AUTOMATED CONTAINER TERMINAL AND MARITIME CONSTRUCTION RISK

ARTICLES FOR FACULTY MEMBERS

Title/Author	AGV-Based Vehicle Transportation in Automated Container Terminals: A Survey / Sun, P. Z. H., You, J., Qiu, S., Wu, E. Q., Xiong, P., Song, A., Zhang, H., & Lu, T.
Source	*IEEE Transactions on Intelligent Transportation Systems* Volume 24 Issue 1 (2023) Pages 341–356 https://doi.org/10.1109/TITS.2022.3215776 (Database: IEEE Xplore)

Title/Author	A Hybrid Dynamic Method for Conflict-Free Integrated Schedule Optimization in U-Shaped Automated Container Terminals / Xu, B., Jie, D., Li, J., Zhou, Y., Wang, H., & Fan, H.
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Title/Author	A probabilistic model of human error assessment for autonomous cargo ships focusing on human–autonomy collaboration / Zhang, M., Zhang, D., Yao, H., & Zhang, K.
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Title/Author	How to control cruise ship disease risk? Inspiration from the research literature / Li, H., Meng, S., & Tong, H.
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Title/Author	The role of ship inspections in maritime accidents: An analysis of risk using the bow-tie approach / Sotiralis, P., Louzis, K., & Ventikos, N. P.
Source	*Proceedings of the Institution of Mechanical Engineers* Volume 233 Issue 1 (2019) Pages 58-70 https://doi.org/10.1177/1748006X18776078 (Database: Sage Journals)

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AGV-Based Vehicle Transportation in Automated Container Terminals: A Survey

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***Abstract*— To respond to the rapid growth of shipping container throughput, terminals urgently need to improve the efficiency of thier operations and reduce operational costs through automation and intellectualization upgrades, thereby improving service levels and enhancing market competitiveness. Due to the advantages of reliable transportation, efficient operation, and environmental friendliness, AGV-based automated container terminal (ACT) has become the development trend of container terminals. To help ACT improve its operational management capabilities, plenty of scholars have explored the transportation system of ACT. Through the analysis of operational management issues, the paper defines the four main research topics in vehicle transportation of the ACT including equipment scheduling, path planning, exception handling, and vehicle management. Then, in each topic, the works in the recent 25 years are summarized and several research opportunities for possible follow-up research directions in different fields are proposed. We expect our survey could not only provide references for more scholars on the research of operation and management of terminals, but also provide guidance for system evaluation and improvement for terminal system engineers and operation managers.**

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***Index Terms*— Automated container terminal, vehicle transportation, equipment scheduling, path planning, exception handing, vehicle management.**

I. Introduction

As THE demand for cargo transportation between different countries and regions continues to increase, container transportation has become one of the main international transportation approaches. Container transportation has the characteristics of standardization, uniformity, and large scale, as well as the advantages of high efficiency and high benefit. It provides an efficient way to realize transport intermodality [1].

As a buffer zone for container transportation, the container terminal occupies an important position in the entire container transportation. As the technology of automation equipment matures, traditional container terminals are actively undergoing automation upgrades or new construction [2], [3]. Automated container terminal (ACT) refers to the realization of automatic operation of all links such as container loading and unloading from the ship, vehicle transportation, and yard loading and unloading through the use of modern communication technology, computer technology, and intelligent control technology. ACT has successfully liberated employees from heavy manual labor and harsh working environments [4].

The standard ACT could be divided into three areas, the quayside operation area, the vehicle transportation area, and the yard operation area. The positional relationships of the three areas are illustrated in Fig. 1. The quayside operation area is responsible for unloading or loading cargo from the ship. The vehicle transportation area is responsible for the transfer of cargo. The yard operation area is responsible for the temporary storage of cargo. It can be seen from Fig. 1 that the vehicle transportation area serves as the connection between the quayside operation area and the yard operation area. The efficiency of vehicle transportation will greatly affect the operation of the entire ACT.

Throughout the development of ACT, from the ECT (operated in 1993) in Rotterdam, Netherlands, the CTA (operated in 2002) in Hamburg, Germany, to the Euromax terminal (operated in 2008) in Rotterdam, the Netherlands, the Ocean Gate (operated in 2016) in Xiamen, China, the Yangsha Terminal (operated in 2017) in Shanghai, China, etc [5], [6],

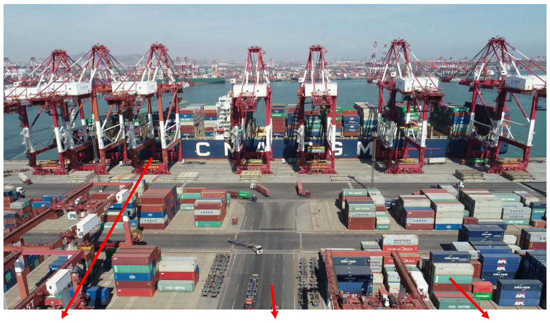


Fig. 1. Real layout of ACT: Take Qingdao Port in China as an example.

