Review

Yard Operations and Management in Automated Container Terminals: A Review

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Abstract: With the increasing volume of global moving containers and the application of automation technologies, it is important for container terminals to improve handling efficiency. This paper provides a comprehensive literature review on yard management issues in automated container terminals, which is proven to be the key to improve container handling efficiency. This paper analyzes the hotspots in the current yard management research based on the VOSviewer for the last 20 years. More than 600 papers are recorded, and we further discuss 75 papers closely related to the research aiming to identify main features in current research. The research is divided into several clusters based on the 75 papers by VOSviewer. After reviewing and analyzing the literature on these clusters, this paper demonstrates the contribution and gap in the current research and puts forward emerging pressing research topics on yard management in automated container terminals for future research.

Keywords: green port; automated container terminal; review; yard management; VOSviewer

1. Introduction

The Background of This Research

As the connection between water and land, the container terminal plays an important role in the maritime logistics transportation system. The acceleration of economic globalization and regional economic integration leads to the rapidly increasing of trades. The substantial growth of global container freight volume shown in Figure 1 has brought the demand of operating mega container ships [1,2]. Meanwhile, the berthing of mega ships has increased the difficulty of daily operations in container terminals, while the port is preparing for the challenge to handle mega vessels, which already exceed 20000TEU [3].

In order to conquer the mega handlings (Figure 1), advanced scheduling and efficient operations should be considered carefully by the terminal. For many years, optimizing the process flow and improving the management have become the trend of the container terminal development for obtaining the best effect with the least investment [4]. Meanwhile, it should be emphasized that the container terminal is always a place with high incidence rate of safety accidents, which are mostly caused by humans, such as fatigue operation, going against the operating specifications, violating the rules and regulations, carelessness [5]. Beyond the global spread of COVID, the efficiency of container handlings is also highly restricted by lockdown once the pandemic gets worse. As a result, along with the booming handling capacity, the incidence rate of man-made container handlings will undoubtedly keep increase. In addition, the terminal still needs to figure out the problems of aging equipment and the high failure rate of it. The rising maintenance costs force

ports to seek new methods for reducing personnel and improving operation efficiency [6]. To cope with all the above issues, the realization of automated container terminals is a possible path. The application of advanced intelligent automatous technology can greatly reduce the port operational and maintenance costs and forms a new idea of the ports' development. Automated container terminals (ACT) have the advantages of high efficiency, 24 h' all-weather operation and low labor cost [7]. Therefore, they are globally widely used and play an important role in the field of modern port logistics. With the development of artificial intelligence, the automated container terminals are ushering in a period of rapid development, and it goes without saying that automated container terminals will replace the manual terminals [8]. Up to now, a series of new technologies in ACT [9] have brought up many new challenges, which also motivate the related research for ACT [10]. As the main system of the container terminal, the container yard is the key to coordinate different sub-systems in a container terminal. Whether the yard space can be allocated effectively has an important impact on the production cost, throughput, and handling efficiency of the terminal [11]. In pace with advanced technology's development, artificial intelligence, big data, and more technologies are applied to automated container terminals, while the digitization and automation are the inevitable trends of yard management development in the future [12].
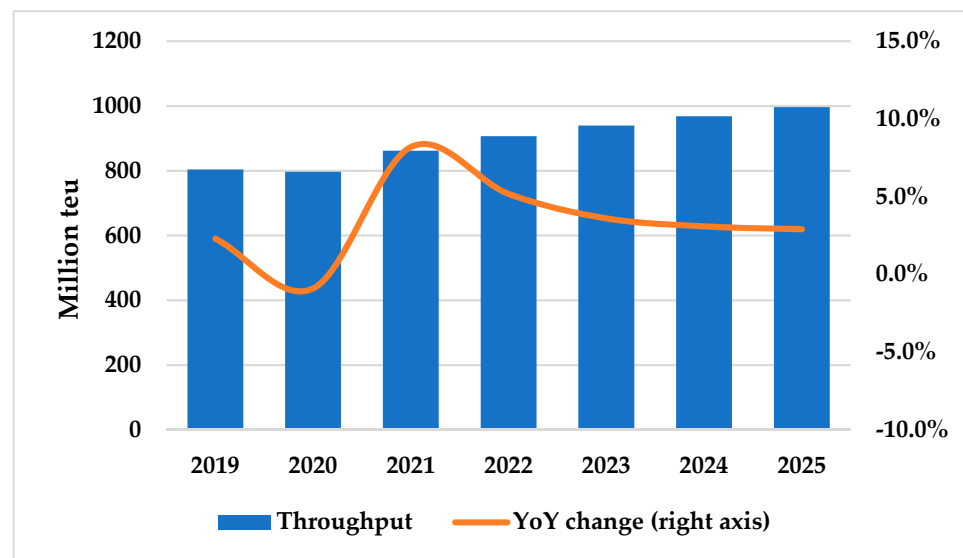

Figure 1. Global container port throughput. (Drewry Maritime Research).

Under the improvement on mechanical dynamic positioning technology, the advantages of an automated container terminal yard management in terms of operation cost, efficiency, and safety are gradually reflected [13]. In order to increase the competitiveness of the port operation in the international market, it has become common sense to improve yard management of automated container terminals or semi-automatic terminals, which can effectively reduce energy consumption [14], cut down production safety risks [15], save manpower [16], and work more efficiently and economically [17]. At present, the research on terminal yard is mostly about the traditional container terminal [18], and the research on automated container terminal yard is still in the initial stage. Currently, several automated terminal management strategies are formulated to improve the yard space utilization and operation efficiency [19]. However, there is a lack of ordering for the yard management research. This paper, based on literature reviews, conducts a systematic investigation on the management of yard in the automated container terminals. Some future research directions on yard management in ACT are also discussed at the end of this paper.

2. Yard Management in Automated Container Terminals

2.1. The Operation of Automated Container Terminals

We have mainly searched for the design of 39 automated container terminals in operations around the world from their official websites and based on Rintanen et al. [20] in Table 1, which summarized and combed the specific operation time, yard layout, and equipment composition corresponding to each terminal, and we list the abbreviation of the main equipment in container terminals in Table 2. Most of these abbreviations are widely used by other scholars or established academically.

Table 1. Comparison of global typical automated container terminals.

Port	Terminal	Start of Operation	Operation Mode	Yard Layout
Port Of Rotterdam	ECT Delta Terminal	1993	Single Trolley QC+ASC+AGV	Perpendicular
Port Of London	Thames port	1996	Single Trolley QC+ARTG+IT	Parallel
Port Of Kawasaki	Kawasaki Automated Terminal	1996	Double Trolley QC+ARMG+IT	Parallel
Port Of Singapore	Pasir Panjang Terminal	1998	Single Trolley QC+ARMG+AGV/IT	Mixed
Port Of Hong Kong	Hongkong International Terminal	1999	Single Trolley QC+RMG/ARMG+IT	Mixed
Port Of Germany	Altenwerde port	2002	Double Trolley QC+ARMG+AGV/ASC	Perpendicular
Port of Tokyo	Wanhai Terminal	2003	Single Trolley QC+ARMG+IT	Parallel
Port of Nagoya	Tobishima	2005	Single Trolley QC+ARTG+AGV	Parallel
Kaohsiung Port	Evergreen Terminal	2006	Single Trolley QC+ARMG+IT	Parallel
Virginia Port	Virginia terminal	2007	Single Trolley QC+ARMG+SC	Perpendicular
Port of Busan	Hanjin New Port Company Terminal	2008	Single Trolley QC+ARMG+IT	Parallel
Port of Busan	Hyuandai Pusan New-port Terminal	2009	Single Trolley QC+ARMG+IT	Parallel
Port of Busan	Pusan New Port Company Terimal	2009	Single Trolley QC+ARMG+ASC/IT	Parallel
Taipei Port	Taipei port container terminal	2009	Single Trolley QC+ARMG+IT	Parallel
Port Of Rotterdam	Euromax port	2010	Double Trolley QC+ARMG+ASC	Perpendicular
Port Of Belgium	Uantwerp DPW	2010	Double Trolley QC+ARMG+SC	Perpendicular
Port Of SPAIN	TTI Algeciras	2010	Single Trolley QC+ASC+SC	Perpendicular
ABU DHABI Port	Khalifa terminal	2012	Double Trolley QC+ARMG+IT	Perpendicular
BUSAN Port	Pusan NewPort Container Terminal	2012	Single Trolley QC+ARMG+SC	Perpendicular

