10. Quay crane farm LGC-CT cluster centers.

	Cluster 1	Cluster 2	Cluster 3	Cluster 4
QCID	5	7	6	5
Berthing Time	12.3015	22.4221	16.3340	9.5232
QC-HCU	183	619	334	66
QC-HTU	239.964	829.321	462.996	88.977
QC-ORT	8.336	19.627	13.084	3.436
QC-DPT	0.551	0.843	0.639	0.250
QC-AHT	7.785	18.784	12.445	3.187
GCR-CU	25.452	34.293	28.118	23.748
GCR-TEU	33.887	46.324	39.180	32.446

the latter. The cases in the cluster 1 and cluster 4 reach up to 8707 items which represents 81.457 percent of the entirety. The liner berthing time and single QC-ORT has turned into low correlation for the cluster 4, which is exactly the largest cluster.

Coincidentally, for the execution of LGC-CT, the QC-HCU and the QC-ORT are the most direct embodiment of CHCU running behaviors. For the whole LGC-CT log, the Pearson correlation coefficient between the QC-HCU and the QC-ORT reach up to 0.870. It seems that the QC-HCU and QC-ORT has high positive correlation, and the utilization and efficiency of CHCUs are worthy to be confirmed. Nevertheless, for the different clusters, we can find that the Pearson correlation coefficients between the QC-HCU and the QC-ORT are only 0.513, 0.425, 0.510, and 0.748 respectively for the four clusters, which are illustrated by Fig. 5. It indicates that there is merely a positive moderate correlation between QC-HCU and QC-ORT for any cluster.

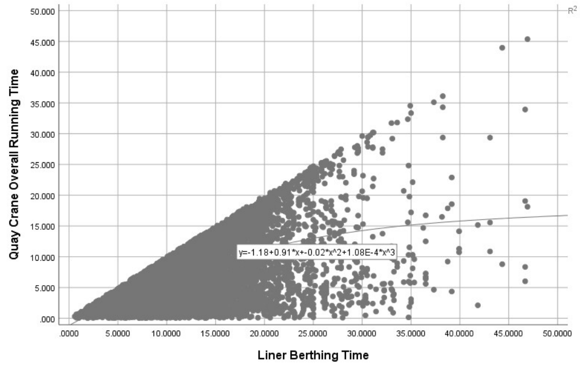


FIGURE 4. **CHCU LGC-CT time and liner berthing time.**

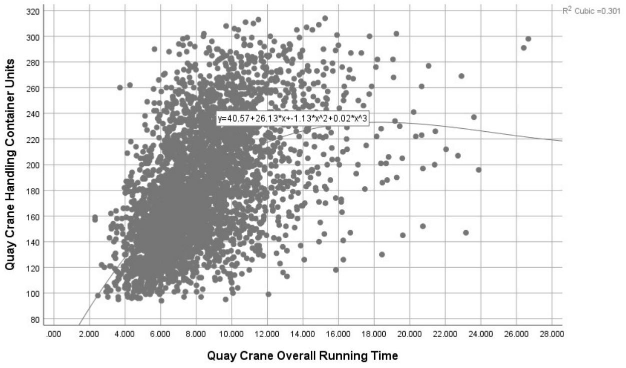
The correlation between the QC-HCU and the QC-ORT decreased dramatically, especially for the cluster 2 and cluster 3. The two have the better performance in terms of the cooperation between liner berthing time and single QC-ORT. But in terms of the QC-HCU and QC-ORT, the cluster 2 and cluster 3 performance actually barely satisfactory. From the above cluster analysis and the associative correlation analysis, it is concluded that there is still much room for improvement in terms of berth allocation and QC allotment.

We make a further correlation analysis among the indicators of CPE-CIF. It is concluded that the QCID has low correlation with the other eight indicators, which shows the quay crane allocation and scheduling (QCAS) should be improved because it is grossly inefficient. Moreover, the QCID with the calling liners has the very low correlation as the Pearson correlation coefficient is only 0.031. In fact, the given liners usually serve the fixed route. The above conditions are surely broken. All indicates the performance of communication on LGC-CT need to be improved distinctly.

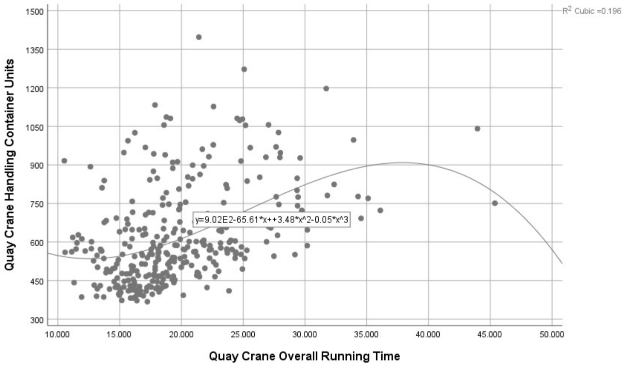
E. CENTRAL HANDLING COMPUTATIONAL UNIT FARM EXECUTIVE PARALLELISM

For the visiting liner, the berthing time is supposed to be made full use of to fulfilled the LGC-CT task as soon as possible. As a result, the parallelism of CHCU is put on the agenda. The range of allocated QCs for one calling liner is from one to seven, and the specific circumstances are listed from Table 11 to 14, which reflects the parallel computing conditions of the generalized program in CTLS. Actually, that is also aimed at exploiting the principle of coordination in GPC, which means effectively using many autonomous computers in its original definition, for CTLS.