the automation of the vehicle transportation area in these ACT are all realized by the Automated Guided Vehicle (AGV). Therefore, AGV is particularly important as a medium that physically connects the quayside area and the yard area. Besides, the intelligent interconnection technology developed in recent years is also requiring ACT towards intelligentization. Nowadays, more and more terminals are changing from traditional terminals to intelligent AGV-based terminals. Also, more and more new AGV-based terminals are emerging every year. For the actual operation and management of the terminal, it is required to solve the following two engineering problems urgently. The first aspect is how to design targeted and efficient transportation solutions for different terminals that are built on the geographical environment and budget costs. The second aspect is how to provide an effective performance evaluation for the intelligent terminals to guide the further improvement of its operational efficiency. Through systematic surveys and analyses of the literature, beneficial guidance could be provided for terminal operation managers and system engineers for better operational management. Besides, the intelligent AGV-based terminals also bring potential research opportunities for AGV-based vehicle transportation in the context of ACT. It encourages scholars to adopt new technologies to further explore theories and methods of terminal operation management based on the results of previous studies.

To the above consideration, it is necessary to identify the current main academic research on AGV-based vehicle transportation in the context of ACT and then analyze the current state of the research. The paper summarizes the research progress of the past 25 years by dividing the core tasks of AGV-based vehicle transportation.

The contributions of the paper are threefold. Firstly, we sort out the main research topics about ACT according to the needs of terminal business development to inspire scientific research. Secondly, for the above important topics, mathematical models of topics are given to illustrate the scientific problems behind the research topics. Finally, by reviewing the literature, the research gaps and the urgent research work that needs to be carried out in the future are proposed. We hope the survey could inspire follow-up research work to help the vehicle transportation system further improve efficiency and reduce operational costs.

The rest of this paper is organized as follows. Section II gives the operational management issues of AGV-based vehicle transportation. Then, Sections III-VI detail the literature reviews of equipment scheduling, path planning, exception handling, and vehicle management, respectively. Next, the research status and research gap are discussed in Section VII. Section VIII summarizes and points out future research directions.

II. Operational Management Issues of AGV-Based Vehicle Transportation

The operational management issues of AGV-based vehicle transportation could be roughly divided into the following four problems, (1) vehicle assignment, (2) vehicle routing, (3) vehicle quantity selection, and (4) vehicle maintenance. (1) and (2) are micro-operation management problems, while (3) and (4) are middle-or macro-operation management problems.

(1) Vehicle Assignment: Vehicle assignment refers to assigning specific AGVs to specific containers during the container transportation process. The most important input for vehicle assignment is the starting point and destination of the container to be transported. Sometimes for urgent tasks, transportation time also needs to be taken into account in the decision-making process. Through a specific mechanism or algorithm, the vehicle assignment determines which vehicle performs the transportation task at the corresponding time.

(2) Vehicle Routing: Vehicle routing refers to planning the path for AGV during the entire task execution process if a specific AGV is determined to perform a specific container transportation task. Vehicle routing has the characteristics of dynamic complexity. The generation of the route not only should consider the starting point and the destination of the container, but also should consider how to coordinate the AGV with other AGVs for avoiding congestion, conflict, and even deadlock of multiple AGVs on roads.

(3) Vehicle Quantity and Type Selection: The selection of vehicle quantity has an important impact on vehicle transportation. Too few or too many AGVs are all not good for vehicle transportation. Too few AGVs will make it difficult to meet the heavy transportation task requirement of ACT. Too many AGVs will increase the burden of terminal operating costs. Besides, when a large number of AGVs operate in the terminal, it will increase the probability of conflicts and deadlocks between AGVs. Therefore, it is an important research topic in the operation and management to put an appropriate number of AGVs to the ACT. The selection of vehicle type needs to balance the investment, operating costs, and carrying performance. It also needs to match the operating mode of the entire terminal. When the vehicle type is not strictly distinguished, the concept of AGV is more widely used to refer to the transportation tool in vehicle transportation. In addition to AGV, the automated lifting vehicle (ALV) is also a typical transportation tool used in the ACT to a certain extent [7]. It should be noted that to not lose generality, except when the selection of vehicle type is specifically discussed, in other places in the paper, AGV is used to refer to the tool of vehicle transportation.

(4) Vehicle Maintenance: Vehicle maintenance refers to the maintenance of the AGV during the entire ACT operation.