Table 1. *Cont.*

Port	Terminal	Start of Operation	Operation Mode	Yard Layout
Port Of SPAIN	BEST port	2013	Single Trolley QC+ARTG+SC	Perpendicular
Port Of London	London Gateway Terminal	2013	Double Trolley QC+ARMG+SC	Perpendicular
Kaohsiung Port	GaoMing terminal	2013	Double Trolley QC+ARMG+IT	Parallel
Port of Brisbane	Brisbane container terminal	2013	Single Trolley QC+ARMG+SC	Perpendicular
Port of Sydney	Sydney International Container Terminal	2013	Single Trolley QC+ARMG+SC	Perpendicular
Port Of Rotterdam	APM Terminal Maasvlakte II	2014	Double Trolley QC+ARMG+AGV	Perpendicular
Port Of Rotterdam	Rotterdam World Gateway Terminal	2014	Double Trolley QC+ARMG+AGV	Perpendicular
Xiamen Port	Xiamen Ocean Gate Container Terminal	2014	Double Trolley QC+ARMG+AGV	Parallel
Port of New Jersey	Global container terminal	2014	Single Trolley QC+ARMG+SC	Parallel
Port of Brisbane	Patrick Terminal	2014	Single Trolley QC+ARMG+ASC	Perpendicular
Indonesia's Surabaya port	Lamong Bay Terminal	2016	Single Trolley QC+RTG+SC	Parallel
Long Beach port	Long beach container terminal	2016	Double Trolley QC+ARMG+AGV	Perpendicular
Port of Los Angeles	TraPac Terminal	2016	Single Trolley QC+ARMG+ASC	Perpendicular
Shanghai Port	Yangshan Phase VI Automated Terminal	2017	Double Trolley QC+ARMG+AGV	Perpendicular
Qingdao Port	Qianwan Phase IV Automated Terminal	2017	Double Trolley QC+ARMG+AGV	Perpendicular
Port of Melbourne	Victoria International Container Terminal	2017	Single Trolley QC+ARMG+ASC	Perpendicular
Tianjin Port	Five Continents International Container Terminal	2019	Single Trolley QC+ARMG+IAV	Parallel
Ningbo Zhoushan Port	Ningbo Zhoushan Port Meishan	2020	Double Trolley QC+ARTG+IAV	Parallel
Guangxi Qingzhou Port	Dalanping South. Qingzhou Port	2021	Double Trolley QC+ARMG+AGV	Perpendicular
Guangzhou Port	Nansha Phase IV Automated Terminal	2021	Single Trolley QC+ARMG+AGV	Parallel

In relation to the operational mode from Table 1, the operational mode can be divided into two major categories: one is the QC+ARMG+AGV mode with AGV as the transportation equipment, the other is the QC+ARMG+ALV mode where the ALV acts as both the transportation and lifting equipment. While the abbreviation of Table 2 is defined based on former research, Figure 2 schematically present the operation mode of the two types, and the terminal can be roughly divided into three areas: Berth (where the quay cranes perform ship operations), Yard (where containers are temporarily stored), and Gate (where external

trucks are collecting and distributing). The transportation of containers between the berth and the yard is completed by AGVs/ALVs. In the yard, the perpendicular layout is more popular as shown in Table 1 and there are usually dozens of bays in a block, while each bay consists of several stacks storing containers in several layers.

Table 2. The abbreviation of the main equipment in container terminals.

| Abbreviation |
|:---:|
| QC (Quay Crane) |
| AQC (Automated Quay Crane) |
| A-SHC (Automated SHuttle Carrier) |
| IT (Internal Truck) |
| AGV (Automated Guided Vehicles) |
| IAV (Intelligent and Autonomous Vehicle) |
| ALV (Automated Lifting Vehicle) |
| SC (Straddle Carrier) |
| ASC (Automated Straddle Carrier) |
| YC (Yard Crane) |
| AYC (Automated Yard Cranes) |
| RMG (Rail-Mounted Gantry cranes) |
| ARMG (Automated Rail-Mounted Gantry cranes) |
| ARTG (Automated Rubber Tyre Gantry) |
| RTG (Rubber Tyre Gantry) |
| XT (eXternal Truck) |
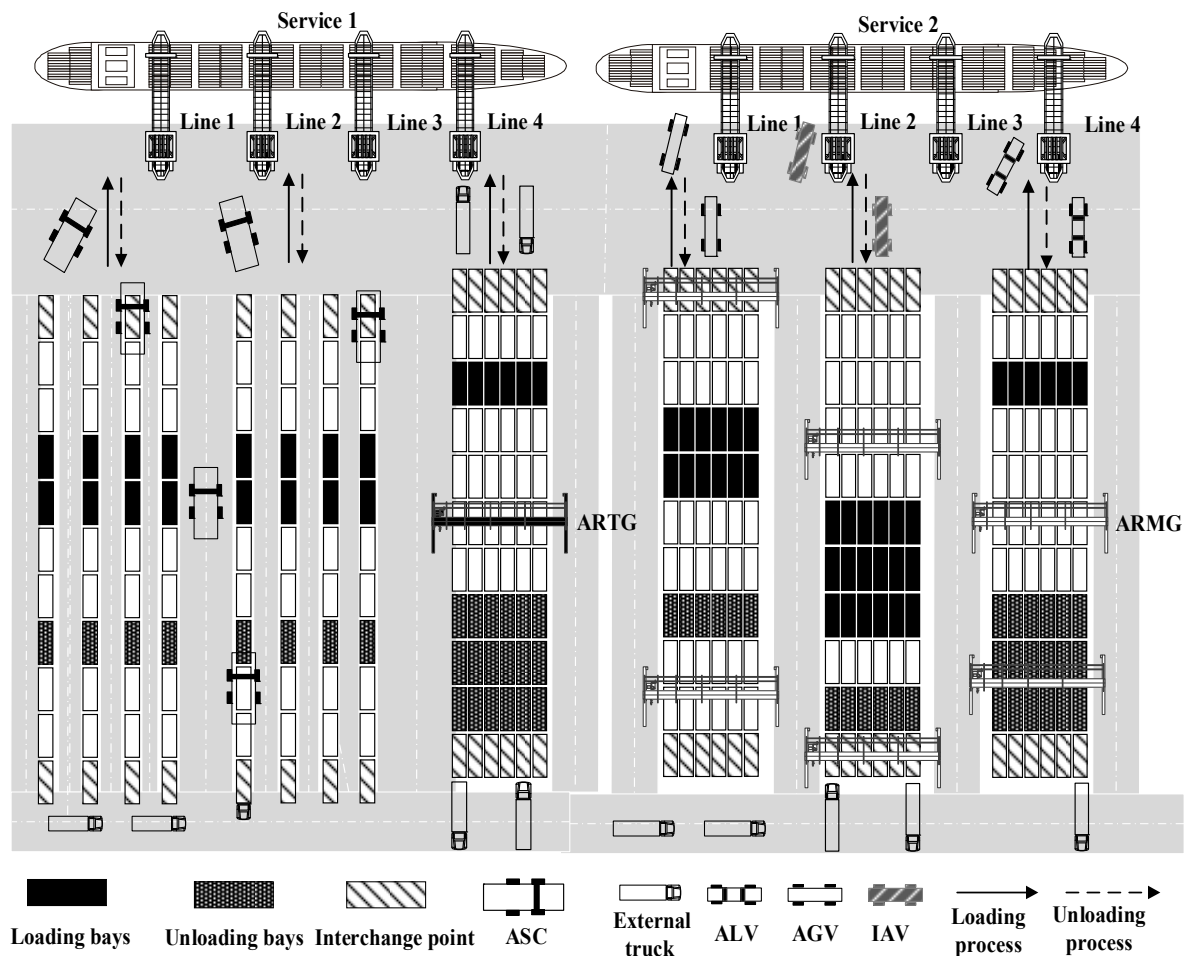
Figure 2. Comparison of two storage yard layout modes.

As shown from the Table 1, ALV is mostly equipped with single trolley quay cranes, while AGVs are more cooperated with double trolley quay cranes. At this stage, compared with those ACTs that have already been put into operation and in the use of AGV, the ALV has a lifting system and spreaders, therefore, an ALV-based terminal saves the time waiting for each other during interaction, which makes the efficiency of the container transportation higher. However, on the cost side, the mode with ALV is always higher than that with AGV. Currently, ALVs are mostly used in European countries. Meanwhile, as shown in the Figure 2 and Table 1, the yard layout can be mainly divided into two forms. One is that the layout of container yard is perpendicular to the berth, and the other layout has the container yards parallel to the berth [21]. At present, most of the newly built automated container terminal yards adopt the perpendicular layout as shown in Table 1.

2.2. Yard Management in the Automated Container Terminals

During the operation of the container terminal, the storage yard plays an important role in the overall performance [22], because it connects the berth and hinterland, acting as a buffer for storing containers [23]. No matter in which type of container terminals, the yard management is always the key to coordinate different handling systems, which has an important impact on the production cost, throughput, and handling efficiency of the terminal [24]. Specifically, Zhen et al. [25] have pointed out that the difficulties of port operations has transferred from quay side to yard side with the advancements of quay side equipment and technologies in automated container terminals. The updated technologies of the automated container terminal have brought about changes in yard usage, equipment operation, interaction, operational process, and stacking mode, thus new yard management and stacking strategies are needed, such as that the interchange point for each block is changing. As the increasing daily operations in an automatic yard generate more uncertain information, rehandling may occur during retrieval operations as containers can be stacked in a sequence, which does not amount to the actual retrieval sequence [26]. Meanwhile, since well-designed yard planning considering equipment assignment is the only way to maximize productivity [27], operational planning that considers integrating both storage allocation and equipment workload distribution is also a crucial step in yard management [28].

Overall, the research on yards is very important for the operation optimization of an automated container terminal, but there is a lack of sorting out the existing research. For this purpose, the major management problems should be clearly defined and the key properties for both practical yard management and theoretical analysis should be compared and classified systematically. In this way, we analyze the current research of yard management in ACT as follows.