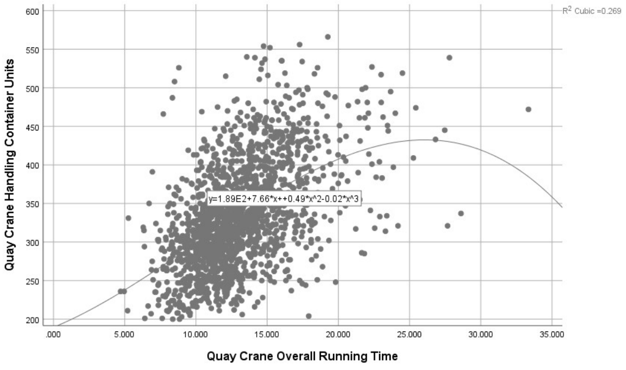
It is worth pointing out the four parallel LGC-CT core indicators. Those are the quay cranes overall handling time for a visiting liner (OHT-VL), the quay cranes actual handling time for a visiting liner (AHT-VL), the quay cranes handling container units for a visiting liner (HCU-VL), the quay cranes handling twenty-foot equivalent units for a visiting liner (HTU-VL). The above four are the effect of parallel LGC-CT from the perspective of the CHCU consuming time and the generalized handling capacity.



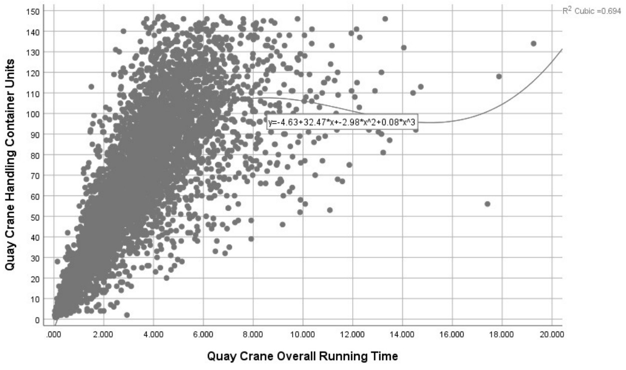
(a) LGC-CT Cluster 1



(b) LGC-CT Cluster 2



(c) LGC-CT Cluster 3



(d) LGC-CT Cluster 4

FIGURE 5. **Correlation analysis between QC-HCU and QC-ORT.**

From the above four tables, we find that the LGC-CT parallelism is from one to seven, and the value domain from

TABLE 11. Parallel LGC-CT core indicators by quay cranes overall handling time for a visiting liner.

Allocated QCs	Voyages	OHT-VL Minimum	OHT-VL Maximum	Median of OHT-VL	Average of OHT-VL	Standard Deviation of OHT-VL	Variance of OHT-VL
1	1771	0.050	26.670	5.400	5.939	3.835	14.707
2	1996	0.650	63.500	10.990	12.026	6.607	43.658
3	717	3.070	99.770	16.820	19.819	11.554	133.501
4	373	6.620	107.090	36.020	36.859	16.416	269.469
5	206	13.790	108.220	52.975	53.220	15.176	230.301
6	40	20.410	148.020	61.800	64.590	22.750	517.544
7	1	70.070	70.070	70.070	70.070	/	/

TABLE 12. Parallel LGC-CT core indicators by quay cranes actual handling time for a visiting liner.

Allocated QCs	Voyages	AHT-VL Minimum	AHT-VL Maximum	Median of AHT-VL	Average of AHT-VL	Standard Deviation of AHT-VL	Variance of AHT-VL
1	1771	0.050	25.000	4.920	5.465	3.640	13.249
2	1996	0.650	62.000	10.120	11.179	6.376	40.651
3	717	2.280	92.070	15.690	18.802	11.285	127.362
4	373	6.620	97.110	34.020	34.878	15.757	248.276
5	206	11.310	98.940	50.960	50.711	15.071	227.137
6	40	19.120	142.080	60.445	61.878	21.548	464.296
7	1	69.570	69.570	69.570	69.570	/	/

TABLE 13. Parallel LGC-CT core indicators by quay cranes handling container units for a visiting liner.