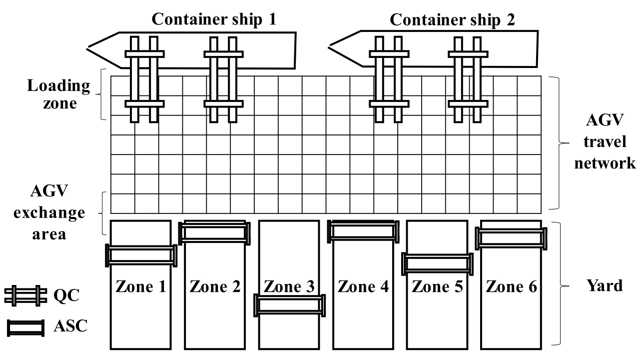


Fig. 2. Classical Layout of the ACT in the literature.

Considering that the AGV needs to operate for a long time in an open harsh environment, the main body and tires of the vehicle will experience varying degrees of wear and erosion. Therefore, timely and efficient vehicle maintenance is an important guarantee for the normal operation of AGV and the saving of ACT operating costs.

Based on the review of papers related to the above four operational management issues, the main research issues are identified. It can be roughly divided into the following four topics: equipment scheduling, path planning, exception handling, and vehicle management. Equipment scheduling refers to the task scheduling of different equipment used in the execution of container loading & unloading tasks. Path planning focuses on the path of the vehicle during driving, which uses different optimization methods to ensure the punctual delivery of transportation tasks as much as possible. Exception handling aims at avoiding accidents such as vehicle collisions and deadlocks that may occur during vehicle driving. Various control methods are used to timely avoid exceptional situations. Vehicle management is mainly related to the vehicle equipment itself. The types of vehicles, the number of vehicles, and vehicle operational situations all need to be considered. Sections III-VI discuss the four topics respectively.

III. Equipment Scheduling

After the container ship arrives at the port, as shown in Fig. 2, the quay crane (QC) places the container on one AGV to transport it to the yard, and then one automated stacking crane (ASC) completes the loading and unloading tasks. To ensure the completion of the transportation tasks, it is required to reasonably schedule the terminal equipment. The starting point and destination of the task, the deadline of the task, the state of the AGV, the site information of the ACT, and other factors should be fully considered during the equipment schedule. So far, plenty of literature has tried to explore the optimal equipment scheduling models and algorithms for certain targets [8], [9], such as achieving the on-time delivery of transportation tasks, improving the utilization rate of pieces of equipment, and reducing the waiting time of the equipment.

A. Basic Scheduling Model of AGV in ACT

Considering that AGV is the core transportation equipment of the ACT, the AGV operation scheduling is taken as an example to establish the basic scheduling model for the operations of terminal equipment.

TABLE I
Definition of Parameters and Decision Variables of AGV Scheduling

Symbol	Definition	Remark
J	Set of tasks	P
J_D	Set of tasks to be assigned	P
J_C	Set of tasks to be delivered	P
V	Set of AGVs	P
R	Set of task requests, which consists of a pair of tasks assigned and delivered	P
T	Global time-series	P
S	Set of received time of all tasks	P
D	Set of time of all tasks plan to reach their destinations	P
F	Set of actual completion time of all tasks	P
L	Set of loading and unloading time of all tasks	P
E	Set of deadline time of all tasks	P
$T(a, b)$	Shortest time from a to b	P
$location(V_i, t)$	Position of V_i at time t	P
A_{sj}	Starting point of W_j	P
A_{ej}	Destination of W_j	P
x_{ij}	If J_j transported by V_i, it is 1, otherwise 0.	D.V.

To better describe the scheduling of multiple AGVs in ACT, a general model is summarized for the mathematical problem of the scheduling. Before that, the parameters and decision variables of the model are defined as shown in Table I. The mark of "P" in the column of "Remark" indicates that it defines a parameter, and "D.V." indicates that it defines a decision variable.

The primary purpose of AGV scheduling is to minimize the total delay time of the tasks, as shown in (1):

$$min \sum_{j \in J} (f_j - e_j). \tag{1}$$

In order to ensure the smooth operation of scheduling, the scheduling model complies with the following constraints.

The total completion time of the task is composed of the delivery time of the task and the loading & unloading time of the cargos, as shown in (2):

$$f_j = d_j + l_j, \quad \forall j \in J. \tag{2}$$

Also, it is required the one-to-one correspondence between AGVs and the tasks they undertake, which means one AGV can only perform one task at any time, and a task can only be performed by one AGV at any time, as shown in (3) and (4):

$$\sum_{j \in J} x_{i,j} = 1, \tag{3}$$

$$\sum_{i \in V} x_{i,j} = 1. \tag{4}$$

Considering the realistic constraints of the scheduling process, the completion time of the task must be at least greater than the time required for the AGV to arrive along the shortest path; the completion time of the task cannot be earlier than the received time of the task; the starting time of task allocation cannot be later than the starting time of task delivery; and also the received time of the task must be a positive number,