3. Research Method

This paper mainly reviews the related research of automated terminal yard management, so we need to screen out the most related papers. First of all, we need to determine the appropriate database. We selected Web of Science as the database of our research. Web of Science is the largest global integrated website of academic information resource citation index, which broadly gathers the research results of scholars from all around the world. After determining the database, we selected the keyword "container yard" as the initial string of keywords for article retrieval. The time span is from 2000 to 2020, and a total of 628 articles were obtained. We visualize the publication of the reviewed articles in Figure 3. Figure 3 from Web of Science (Figure 3a) shows the publication 628 reviewed articles per year and (Figure 3b) shows the publication of 96 reviewed articles per year. We also visualize the cited times of the reviewed articles in Figure 4; Figure 4 is also from Web of Science and (Figure 4a) shows the cited times of 628 reviewed articles per year and (Figure 4b) shows the cited times of 96 articles per year. They show the development of container yard literature over years. As shown in these figures, the research on container yards has gradually increased in recent years. It can also be proved from these figures that

in the last decade, the automated yard has become a research hotspot, and keep attracting more concern.

Then, we input the keywords "automated" and "automatic" to further refine the articles, thus 96 articles were obtained. As this paper is a review of the yard management of automated terminals, we need to exclude the articles on traditional terminals and other fields out of yard management. After refining the articles, we found that there are seven articles in other fields and 14 articles based on a traditional terminal. Therefore, we excluded these articles, and there were still 75 articles for us to review. The whole refining process can be found in Figure 5.
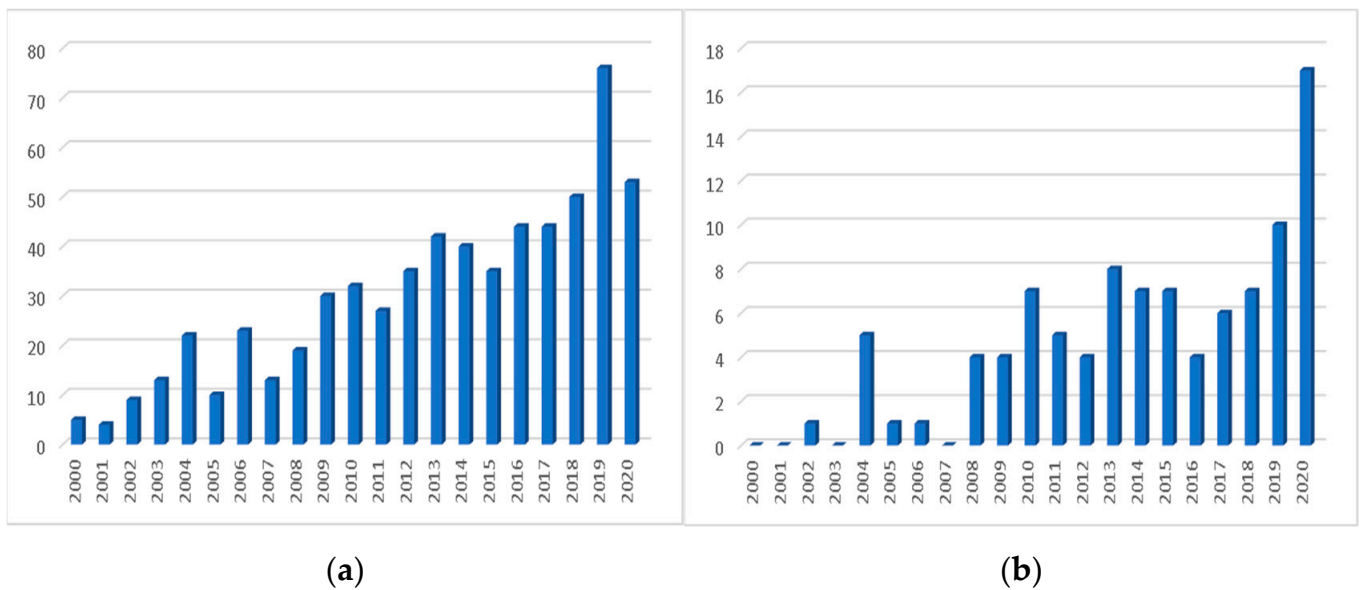

(a)　　　　　　　　　　　　　　　　　　　　　　　　(b)

Figure 3. Publication per year. (**a**) Publication per year for the 628 articles. (**b**) Publication per year for the 96 articles.

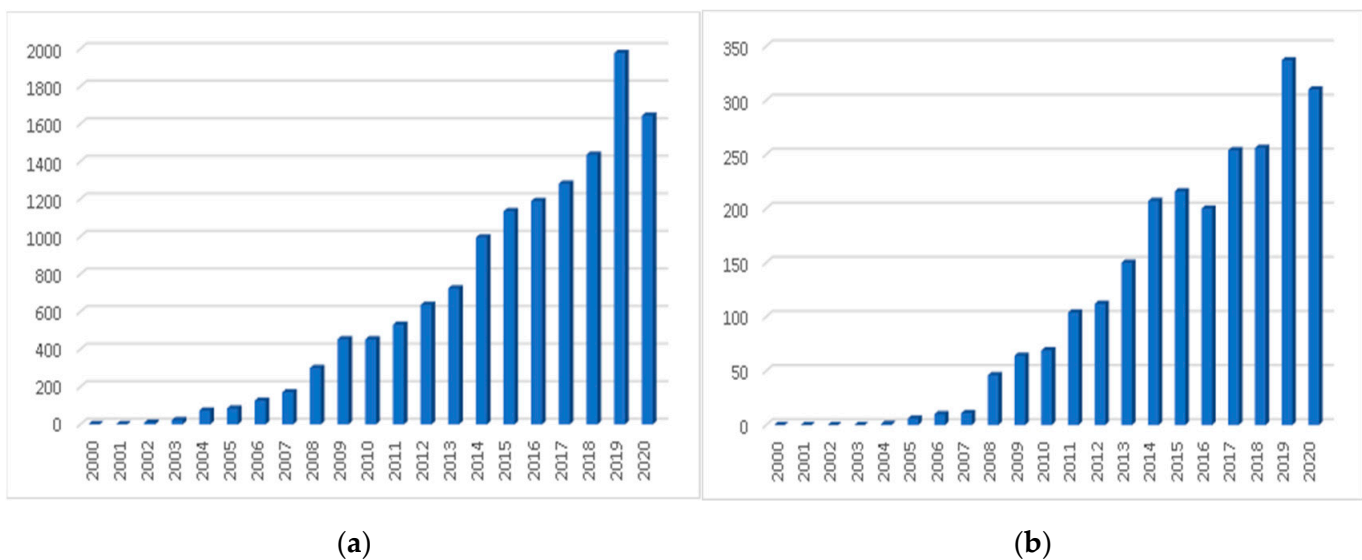(a)　　　　　　　　　　　　　　　　　　　　　　　　(b)

Figure 4. Cited times per year. (**a**) Cited times per year for the 628 articles. (**b**) Cited times per year for the 96 articles.
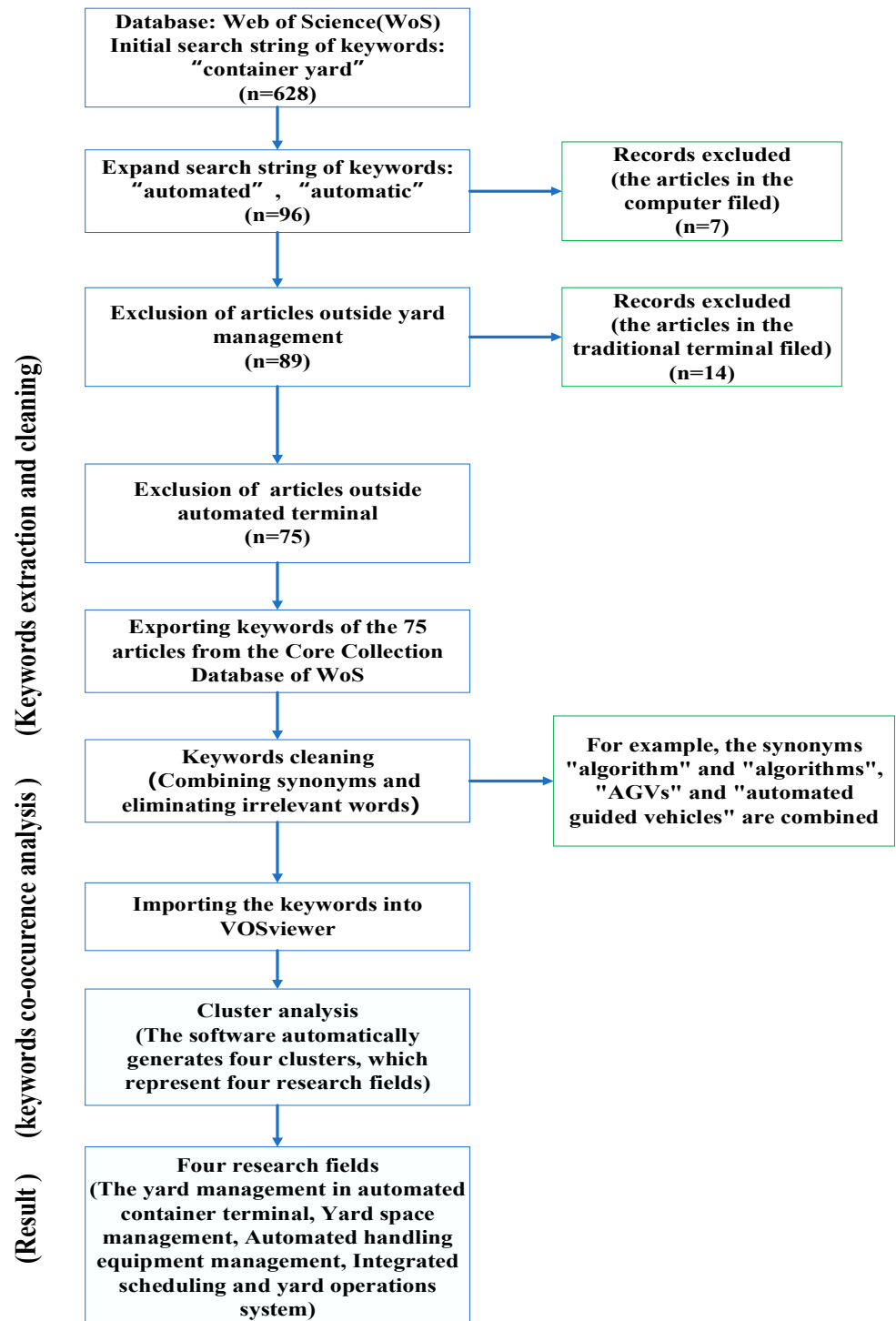
Figure 5. Research background visualization process of automated container yard.