Allocated QCs	Voyages	HCU-VL Minimum	HCU -VL Maximum	Median of HCU-VL	Average of HCU-VL	Standard Deviation of HCU-VL	Variance of HCU-VL
1	1771	1	574	116.000	126.670	81.903	6708.090
2	1996	21	1408	237.000	255.750	145.098	21053.292
3	717	69	2348	352.000	463.700	310.097	96160.445
4	373	150	2228	907.000	925.900	442.068	195424.056
5	206	263	2148	1347.500	1364.730	414.715	171988.870
6	40	458	5036	1643.500	1643.830	769.552	592210.661
7	1	3078	3078	3078.000	3078.000	/	/

TABLE 14. Parallel LGC-CT core indicators by quay cranes handling twenty-foot equivalent units for a visiting liner.

Allocated QCs	Voyages	HTU-VL Minimum	HTU -VL Maximum	Median of HTU-VL	Average of HTU-VL	Standard Deviation of HTU-VL	Variance of HTU-VL
1	1771	2.000	674.000	166.750	172.175	100.121	10024.235
2	1996	21.000	1513.000	304.000	334.666	175.144	30675.550
3	717	117.250	4103.000	463.000	585.526	432.269	186856.648
4	373	155.000	3214.500	1155.000	1233.712	620.107	384533.133
5	206	402.000	4077.500	1961.500	1974.394	673.221	453226.888
6	40	838.750	5062.000	2618.500	2608.938	1013.002	1026172.163
7	1	4086.000	4086.000	4086.000	4086.000	/	/

one to five is the overwhelming majority that accounts for more than 99%, and the value domain from one to four also occupies the vast majority of that accounts for more than 95%, and the allocated QCs of one or two is close to three quarters. Hence, we focus on the conditions that the number of allocated QCs is from one to five.

For the indicator of allocated QCs for a visiting liner, the mean is 2.09, and the median and mode both are 2, and the standard deviation and the variance are 1.125 and 1.265 apart. For one thing, this is consistent with the condition of the visiting ships for the given terminal because most of them are domestic container shipping liners whose proportion is as high as 83%. For another, it is concluded that the QCAS has great randomness and contingency by the standard deviation and variance for the diverse indicators in the Table 11, Table 12, Table 13 and Table 14. This is partly determined by the characteristics of terminal operation, such as the fluctuation of the liner arrival time, handling container volume and stowage distribution conditions, but also it demonstrates that the QCAS is unreasonable to a large extent.

We make a further discussion on the parallel LGC-CT for a calling liner. On the one hand, the Pearson correlation coefficient between the liner berthing time and the OHT-VL is 0.836, 0.709, 0.729, 0.614, and 0.645 respectively while the number of the allocated QCs is 1, 2, 3, 4, and 5, which shows the two are moderate or high correlation. On the other hand, the Pearson correlation coefficient between the liner berthing time and HCU-VL is 0.727, 0.603, 0.674, 0.590, 0.628 on condition that the number of the allocated QCs is 1, 2, 3, 4, and 5. It indicates that the two are moderate related. In addition, the Pearson correlation coefficient between the OHT-VL and the HCU-VL is 0.858, 0.856, 0.924, 0.899, and 0.850 while the number of the allocated QCs is 1, 2, 3, 4, and 5. It shows the OHT-VL is highly correlated with the HCU-VL.

Through the above three sets of data, we can come to the following conclusions. Above all, the allocation of CHCUs is almost directly proportional to the LGC-CT throughput. It indicates that the utilization of QCs is quite sufficient once the CHCU is allotted and bound to a certain liner. Moreover, the synergy among the multi-CHCU is favorable and reliable. Namely, the performance of coordination on LGC-CT is preferable and satisfactory. In the next place, the OHT-VL and the berthing time only has the limited correlation, especially on the conditions of the QCs with 4 or 5. It demonstrates that the cooperation between berth allocation and QCAS is supposed to be further improved. Lastly, the HCU-VL and the berthing time has a little more limited correlation with respect to the OHT-VL, especially for the QCs with 2 or 4. It testifies that the CHCU farm catch one and lose another even under the current workload. Therefore, it is necessary to configure the new QCs for this terminal. As a matter of fact, the container terminal is planning to purchase new QCs with the more advanced specifications to meet the requirements of LGC-CT for the new generation of container ships.

VI. CONCLUSION

The RGT-UIF-PoC is the core concept of computational logistics, and the LGC-DIE-AEH by the integration of computational lens and GPC provides a transferring, design, implement, execution and evaluation architecture, paradigm and pattern for the RGT-UIF-PoC at container terminals. This is an exploration and attempt of computational logistics for complex logistics hubs in the physical world rather than cyberspace. The LGC-DIE-AEH presents a referenced theoretical path and practical solution for the exploration and exploitation of computational thinking, theory of computation, nature of computation in the specific field of container unit logistics hub. The computational logistics is supposed to be answerable for the HDT-NCC in CTLS by the decomposition, abstraction, automation and pattern recognition. Consequently, the computational logistics is a unique analytical framework, transferring origins, design paradigm, implementation guide and evaluation compass for CTLS. In fact, the LGC-DIE-AEH scheme is expected to be extended to the other complex automated unit logistics hubs for PDP-SAD to overcome HDT-NCC, but not just for the container terminals.

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