TABLE II

EQUIPMENT SCHEDULING RESEARCH IN THE LITERATURE

Reference	Year	Problem	Main objective	Model	Solution method	Constraint
Kim [10]	1999	AGV scheduling	Completion time of loading & unloading operations by QCs; Total traveling time of QCs	MIP model	Heuristic algorithm	Operation delay of the ships
Lu [2]	2019	Multi-ASC scheduling	Waiting time of AGVs and ASCs	Graph model	PSO	Seaside bracket capacity and relay rule of the ASC
Luo [11]	2015	AGV scheduling; Container storage allocation	Docking time of ships	MIP model	GA	
Kim [12]	2004	AGV scheduling	Operations delay time of ASCs; Total travel distance of AGVs	MIP model	Heuristic algorithm	
Jin [13]	2016	AGV scheduling	Completion time of container transportation; Standard deviation of handling time of QCs	MIP model	GA	Sequential order of jobs
Shen [14]	2021	AGV scheduling	Operations time of AGVs	MIP model	Hybrid GA	Operation area of AGVs
Rasidi [15]	2011	AGV scheduling	Total waiting time of AGVs; Total traveling time of AGVs; Total delay time of jobs; Total delay and waiting times of AGVs	Minimum cost flow model	Extended network simplex algorithm and Greedy vehicle search algorithm	Static or dynamic scheduling
Zhong [16]	2020	Integrated scheduling of QC, AGV, and ASC	Loading and unloading time of ships	MIP model	Hybrid method of GA and PSO	
Henry [17]	2005	Integrated scheduling of QC, AGV, and ASC	Operations delay time of QCs; Total traveling time of AGVs; Operations time of ASCs	MIP model	Hybrid method of GA and bat algorithm	
Zhao [18]	2019	Joint scheduling of QC and AGV	Total energy consumption of QCs and AGVs	MIP model	Two-stage taboo search	Capacity limitation of transfer platform on QCs
Chen [19]	2020	Joint scheduling of ASC and AGV	Total turn time of AGVs	Multi-commodity network flow model	Alternating direction method of multipliers	Gate capacity
Skinner [20]	2013	AGV scheduling	Waiting cost of QCs and AGVs; Operations and waiting cost of ASCs; Complete time of high priority jobs	MIP model	GA	
Ji [21]	2020	Integrated scheduling of AGVs, QCs, and ASCs	Completion time of jobs; Total traveling distance of AGVs	Bi-level programming model	Bi-level adaptive GA	
Yang [22]	2018	Integrated scheduling of AGVs, QCs, and ASCs	Loading and unloading time of ships; Total traveling time of AGVs	Bi-level programming model	Congestion prevention rule-based bi-level GA	
Zhang [23]	2021	Joint scheduling of ASC and AGV	Waiting time of AGVs; Operations time of ASCs	MIP model	Three-stage GA	Buffer capacity and operation interference between ASCs
Homayouni [24]	2014	Integrated scheduling of AGVs, QCs, and ASCs	Total traveling time of the platforms and vehicle; Delay in loading & unloading tasks of the QCs	MIP model	GA	

as shown in (5), (6), (7) and (8):

$$t_{r_d} + T(location(V_i, t_{r_d}), A_{sj}) \leq t_{r_c}, \quad \forall r \in R, \tag{5}$$

$$t_{r_d} \geq S_r, \quad \forall r \in R, \tag{6}$$

$$t_{r_c} \geq t_{r_d}, \quad \forall r \in R, \tag{7}$$

$$S_r \geq 0, \quad \forall r \in R. \tag{8}$$

In the model, the total delay time of tasks as the target is expected to be minimized. It fully considers the factors such as the matching relationship between tasks and corresponding equipment, the time constraints, and the task delivery order. Considering that the AGV scheduling is an example of terminal equipment scheduling, the equipment scheduling of the ACT is an NP-hard problem that involves many factors, and the overall solution process is complicated. Based on the given basic model, many scholars combined the different needs of equipment scheduling and took different constraints into account to solve the problem. The specific information of the main research work in the past is shown in Table II.

B. Category of Equipment Scheduling

As shown in Table II, the equipment scheduling optimization of ACT could be divided into three categories: single-type equipment-oriented scheduling, multi-type equipment joint scheduling, and multi-equipment integrated scheduling.

1) Single-Type Equipment-Oriented Scheduling: The optimization of scheduling for the single-type equipment in the ACT is one of the common optimization schemes, such as the scheduling optimization of the QC [25], [26], [27], [28], [29], AGV [30], [31], [32], [33], or ASC [34], [35], [36], [37], [38]. Most scholars focus on the scheduling optimization of AGVs [10], [11], [12], [13], [14], [15], [39]. This type of research mainly optimizes the allocation of container transportation tasks for AGVs to improve the transportation efficiency of AGVs.