4. Results

We exported the string of 279 keywords of the 75 selected articles from Web of Science, then extracted and roughly cleaned the exported string of keywords. For example, we combined synonyms such as "algorithm" and "algorithms", and eliminated irrelevant words. Finally, we input the 214 cleaned keywords into VOSviewer for keywords co-occurrence analysis and generated a keyword map to visualize the current research as

Figure 6. Figure 6 shows the analysis visualization of all the 214 author keywords by VOSviewer, where the selection frequency is 1 or more.
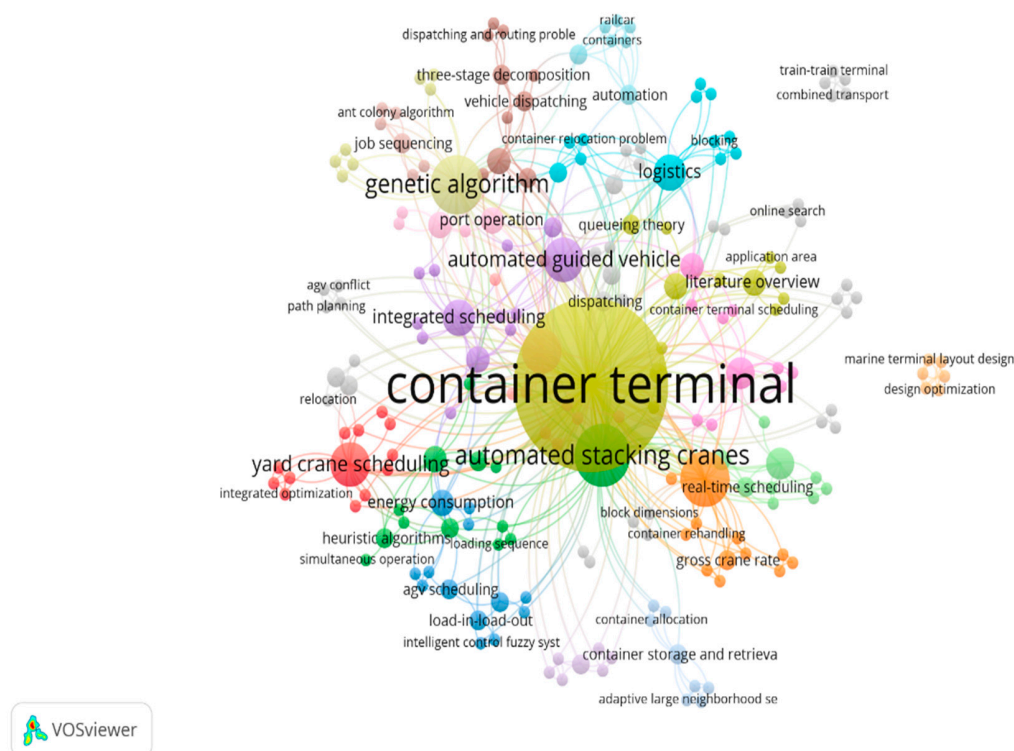

Figure 6. Author keywords network map of 75 recorded papers.

From Figure 6, we can see that the keywords such as "container terminal", "automated stacking cranes", "automated guide vehicles", and "genetic algorithm" appear more frequently, which indicate that they are hot topics in yard management research in ACT. However, there are too many clusters in Figure 6, which makes it difficult to find the focus of current research. In order to better refine the keywords, we further combined the keywords with similar fields, for example, we combined "automated container hub" "automated container port", "automated seaport container terminals" into "automated container hub", etc.

After further combining the 214 author keywords, 22 keywords were chosen. Then, the chosen 22 keywords were imported into VOSviewer, and the frequency was set to 1 or above to generate Figure 7. From Figure 7, we can see that the keywords were divided into four clusters with different colors. To explain, author keywords are generated by the original authors, while keywords plus are distilled from the titles of above references. The keywords plus were analyzed, and the result is shown in Figure 8. After roughly merging 173 keywords plus words exported from Web of Science, 79 keywords were obtained, which were imported into VOSviewer for visualization. The selection frequency was 5 or above, and 29 keywords were chosen to generate Figure 8. It can be seen from Figure 8 that the keywords are divided into four clusters too. In Figure 8, the main keywords of the green cluster include "space allocation", "storage management", etc., so we define this cluster as a yard space management problem, the main keywords of the yellow cluster include "automated container terminal", "container yard", etc., so we define this cluster as a yard management in automated container terminal problem. The main keywords of the red cluster include "equipment deployment problem", "scheduling problem", etc., so we define this cluster as an automated handling equipment management problem. The main keywords of the purple cluster include "operations research", "transportations system", etc., so we define this cluster as an integrated scheduling and yard operations system

problem. Therefore, this paper divides the 75 articles reviewed into these four fields, and studies and discusses the articles in these four fields, and puts forward the shortcomings of current research and the trend of future research.
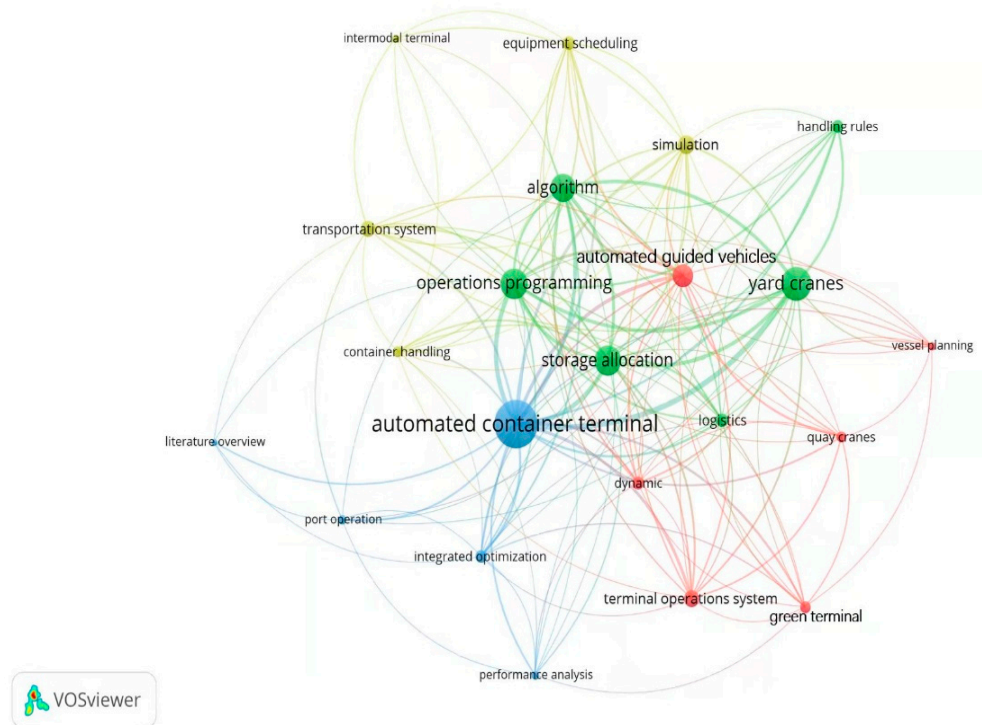

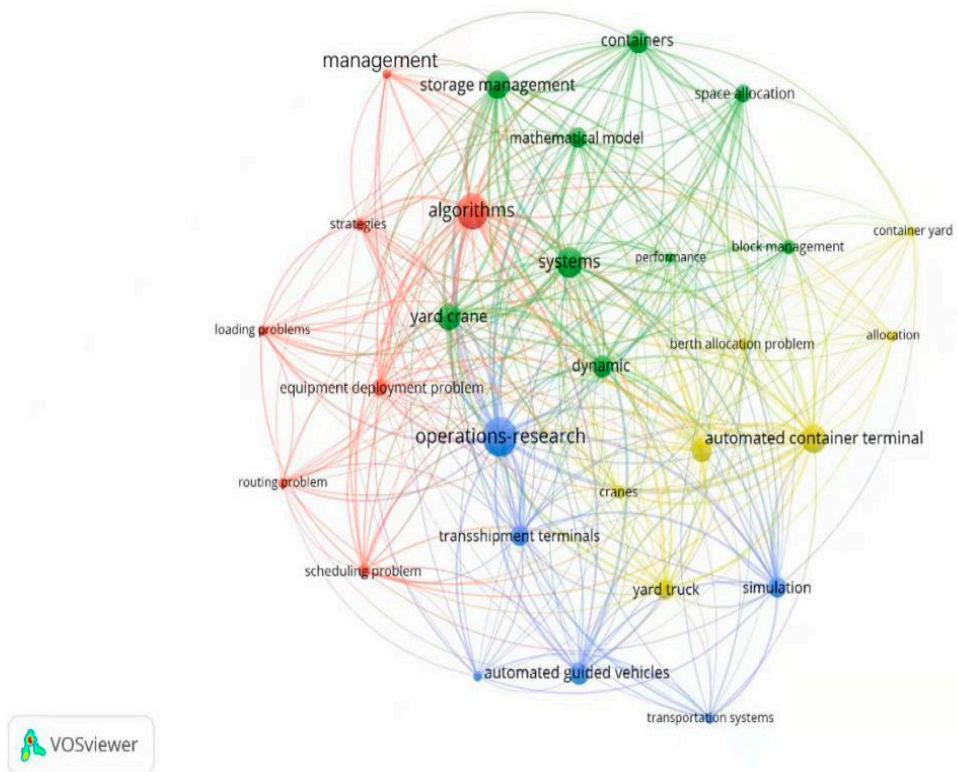**Figure 7.** Author keywords network map after combing keywords in similar fields.

Figure 8. Keywords plus network visualization for five or more occurrences.

5. The Literature Review for Different Clusters

5.1. The Yard Management in Automated Container Terminal

In the last 20 years, the research on yard management of automated terminals has gradually increased. Actually, during the earlier review by Stahlbock et al. [1], the latest development of operational research methods for some automated handling equipment was introduced. They have already pointed out that some former research had proven that the application of automation technologies is efficient to improve the yard performance for traditional container terminals. However, as a vast investment for traditional container terminals, no matter if it is the introduction of new equipment or building new ACT, both need to be carefully considered for terminal operators. The control system is also a challenge for the operation of ACT [29]. As a result, some research starts to figure out whether the automated container terminal will improve the container handlings. Thus, Zhen et al. [30], Hu et al. [31], and Hu et al. [32] estimate the performance of a ground-trolley based automated container terminal, while Tian et al. [33] put forward a network scheduling method to investigate the equipment distribution and the performance of a typical ACT with technologies from Shanghai Zhenhua Heavy Industries Co., Ltd. (ZPMC), Shanghai, China. Meanwhile, Yang et al. [34] apply the concepts of entropy and grey relational analysis (GRA) to compare the operation performance of different yard facilities in Kaohsiung port and discuss the key factors affecting the operation performance in ACT. The research demonstrates the key role of container yard management on coordinating the unloading and loading operations and the storage of containers in ACT. Besides, as a special exploration of the yard system, Hu et al. [35] apply the split-platform automated storage/retrieval systems to form a special layout of ACT and propose a novel yard allocation policy to reduce the possible congestions.

As a more systematical way to capture the operation of ACT, simulation is always applied to analyze the performance of yard management for different facilities, cranes, and layout. Kemme et al. [36] proposes a discrete event simulation model for analyzing the improvement of yard management with the help of automated technologies and compared the impact of different types of yard cranes and layout of yard blocks on the long-run performance of yard handlings. The research reveals a close relationship between the equipped yard cranes in different layouts of yard blocks and the productivity in ACT. Gharehgozli et al. [37] further investigate the effect of a handshake area on the performance of yard management and show that even though the handshake area gives flexibility to reschedule the allocation plan, the yard without a handshake area still outperforms that with a handshake area in most cases. As reviewed by Dragović et al. [38], the simulation model is often applied to analyze port related operations and to evaluate their performance. Specifically, as a combination between ship and terminal gate, the container yard is always proven to be the most important subsystem in a lot of earlier research.

Recently, with the booming capacity of global container transportation, the research about yard management and integrated operations become even more important. As introduced by Kizilay et al. [39], with the application of new technologies, the bottleneck for berth operations is almost overcome. However, the yard management and corresponding integrated operations still challenge most terminal operational systems. Furthermore, the rise of automation at container terminals will undoubtedly increase the requirement for updated yard plans, which not only capture the allocation demand but also the schedules for integrated handlings. It is obvious that the automation of terminal technologies generates new research topics, especially research on yard management in ACT. At present, there is a lack of a systematic summary on the research of related research on yard management in ACT. As a result, our research proposes a new scheme to classify the research on yard management with yard space management, automated handling equipment management and integrated scheduling, while the classification literature is sorted out as follows.

5.2. Yard Space Management

For traditional container terminals, the yard space management can be divided into four sub-problems, including storage strategy planning, storage space allocation, location assignment, and re-marshalling as introduced by Zhen et al. [25]. For the research about yard space management on automated container terminals, most current research mainly talks about the layout of the block when optimizing the yard space, the storage strategies when allocating containers, and the re-marshalling handlings resulting in extra costs. Thus, in our review, we mainly focus on analyzing the research on the automated container terminals from the following three aspects.

5.2.1. Yard Layout

The yard layout is the foundation for handling organizing and equipment scheduling. Reasonable and optimal yard layout is not only important for improving the yard space utilization but also efficient for improving the cooperation among different sub-systems. As proposed by Liu et al. [40], the impact of yard layout and automation on terminal performance are demonstrated by a simulation model. Their research compares the performance of parallel and perpendicular yard layout with and without the automation operations. The research has proven that compared with manual operations, the application of AGVs is efficient in substantially increasing the terminal's throughput. Meanwhile, the research also shows that the perpendicular layout performs a higher throughput than a parallel layout for the same number of AGVs. The advantages of this layout mainly lie in that the running distance of horizontal transportation equipment is greatly shortened, while the number of horizontal transportation equipment in the ACT will reduce [41], which greatly saves operation and energy costs. Furthermore, based on this layout, the seaside operations and the landside operations can be separated to realize the division of operation functional areas and reduce the complexity of path planning. In order to further compare the performance for the layout of the whole ACT, Wang et al. [12] designed a simulation model to capture the interaction between yard and different areas of a typical ACT. The research mainly analyzes the carbon emission resulting from different layouts and shows that a sustainable layout of ACT should have an long enough yard block. Besides, the research also demonstrates that different layouts will affect the performance of equipment operations and the service quality. Thus, the layout of yard space in ACT should always be the first decision for the terminal manager.

For traditional container terminals, a lot of research has talked about the traditional yard layout based on Straddle Carriers (SCs), Rail-Mounted Gantry (RMG) cranes, and Rubber-Tired Gantry (RTG) cranes as reviewed by Gharehgozli et al. [42]. The research on one hand demonstrates that with the increase of global container handlings, the horizontal expansion is still important for creating yard capacities. On the other hand, Dekker et al. [43] propose the potential layout of next generation container terminals, while the tactical, operational, and strategical decision-making problems related to the future layout design are discussed. Meanwhile, Ku et al. [44] propose a three-step framework to design the layout for the next generation of container terminals, where the first step is to design a layout for terminals with new technologies, and then optimizing the configuration and operations of the applied layout, finally analyzing the sustainable impacts.

However, current research about yard layout on ACT are not based on the application of next generation technologies but focus on a more practical discussion. As indicated in Table 1, for current ACTs in operation, most automation equipment is transformed from traditional equipment with an automated control system. As a result, the traditional yard layout has shown to be still fit for most ACTs with AQC+ARMG+AGV, AQC+ARMG+A-SHC modes. In order to analyze the suitable layout for ACTs in operation, current discussions on yard layout in ACT are mainly focused on the horizontal expansion (more bays) and horizontal direction (parallel or perpendicular to the berth), but not on the vertical expansion (higher tier, etc.) [45]. Besides, based on the traditional yard layout, some research studies the storage strategies and re-marshalling problems as follows.

5.2.2. Storage Strategy Planning

The storage strategy is a series of rules to manage the yard space, where the allocation of every export (import) container is determined by considering the following operations of all related equipment. As Dekker et al. [43] proposed earlier, the container stacking on ACT performance has been talked about, different strategies of container stacking in the yard of ACT have been compared, and they pointed out that category stacking performs much better than random stacking, while the control variable of terminal equipment is important to generate available stacking solutions.

As a typical storage planning strategy for ACT, an optimization framework called the weekly yard template was introduced by Ku et al. [44]. Since the liners always call repeatedly for every week, the allocation demand is predictable for the yard. Thus, the weekly yard template made up of consecutive bays (ranges) is efficient in managing the space. However, as the main uncertainty affecting the yard management, the uncertain vessel arrival always causes congestions and rehandles. Thus, a more robust yard template planning for ACT is proposed by Ku et al. [44], where the storage plan is easy to change when uncertainty occurs.