Kim et al. [10] studied the task allocation process of AGV and proposed to optimize the overall unloading process of the container through the adjustment of the AGV scheduling. Luo et al. [11] considered the loading and unloading process of containers and proposed a new scheduling rule to conduct the task allocation and determine the storage location of the container. Jin et al. [13] aimed at the dynamic multi-AGV scheduling. In their work, task priority and AGV transportation time are taken into account. Shen et al. [14] comprehensively considered the tasks of QC and ships, and pre-divided the operation area of the AGV to facilitate subsequent task allocation.

Besides, part of the literature studied how to improve the efficiency of operation by optimizing the scheduling of ASC [2], [40], [41], [42], [43], [44]. Among these research, the following are typical representatives. Choe et al. [40] studied the real-time scheduling of non-crossing ASCs in the

ACT. Lu and Wang [2] researched the dual-ASC scheduling problem. Gharehgozli et al. [44] introduced a handshake area to study the operational performance of dual-ASCs. In their research, the handshake area is a temporary storage location so that one ASC could start a request and leave the container there for the other ASC to complete the request.

2) Multi-Type Equipment Joint Scheduling: Multi-type equipment joint scheduling is the popular research direction of optimization scheduling in the context of the ACT at present. Since ACT is a relatively complex workspace involving multiple pieces of equipment, the optimization of single-type equipment is relatively limited to the overall efficiency improvement. Plenty of scholars have gradually paid attention to the multiple types of ACT equipment. It is expected to improve the overall transportation efficiency of ACT through multi-equipment joint scheduling optimization [16], [17], [18], [19], [45].

Zhong et al. [16] studied the integrated scheduling of QC, AGV, and ASC in the ACT. Henry et al. [17] also studied a similar joint scheduling problem as [16]. Zhao et al. [18] considered the synergistic relationship between QC and AGV. Chen et al. [19] studied the joint scheduling problem of QC and AGV as a multi-robot coordinated scheduling problem to solve. To reduce the waiting time of AGV and the running time of ASC, Zhang et al. [23] designed a scheduling model for the coordination scheduling of ASC and AGV.

3) Multi-Equipment Integrated Scheduling: Considering that scheduling and path planning will have a significant impact on the transportation efficiency of the ACT, and there is a certain correlation between the two, some scholars considered both multi-equipment scheduling and path planning [23], [46], and establishing a two-level optimization model to simultaneously consider the two is a typical solution to this kind of integrated scheduling problem [21], [22]. Ji et al. [21] considered the operation mode of synchronous loading and unloading and studied the integrated optimization of scheduling and AGV path planning. Yang et al. [22] established a two-level programming model for the integrated scheduling of multi-equipment and multi-AGV path planning simultaneously.

With the continuous improvement and development of ACT, based on the growing transportation requirements, more and more scholars have gradually shifted from single-equipment scheduling to multi-equipment joint scheduling optimization. The consideration of factors such as loading and unloading modes is also more comprehensive.

C. Optimization Target of Equipment Scheduling

The overall target of equipment scheduling is to improve the transportation efficiency of the ACT. Around the overall optimization target, different scholars have formulated different decomposition targets for the scheduling. Based on the optimization type, it could be divided into two types: single-objective scheduling model and multi-objective scheduling model.

1) Single-Objective Scheduling Model: According to different optimization requirements in scheduling scenarios, different scholars added the corresponding requirements into the models, then established the corresponding objective functions. Plenty of algorithms were proposed to solve the objective functions and achieve the optimization of scheduling.

The operation time is one of the most common optimization targets. Luo et al. [11] aimed to minimize the docking time of ships. Shen et al. [14] aimed to minimize the maximum completion time of AGV. Zhong et al. [16] set the ship loading and unloading time as the optimization target. Chen et al. [19] took the total AGV turning time as the optimization goal. Besides, part of the research also considers other optimization requirements of transportation, such as the energy consumption during driving [47], [48]. For example, Zhao et al. [18] took the lowest total energy consumption of QC and AGV as the optimization target to reduce the energy consumption of the entire scheduling process.

2) Multi-Objective Scheduling Model: To optimize equipment scheduling from many aspects, many scholars combined multiple targets by multi-objective weighting to comprehensively optimize the operations of ACT. The common consideration factors include loading and unloading time of QC, transportation time of AGV, operation time of ASC, delay time of loading and unloading, and other time factors [2], [10], [12], [13], [15], [17], [20], [21], [22], [23]. Besides, the driving distance of the AGV [12], the waiting costs of each piece of equipment, and the transportation costs [20] were also considered in the works of literature. Kim et al. [10] considered the loading and unloading time of QCs and the total transportation time of AGVs simultaneously. Jin et al. [13] took the completion time of tasks and the standard deviation of QC processing time as the optimization objective. Ji et al. [21] optimized the total driving distance of the AGV and the maximum completion time of tasks simultaneously. Skinner et al. [20] performed an integration optimization of ACT, which considered multiple factors such as the waiting cost of QCs, the waiting cost of AGVs, the transportation cost of AGVs, and the completion time of high-priority tasks, and performs integrated optimization.

D. Problem-Solving of Equipment Scheduling

The problem-solving of equipment scheduling is usually divided into two parts, problem modeling, and solving method.

1) Modeling: For equipment scheduling optimization of ACT, the most common model is the mixed-integer programming (MIP) model. Kim et al. [10] fully considered the delay of the ships and established a mixed-integer linear programming model for the two situations of allowing ship delay and not allowing ship delay. Luo et al. [11] considered the loading and unloading process of QCs and set up a MIP model with the target of minimizing the docking time of ships. Jin et al. [13] aimed at the dynamic multi-AGV scheduling. Also, a MIP model was established, which fully considered the priority of tasks and the transportation time of AGVs. Zhao et al. [18] fully considered the capacity limitation of the QC transit platform and set up a collaborative scheduling model with the goal of minimizing the total energy consumption of QCs and AGVs.

To further simplify the problem, part of scholars establish new problem models through model conversion or graph theory based on the common characteristics of the problem. Lu and Wang [2] established a dual-ASC scheduling model by the graph theory, which fully considered the waiting time of ASCs, the waiting time of AGVs, the capacity of the bracket, and the delay rule of ASC. Rasidi and Tsang [15] defined the scheduling problem of AGVs as a minimum cost flow problem and established the corresponding minimum cost flow model. Chen et al. [19] studied the joint scheduling problem of ASCs and AGVs as a multi-robot coordinated scheduling problem and proposed a multi-commodity network flow model.

2) Solving Method: Since equipment scheduling in the ACT is still an NP-hard problem as a whole, the use of solvers and other methods to accurately solve the problem is relatively time-consuming and complex. To provide a more real-time optimization solution for the problem, most works of the literature use heuristics algorithms to solve the problem.

Some scholars use self-defined heuristic rules and algorithms to solve the problem [10], [12]. Besides, most scholars have made certain improvements and innovations based on the existing mature heuristic algorithms, such as the genetic algorithm (GA), particle swarm optimization (PSO), etc., to achieve better solution results. Lu and Wang [2] adopted PSO to solve the dual-ASC scheduling problem. Numerical experiments show that the feasible solutions obtained by PSO could provide the optimal solution for ASC scheduling. To reduce the waiting time of AGV and the operation time of ASC, the design of the handshake area and the buffer zone was introduced and GA was used for the joint scheduling problem of AGV and ASC [23]. The results show that the establishment of the handshake and buffer areas could reduce task delay time and improve the coordination between AGV and ASC. Also, GA has achieved a good solution performance on the problem. Rasidi and Tsang [15] proposed a combination method of the extended network simplex algorithm (NSA+) and greedy vehicle search (GVS) to solve the minimum cost flow model of the AGV scheduling problem. Experimental results show that NSA+ could minimize the waiting time of AGV, while the GVS could reduce the average delay time of AGV. Ji et al. [21] developed conflict resolution strategies to solve the two-level optimization model. The experimental results verify the effectiveness of the proposed algorithm in reducing the task delivery time of the containers.

E. Summary

In summary, for equipment scheduling optimization, most scholars aimed to reduce the waiting time of various equipment and the completion time of loading and unloading tasks. Based on the established equipment scheduling model, heuristic algorithms were widely used to solve the problem. Previous works have played a positive role in improving the efficiency of ACT operations at different levels and to varying degrees. However, considering the year-on-year increase in the throughput of ACT, the scale of operations in the ACT will continue to increase in the future. The number of QCs, the number of AGVs, the number of ASCs, and the operation area of ACT may all usher in rapid growth. How to efficiently deal with multi-equipment and large-scale equipment scheduling, and to improve operational efficiency in the context of automation and intelligence transformation of ACT, will be one of the meaningful research directions.

TABLE III
DEFINITION OF PARAMETERS AND DECISION VARIABLES OF PATH PLANNING

Symbol	Definition	Remark
J	Set of tasks	P
V	Set of AGVs	P
R	Set of routes	P
D_k	Total distance of R_k	P
v_i	Normal driving speed of V_i	P
T_{ijk}^{drive}	Traveling time for V_i to complete J_j through R_k	P
T_{ij}^{start}	Departure time of V_i to execute J_j	P
T_{ijk}^{arrive}	Arrival time for V_i to execute J_j through R_k	P
T_{ij}^{load}	Loading/unloading time for V_i to execute J_j	P
T_{ijk}^{wait}	Waiting time in the process of V_i executing J_j through R_k	P
T_j^{due}	Deadline of J_j	P
$Cost_{ijk}$	Time left until the deadline that V_i completes J_j through R_k	P
x_{ijk}	If V_i executes J_j through R_k, it is 1, otherwise 0.	D.V.