As mentioned in the former section, the yard space management should also capture the interaction between yard and different equipment. Thus, an advanced storage planning strategy should also consider the scheduling of container handlings. As a result, Wu et al. [46] established both a linear mixed integer programming (MIP) and a non-linear mixed integer programming (NLMIP) model to coordinate the scheduling of different equipment and the storage strategy. The integrated decision for a typical perpendicular yard layout equipped with guided vehicles (GVs) of ACT is discussed, while the effects of the number of blocks and the GVs are evaluated for the proposed storage strategy planning. Meanwhile, the other important feature of yard space management is the dynamic demand of container allocations. Thus, Park et al. [47] propose a dynamic adjustment of container stacking policy to locate each incoming container. Their research also points out that the containers of the same group do not have to be allocated at adjacent bays due to the perpendicularly layout. Instead, the moving speed of AYCs during loading and unloading are a more important concern for stacking. Furthermore, Yu et al. [48] propose the space allocation method for three different segregation strategies for the inbound containers. Their research reveal that the non-segregation strategy is more suitable for a congested terminal, which is efficient in reducing the possible rehandles. In order to coordinate the scheduling of grounding and retrieving containers together, Zheng et al. [49] propose a path optimum algorithm (POA) to generate an integrated strategy to allocate the yard space. The same as the traditional container terminal, the most important objective of the storage strategy planning for ACT is to reduce the extra movement. Thus, the re-marshalling problem in the yard of ACT is also well investigated by many researchers as follows.

5.2.3. Re-Marshalling

In the process of container terminal operation, due to the uncertainty of vessel arrival, it may occur that the order of container picking up is not completely consistent with the initial stacking position, which leads to the demand of re-marshalling. For traditional container terminals, import and export containers are always stored in different blocks, thus, most terminal managers prefer to focus on coordinating the space management with yard crane scheduling to avoid the re-marshalling and reduce the cost from re-marshalling. However, for the typical perpendicular yard management of ACT, the re-marshalling cannot be avoided because the import and export containers are mixed, stored in the same block, and the yard cranes have to transfer the import or export containers from the end of the block to a handshake area and re-marshal later for the loading or retrieving. As demonstrated by Park et al. [50], the re-marshalling of loading containers is very important to improve the loading efficiency in a perpendicularly laid-out storage block in ACT. They propose a method to determine targets slots and movement sequence for the re-marshalling.

As to find a re-marshaling plan for an intra-block in ACT, Choe et al. [51] propose a simulated annealing (SA) algorithm to generate the re-marshalling configuration. According to the initial configuration of the target quay crane, they evaluate different re-marshalling configurations, so as to generate the intra-block reloading plan, which minimizes the interference of the stacking cranes and the rehandles during loading and unloading process. Furthermore, in order to process the re-marshalling during the ordinary jobs, Choe et al. [52] developed a new iterative framework so that the re-marshalling can be scheduled together with other works. The method is efficient in helping the ASCs seize opportunities for re-marshalling during regular handlings.

The re-marshalling is also important for reducing the waiting time of external trucks when they retrieve the import containers. In order to fully integrate the yard operations when generating the re-marshalling plan, Covic et al. [53] discusses the impact of different parameters of the terminal appointment system (TAS) on the generation of a re-marshalling plan. The results indicate that even if the external trucks' (XTs) schedules are not known by the terminal, the crane workload can be balanced if the TAS is efficiently applied. The research also emphasizes that the cooperation between XT companies and terminals are important to reduce both waiting time of XTs and to ensure a minimal number of re-marshalling moves. Besides, as a well-studied topic when processing the container relocation in traditional container terminals, the container relocation problem (CRP) should also be further studied for operations of automated storage/retrieval system (AS/RS) in ACT [54].

As demonstrated in former research, due to the characteristics of yard layout and mixed storage of import and export containers in ACT, the re-marshalling is hard to avoid, which also needs to consider the uncertainty from the arrival of vessels and external trucks. Meanwhile, new challenges of scheduling the yard equipment based on the yard space management are also widely discussed in the next section.

5.3. Automated Handling Equipment Management

After more than 20 years' development, many automated container terminals are already well operated around the world as shown in Table 1. Based on the mode of operations in the Table 1, all the handling equipment of automated container terminal in operations can be mainly divided into three categories: Automated Quay Crane (AQC), Automated Shuttle Carrier (A-SHC), and Automated Yard Crane (AYC). Where the Automated Quay Crane is equipped with different types of trolleys to load and unload the container for the vessel. The A-SHC can be further divided into Automated Straddle Carrier (ASC), AGV, Automated Lifting Vehicle (ALV), Intelligent and Autonomous Vehicle (IAV) to transfer containers between berth and yard, while the AYC can be further divided into Automated Rail Mounted Gantry crane (ARMG), Automated Rubber-Tyred Gantry crane (ARTG) to handle containers in the yard. As described above, a breakdown of the classification of automated handling equipment can be seen in Figure 9. In order to further analyze the features of the equipment scheduling for yard management in ACT, we reviewed the related papers as the framework for Figure 9.

5.3.1. AQC Management

Generally, the scheduling of QCs affects the handling time of the ship, while the sequence of QCs movement always cooperates with the stowage plan and the yard allocation. For traditional container terminals, the scheduling of QC has already been well studied and most recent related research start to capture the resilience and sustainable requirement when proposing cooperated QC schedules like a proactive berth allocation and a quay crane assignment problem strategy has been proposed considering minimum recovery cost under uncertainty in Tan et al. [55]. He et al. [56] studied the integrated problem of berth allocation and quay crane assignment to seek the minimum QC driver cost and the maximum operating efficiency. For some semi-automated container terminals, as shown in Table 1, the traditional QC is still applied to cooperate with other automated equip-

ment. Thus, some current research based on traditional QC scheduling is still inspiring for ACT's management. For example, Liu et al. [57] applied a convex mathematical programming model to assign traditional QCs, aiming to minimize CO_2 emission by reducing the congestions from AGVs.
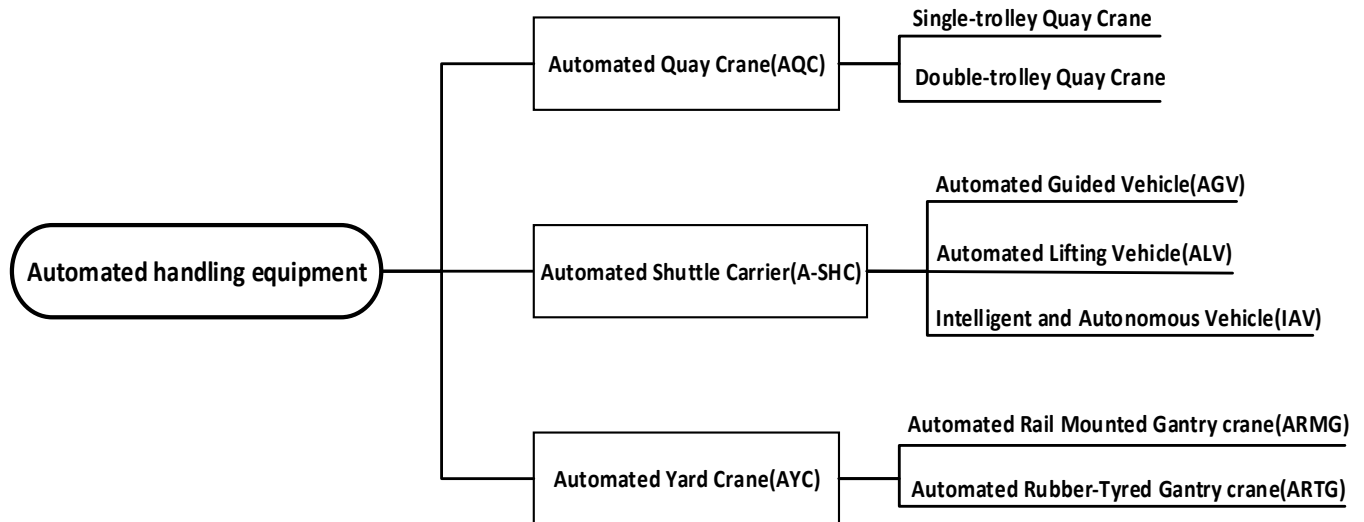

Figure 9. The classification of automated handling equipment.

For current ACT, AQC can be divided into single-trolley AQC and double-trolley AQC. At present, most large, automated container terminals have adopted dual 40ft double-trolley quay cranes to meet the needs of mega ships. The quay crane equipped with double trolley has advantages in terms of efficiency improvement, automation, and labor intensity reduction [30]. On the other side, the quay crane equipped with a single-trolley mode has significant advantages in terms of cost, energy consumption, and space requirements [58]. Comparing with the double-trolley QC in traditional terminals, a typical feature for double-trolley AQC is the design of bridge transfer platform, which consist of the main trolley and the portal trolley, as introduced by Yang et al. [59]. Meanwhile, the cooperative optimization with AYC and A-SHC become more important for AQC scheduling in ACT. In Yang et al. [10], an integrated method to schedule the AQC, AGV, and ARMG is proposed to optimize the loading and unloading operations mode in ACT.