IV. Path Planning

Path planning mainly involves the arrangement of specific driving routes for AGVs [49]. To ensure the punctual completion of transportation tasks, it is required to plan the driving path of the AGV that undertakes each transportation task on time. Path planning usually takes into account factors such as the starting point and destination of the task, the site information of the ACT, the transportation task status, and the deadline of the transportation task [12].

A. Basic Path Planning Model of AGV in ACT

Unlike equipment scheduling, which is researched on multiple types of ACT equipment, the research object of path planning is the AGV group composed of multiple AGVs. To better explain the problem of multi-AGV path planning, the common factors involved in path planning are integrated here to establish the basic model of path planning in ACT. The model parameters and definitions are shown in Table III. The mark of "P" in the column of "Remark" indicates that it defines a parameter, and "D.V." indicates that it defines a decision variable.

Rational route planning aims to ensure the timely completion of the AGV delivery mission, therefore, the primary purpose of path planning is to minimize the total delay time of all tasks, as shown in (9):

$$min \sum_{i\in V}\sum_{j\in J}\sum_{k\in R} x_{ijk} Cost_{ijk}. \tag{9}$$

In modeling route planning, the following constraints are typically considered.

There is a unique matching relationship between the AGV and the selected route, which means that one AGV can only execute the task along one route at any time, as shown in (10):

$$\sum_{k\in R} x_{ijk} = 1, \quad \forall i \in V,\ \forall j \in J. \tag{10}$$

When the driving speed of the AGV fluctuates slightly, the traveling time of the AGV along the selected route can be estimated as the total distance of the route divided by the driving speed of the AGV, as shown in (11). The completion time of the task along the selected routes can be represented as the sum of the departure time, the traveling time on the path, the driving waiting time, and the loading & unloading time of the task, as shown in (12).

$$T_{ijk}^{drive} = \frac{D_k}{v_i}, \quad \forall k \in R, \tag{11}$$

$$T_{ijk}^{arrive} = T_{ijk}^{start} + T_{ijk}^{drive} + T_{ijk}^{wait} + T_{ij}^{load}, \quad \forall i \in V,\ \forall j \in J,\ \forall k \in R. \tag{12}$$

The delay or advance time of the task is the difference between the task completion time and the task deadline, as shown in (13):

$$Cost_{ijk} = T_{ijk}^{arrive} - T_{j}^{due}, \quad \forall i \in V,\ \forall j \in J,\ \forall k \in R. \tag{13}$$

Based on realistic considerations, the task departure time should be no later than the task deadline, the total distance of the selected routes is always greater than or equal to 0, and the task departure time is a non-negative value, as shown in (14), (15), (16).

$$T_{j}^{due} \geq T_{ij}^{start}, \quad \forall j \in J, \tag{14}$$

$$D_k \geq 0, \quad \forall k \in R, \tag{15}$$

$$T_{ij}^{start} \geq 0, \quad \forall i \in V,\ \forall j \in J. \tag{16}$$

Considering different ACTs may have differentiated road layouts and environments, different works in literature have different research focuses. Based on the given basic model of multi-AGV path planning, therefore, the current research could be roughly divided into the following three categories [49]: (1) static path planning under the fixed road layout, (2) dynamic path planning under the fixed road layout, (3) free-range path planning. The following introduces the research status of the three categories of literature. Considering the generality of path planning, we first introduce the general research status of the topic in each section and then focus on the ACT scene.

B. Static Path Planning Under Fixed Road Layout

Static path planning is mainly used to solve the problem of vehicle path planning where the working environment is known and the environment is relatively fixed. It usually regards the path as an arc or polyline between two nodes. All driving departure points and arrival points of AGVs have been determined before departure, The model of static path planning is relatively simple, but the ability to deal with unexpected problems in the transportation process is relatively poor.

For the static path planning of multiple AGVs under the fixed layout, plenty of scholars have conducted in-depth research. Among the literature, many works used Petri nets and graph theory to simplify the model and construct the shortest path. Wu and Zhou [50] proposed a method of using Petri nets and deadlock avoidance strategies to find the shortest conflict-free route. The shortest routes are found by guiding the route layout, and then an alternative route is executed when necessary to avoid deadlock and block. Nishi et al. [51] resolved the conflict and deadlock problems in the multi-AGV system by establishing a Petri net to decompose the AGV scheduling model. However, due to the complexity of the algorithm, the conflict avoidance ability is inversely proportional to the number of AGVs. Sabattini et al. [52] used graph theory to establish a conflict graph to describe possible path conflicts, coded the possible conflicts into corresponding conflict graphs, and then defined some constraints of the optimization problem to simplify the complexity of the proposed model.