As a typical handling mode for ACT, the loading and unloading mode is developed based on the match between the AQC and yard blocks and shown to be efficient for container handlings. In order to optimize the AQC scheduling for the loading and unloading mode, Yue et al. [60] propose a method for joint scheduling a dual-trolley QC and AGVs. They have established a two-phase optimization model, in which the optimization goal of the first phase is aiming to minimize the energy consumption of the dual-trolley quay crane, while the second phase is mainly to maximize the utilization rate of the AGVs. Furthermore, Zhong et al. [61] design the improved metaheuristic algorithm to effectively settle the integrated scheduling for loading and unloading mode. Besides, Ji et al. [62] studied AGV path planning in the loading and unloading mode of ACT and the integrated scheduling problems on the aspect in joint optimization of QC, AGV, and ASC.

Overall, the yard management plays a significant role in coordinating all the schedules including AQC in ACT, as introduced by Luo et al. [11], yard management are the crucial connection between all the equipment in the integrated optimization. Currently, it is hard to find a related method that can be applied to optimize the yard allocation and the AQC schedules together. Most above optimization or integrated optimization models are based on a strong assumption that the yard storage locations are given. However, for a better improvement of AQC scheduling in ACT, a combinational optimization considers both the berth template and yard template are important for assigning AQCs effectively.

5.3.2. A-SHC Management

The transportation efficiency between the berth and the yard always determines the productivity of the terminal Luo et al. [11], thus, most earlier research has conducted studies about A-SHC management. For the ACT, it required an exchange between investment costs and operating costs for operators to choose the suitable type of A-SHC [63] while evaluating under which conditions the application of A-SHC is more efficient than a semi-automated system [64]. With the development of the transportation equipment, A-SHC mainly contains three types of carriers as show in Figure 9. Since the global first ACT operated in ETC-Delta terminal in 1993, the AGV is shown to be very common in most ACTs. After that, ALV is first applied by Maasvlakte II terminal in Rotterdam in 2014. Comparing with the traditional AGV, ALV is equipped with lifting equipment, which makes it easier to cooperate with the quay crane and yard system, and it is effective for horizontal yard transportation. With the further development of automation and intelligence technology, IAV is more flexible without the signed segments and hope to be more popular for recent ACTs. In order to further analyze the current research about these four pieces of equipment, we make a brief review as follows:

(1)   AGV MANAGEMENT

As the most common A-SHC, the AGV is chosen by many ACTs. The potential problems when applying AGV is tested by Liu et al. [65] based on the simulation method. A timed place petri net (TPPN) is developed to construct a simulation framework for the design of the ACTs. The proposed framework is effective in capturing the behavior of AGVs, which also coordinate crane systems. As the main transportation equipment between berth and yard, the most important issue for AGV management is the dispatching method and the routing planning. Thus, Kim et al. [66] solve AGV task allocation problem by a mixed integer programming model that assigns delivery tasks to AGVs. Various dispatching rules have been compared in Kim et al. [66] and the results reveal the effects of the number of AGVs on the delay and travel time of AGV transportation. In order to improve the throughput of ACTs and the utilization of AGVs, Xu et al. [67] propose a load-in and load-out route planning for AGVs, which provide a two-way loading between berth and the container yard. They also develop a simulated annealing algorithm to improve the solving efficiency and the results show that the two-way loading is outperformed for container handlings in ACTs.

Furthermore, to capture more practical factors during AGV management, Hu et al. [68] propose the integrated problem on dispatching and routing of AGV system, a three-stage decomposition method is designed by combining the A * algorithm with the consideration of time window. The method highly reduces the response and completion time of all the tasks. Besides, some recent research also improves the control strategy of AGVs during the path planning to improve the AGV performance. Zhong et al. [69] propose the priority-based speed control strategy; the strategy is efficient to cooperate with the priority on reorganizing the pathing of AGVs to achieve lower effects of routing conflicts.

(2)   ALV MANAGEMENT

Compared with AGV, ALV is equipped with lifting handles, which makes it easier for both horizontal and vertical transportation for the yard. Yang et al. [70] first compared the performance of applying ALVs instead of AGV. They developed an ACT simulation model with a perpendicular layout and applied ALV to improve the productivity of ACT. Their research verifies that the application of ALV is efficient to utilize the waiting time of AGVs for loading and unloading, which is also of great value to save vehicles. After that, Bae et al. [71] analyze the performance of ALV and AGV for various types of QC handlings, that the self-lifting capability of the ALVs lead to shorter cycle time and higher efficiency than the AGVs due to the shorter waiting time from the YCs and QCs. AGVs eventually catch up to the ALVs when the number of vehicles highly increase. The same conclusion is also draw by Kumawat et al. [72], that the choice of ALV is always outperformed by AGV. Meanwhile, during the comparison between the application of ALV and AGV, they

investigated the effects of yard layout and proved that the optimal yard layout for ALV and AGV are similar.

However, the above simulation-based comparison has the same assumption that the couple between ALV and yard system are very smooth, which is hard to realize because of the complexity of ALV dispatching. In order to dispatch the ALV effectively, Nguyen et al. [73] modelled the tasks delivery of ALVs to improve the transportation between berth and yard. How the size of the buffer zone affects the number of ALVs was revealed by them as well. Meanwhile, in the most current research, the configurations for ALV yard is fixed, which does not consider the best block or bay configuration for ALV transportation system. To solve that problem, Roy et al. [74] develop a stochastic model to discuss the best yard layout configurations for different QC operations. If there are fewer blocks in the yard but each block has more bays, then the trade-off between the travel time of ALV and AYC will be more balanced.

Besides, as a typical type of ALV, ASC (Automated straddle carrier) is also applied in some ACTs like Partrick AutoStrad terminal in Australia. Owing to the lifting and transportation requirements from the ASC, the yard layout is different from general ALV yard layout. The block is formed with multi-single lanes to make sure the ASC can reach each stack. As the main scheduling to transfer containers among QC, yard and trucks, the job sequencing for ASC is crucial to determine the container location and reduce the ASC waiting time. Thus, Yuan et al. [75] propose a grouping approach to organize the container stacking and sequencing in multiple levels. The results reveal that the scheduling of ASCs should coordinate with the yard allocation to improve the handling performance.

(3)   IAV MANAGEMENT

With the development of intelligence and automation technology, more advanced vehicles have been invented, such as the self-driven railcars developed by Delft University of Technology, which improve the conventional shunting and create a more flexible train formation in the Rotterdam Maasvlakte terminal [76]. The self-driven railcars are applied for rail infrastructure in port and intermodal terminals with automatic center coupling on terminal tracks. The technology is efficient in reducing the congestion due to the shunting and easy to coordinate with marshalling yard management. The motivation of introducing intelligence technologies is always to improve the scheduling flexibility while decoupling the equipment to make it self-intelligent. Thus, the intelligent and autonomous vehicle (IAV) is designed and funded by the European Union [77]. As a generalization of AGV, IAV do not need signed segments to follow particular paths. Instead, IAV is equipped with several sensors to navigate and detect other IAVs, and it is easier to adapt to the surrounding environment. The paring and unpairing collaboration strategies of IAVs have shown to be efficient for some small terminals with confined space in Gelareh et al. [77].

To sum up, most current A-SHC management research related to yards focus on AGVs and ALVs. For the yard management in AGV systems, the couple between AGV and the interchange point in the yard is crucial to improve the transportation efficiency. As the interchange point in ACT is mainly located at the end of the block, most research mainly improve the dispatching of AGVs instead of talking about the effects from yard allocation. On the other side, the ALV has the advantage of non-coupling, that they can operate the loading/unloading and the horizontal transportation together. As a result, the yard configuration and container sequencing become more important for ALV scheduling. Besides, most AGV and ALV are operated on a fixed route based on signed segments, which lead most earlier research to focus on how to optimize the routing or path planning of the A-SHCs. However, with the introduction of IAV and further development of AGVs and ALVs, the yard allocation will undoubtedly play a more important role in coordinating with the retrieving sequencing of different A-SHCs.

5.3.3. AYC Management

Because of the perpendicularly layout and the design of interchange point, the moving of AYCs always determine the container grounding and retrieving performance. Therefore,

most research about AYC management focus on the scheduling of AYCs and compare the AYC performance of different yard crane system [78]. However, the yard allocation is still crucial for AYC scheduling since the allocation plans restrict the possible solutions of the AYC scheduling. For ACT, the containers belonging to the same group do not have to be allocated at adjacent bays compared with the traditional terminal [79]. Instead, updated yard allocation strategies are needed to coordinate the scheduling of AYCs. In order to figure out the yard management requirements for AYC scheduling, this part analyzes the recorded papers from the following two aspects.

(1)   SINGLE CRANE PROBLEM

For a typical single AYC scheduling, the horizontal and vertical movements of container handling (loading/unloading) are considered by Huang et al. [80]. They propose a routing model to optimize the AYC scheduling including length, smooth degree, and safety distance, while the cycle time is minimized. Comparing with the traditional yard crane scheduling, the generation of handling sequence for AYC in ACT should further coordinate the plan of other subsystems, such as the stowage plan [81]. As the stowage plan always restricts the container to be loaded, the rehandles of AYC should be minimized to guarantee the loading efficiency. Thus, Shu et al. [81] optimize the retrieving sequence of AYC to coordinate the stowage plan instead of relocating containers due to the stowage plan. Meanwhile, they have emphasized that the rehandle (turn-over) operations should be avoided for the yard management in ACT to improve the efficiency of AYC. Overall, for the scheduling of single AYC, the focus is the handling sequencing or routing, and the storage strategy is always fixed while the locations of the containers are given.

(2)   MULTI CRANES PROBLEM

Currently, most yard systems in ACT are equipped with two AYCs (as shown in Table 1). Compared with single crane scheduling, two AYCs are always outperformed, which was investigated by Dell et al. [82], especially for a high fullness block in a yard system working with straddle carriers. Their results also show that the number of bays in the block significantly affects the performance of multi AYCs. In order to study the AYC scheduling method for a typical perpendicularly laid out block in ACT, Park et al. [79] talk about the problem of real-time scheduling for two ARMGs. By optimizing the workload of ARMGs to minimize the waiting time of AGV and external trucks, heuristic-based and local-search-based crane scheduling methods are compared. The research also shows that the prior preparatory works and cooperation are always needed for better AYC performance. After that, several studies were carried out to propose the method of scheduling twin yard cranes, such as Gharehgozli et al. [83] that attempted to model the container grounding and retrieving request as a multiple asymmetric generalized traveling salesman problem with precedence constraints. Hu et al. [21] aimed to reduce the conflicts between two AYCs in the same block during handlings by analyzing the minimum time interval of any two tasks. Meanwhile, Lu et al. [84] established the twin cranes scheduling problem as a job shop problem based on the graph theory. In order to improve the solving efficiency of the twin cranes scheduling, a polynomial-time algorithm was introduced by Eilken et al. [85]. The proposed algorithm is well fitted for all realistic problem sizes.

With considering the set-up of handshake area within blocks for the cooperation between the twin cranes, both Carlo et al. [86] and Gharehgozli et al. [37] established the simulation model to test the yard storage strategies with a handshake area. Carlo et al. [86] compared 14 twin AYC priority rules and show that the best rule combination should always give priority for seaside yard crane. Meanwhile, Gharehgozli et al. [37] studied the influence of a handshake area on the performance of twin cranes. Their research also proposes a method to confirm the number of handshake areas, the size and location of the handshake area, along with the container location in the handshake area. After that, Han et al. [87] modelled the scheduling of twin AYCs with a handshake area. The research reveal that the size and location of a handshake area have significant effects on the makespan of all handling once the container task list is confirmed.

In addition, the cross-over stacking cranes are also equipped for some different yard layouts. As demonstrated in Dorndorf et al. [88], synchronizing the multi-ASCs schedules within blocks is key to achieving productive moves for cross-over cranes. Meanwhile, the assignment and sequencing of containers become more important for cross-over cranes [89]. As a result, some research focuses on the scheduling of dispatching containers and routing the cross-over cranes to avoid conflicts. Ehleiter et al. [90] proposed the double-cycling strategy using a heuristic solution process based on priority rules to arrange two crossover cranes during peak hours. The proposed method is especially efficient for scheduling the big crane and cross-over cranes if there are as many inbound as outbound containers. While Nossack et al. [91] evaluated the exact order and by which crane the container should be handled with decomposing the problem into a classical routing problem and a conflict-free scheduling problem. Furthermore, in order to reduce the possible relocation during the crossover handlings, Chen et al. [92] adjusted the operation sequence when generating the cross-over schedules. Besides, for the AYC scheduling in a special yard layout based on the Ground Trolley-based Automated Container Terminal, Jiang et al. [93] and Yang et al. [59] discussed the cooperative operation among the twin cranes, the ground trolley, and the transport vehicles, while Fibrianto et al. [94] developed a job sequencing method for the overhead shuttle cranes in a rail-based automated container terminal.

Overall, it is clear that no matter if it is for single or multi AYC scheduling, current research is based on given yard layout or container allocations. Even though most of them have pointed out that the yard layout and allocations have significant effects on the container dispatching and AYC assignment, there are still fewer studies about optimizing the yard management to improve the AYC performance.

5.4. Integrated Scheduling

In order to coordinate the yard management with other operation systems to improve the handling performance, some research has explored the integrated scheduling in ACT, such as Homayouni et al. [95] that proposed a genetic algorithm-based approach to optimizing the scheduling of the split-platform storage/retrieval system (SP-AS/RS), which is a special yard system for ACT. Hu et al. [96] first designed a method to joint schedule the vehicle dispatching and container location, so that the storage capacity of blocks and the travel time of vehicles are considered together. Furthermore, Gharehgozli et al. [26] studied the integrated problem of allocating containers and sequencing a yard crane with multiple open locations to minimize the total travel time.

Recently, most integrated optimizations have appeared in coordinating the scheduling of AGV and AYC, such as Zhao et al. [97] that proposed a cooperative model to minimize the total energy consumption with considering the possible interference between the dual AYCs. Zhou et al. [98] investigated the simultaneously scheduling for the yard crane and the vehicle parking positions, which is important for both the conventional and automated container yard. Besides, a multi-commodity network flow model based on the task decomposition was designed by Chen et al. [99] to precisely provide the space–time schedule of AGV and AYCs.

Overall, even though some current research has optimized the yard location of each container during the scheduling of AGVs or AYCs, the generation of original templates is always given as input. As a result, the solution of the integrated scheduling is always restricted by the yard template. Therefore, in order to further improve the scheduling of container handlings, the discussion of yard templates become even more important.

6. Summary and Research Challenges

Above all, we have reviewed most current research about the yard management in ACT. With the development and application of automated technologies on container terminals, many discussions have pointed out that the yard management is very important for ACT because of the highly integrated operational demand, while other related research mainly focuses on yard space management, automated handling equipment, and integrated

scheduling. Currently, to evaluate the application of ACT, most studies have analyzed the performance of different types of automated container terminals while the event-based simulation model for ACT is well developed. For the yard space management, the block layout when optimizing the yard space, the storage strategies when allocating containers, and the re-marshalling during the yard handlings are the most popular research topics. Meanwhile, in order to improve the efficiency of handling equipment, the scheduling of automated quay cranes, automated shuttle carriers, and automated yard cranes have been well discussed in order to optimize the container handlings based on given yard allocations. Furthermore, some research has also explored the integrated optimization of the yard management and equipment scheduling to better sequence the container dispatching. However, we should notice that there are still clear gaps between current research and the improvement of yard management, especially in terms of the space management. As a result, we mainly propose some research challenges about the space management, which also has significant effects on the equipment scheduling as follows.

6.1. Yard Template Generation for Automated Container Terminals

The original yard template in current research for ACT is always given as input, which highly limits the solutions for other schedules. However, the yard template generation method for ACT is seldom touched in former research. As the key to coordinate different systems, the generation of yard templates should consider more features of container handlings in ACT. Compared with the yard template generation of traditional container terminal, the first question we should answer is how to confirm the clustering unit for every block. For traditional container terminals, the sub-block (a serious of adjacent bays) has shown to be a suitable clustering unit. However, for ACT, which clustering unit is better still need a validation. Secondly, the mix storage of import and export containers in the same block cannot be avoid for a perpendicular yard, which is seldom discussed in traditional container terminals. As a result, a new question is how to mix the import with export containers during the yard generation. Thirdly, the yard template is shown to have significant effects on the container handlings. Thus, how to generate the yard template with capturing the handling requirements from other systems in ACT is also a new challenge.

6.2. Housekeeping Strategies for Yard Operations

For traditional container terminals, housekeeping has always been avoided by a proper yard allocation and the balancing between cost and efficiency. However, for ACT, the housekeeping plays a more important role in order to achieve higher handling efficiency. Even some perpendicular blocks are equipped with a cantilever to increase the number of interchange points. The main interchange points for most ACTs with a perpendicular yard are always located at the end of the block. As a result, the ARMG transportation between the interchange points and the target location have significant effects on the handling efficiency. To guarantee the loading and unloading efficiency during peak time, the housekeeping strategies should be optimized to improve the ARMG efficiency for berthing vessels. On one hand, seaside ARMGs cannot transport every unloading container to the landside on time during berthing time, thus, the housekeeping mainly transports the unloading containers to the landside to improve the retrieving efficiency. On the other hand, to achieve a higher loading efficiency for seaside ARMG, the housekeeping should sequence the loading containers from grounding bays to better locations near the berth. Obviously, the housekeeping should be scheduled during idle time for both seaside and landside ARMGs, but how to design an optimal housekeeping strategy is worth investigating.

6.3. Integrated Optimization of Space Allocation and Other Operational Systems

Currently, some research has talked about the integrated optimization of container allocation and scheduling of other equipment. However, the integrated optimization for ACT is just beginning, which needs further studying, especially considering the space allocation. Compared with the traditional terminals, the handshake area is always applied

for a perpendicular yard in ACTs to decouple the conflicts between seaside and landside ARMGs. However, how to determine the size and the location of the handshake area is seldom discussed. The set-up of a handshake area is clearly an integrated optimization problem that needs to coordinate the scheduling of both seaside and landside handlings. On the other hand, the container location based on an optimized yard template for ACT is worth further discussion. Even the space allocation has been optimized, the arrival and retrieval sequence still highly affected the grounding of each container. Fewer relocations and higher efficiency of ARMG are two main objectives to achieve for the integrated optimization, while clearer decking strategies are needed to guide each container allocation.

Furthermore, while studying the above three main challenges of yard management, the robustness of the proposed solutions, the effects of the uncertain information, and the data driven analysis are all important extensions that should be considered step by step.

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