Besides, some works have fully considered the operating environmental characteristics of the AGV. These works combined with the specific operating environment of the AGV to choose the route. Miyamoto and Inoue [53] considered the system component capacity, route replacement difficulty, anti-interference, and other factors in the actual AGV system application process and studied the scheduling and conflict-free routing problems of the limited-capacity AGV system. According to the system characteristics and related constraints proposed above, an integer programming model is established, and a local search method is developed. Małopolski [54] established a square topology map based on the chain of reservations and established a Spatio-temporal network as the model to achieve multi-objective and multi-AGV path planning. Ren et al. [55] used the Niche method to perform multi-modal optimization on the problem and obtained multiple optimal paths. Then the obtained paths are calculated according to the actual situation to select the optimal path.

Also, considering the specific layout of the ACT, many scholars have conducted research specifically on the static path planning of multi-AGV under the ACT layout. Jeon et al. [56] proposed a path planning method based on Q-learning technology for multi-AGV path planning in the ACT. It considered vehicle conflicts during vehicle driving and made a relatively accurate estimation of the vehicle waiting time in advance. The shortest travel time and waiting time of AGVs are taken as the optimization objective to select the optimal plan. The simulation experiment illustrated that their method is superior to the plan selection scheme that takes the shortest traveling path of AGVs as the target. Zhong et al. [57] established a path planning model to minimize the driving distance of the AGV between the QC and the ASC and carried out the optimization of route selection by testing the overlap rate of the vehicle driving road and conflict time. It also considered the use of priority-based speed control strategies to preempt possible vehicle conflicts. Dijkstra algorithm with depth-first search was used to solve the model. Chen et al. [19] considered the joint scheduling of AGV and QC. The factors such as AGV driving energy consumption, full load & no-load were considered in the establishment of the joint scheduling model. A two-stage taboo search algorithm was adopted to obtain the optimal solution. Koo et al. [58] proposed a two-stage integrated scheduling method of fleet planning and route selection for terminal AGV route planning. After determining the fleet size, a heuristic algorithm based on tabu search was used to generate suitable driving routes for AGVs. Zhao et al. [18]

fully considered the operations requirements of ACT. A two-stage tabu search algorithm was proposed to simultaneously consider the scheduling problem of ASC and AGV. According to the loading & unloading sequence of containers, the optimal AGV scheduling plan was formulated, and the scheduling of ASC was continuously adjusted through the results of the AGV scheduling plan.

C. Dynamic Path Planning Under Fixed Road Layout

In dynamic path planning, the driving route of the AGV is dynamically updated with time and road conditions. Compared with static path planning, dynamic path planning has more consideration factors and is more time-dependent, so the model and calculation process are more complicated.

For dynamic path planning of multi-AGV, many scholars have proposed different routing schemes based on time windows. Smolic-Rocak et al. [59] proposed an arc-based time window planning method. Based on a predetermined route, by extending or delaying the time window of the AGV on the arc, the time conflict of each AGV could be avoided. Considering the limitation of the driving area, based on the time window, some works in the literature simplify the model by pre-processing situations such as conflicts and deadlocks. Gawrilow et al. [60] considered the conflict and deadlock of vehicles and proposed a dynamic routing model for AGVs, which could avoid the conflicts and deadlocks during routing calculation. The experimental results showed that their method has good practicality for real scenarios. Möhring et al. [61] simplified the problem to the shortest path problem with a time window. Also, the conflicts and deadlocks of vehicles are avoided in the preprocessing step. Then, the time windows of vehicles are adjusted in real time. The dynamic routing algorithm has been verified in the container terminal Altenwerder (CTA) in the Port of Hamburg. Compared with the static routing method, the proposed dynamic routing algorithm has obvious advantages.

Besides, considering the complicated factors involved in dynamic path planning of multi-AGV, some scholars use heuristic algorithms to search the optimal routing [21]. Hu et al. [62] modeled the AGV scheduling as a Markov decision process and used deep reinforcement learning to achieve real-time scheduling of AGV. Guo et al. [63] aimed at the path planning problem in the rectangular environment, and recorded the estimated traveling time of the AGV as the path evaluation standard. Then, an improved Dijkstra algorithm is proposed to obtain the optimal driving path with the shortest driving distance and time. Wang et al. [64] introduced the turning factor and proposed a dynamic path planning method based on the A* algorithm, which could effectively search for the shortest time path and avoid collisions.

Focusing on the dynamic planning of multiple AGVs in ACT, it can be seen that some scholars have tried to introduce new theories or innovative methods based on the classical algorithms for routing planning. Li et al. [65] proposed a new type of quantum ant colony optimization algorithm for AGV path planning based on Bloch coordinates of pheromones. It combined the advantages of quantum theory and ant colony algorithm to calculate a conflict-free optimization driving path. Zhou et al. [66] proposed an anisotropic Q-learning method for AGV. In this work, the real-time status of the vehicle includes current and destination positions, heading directions, and Vehicle numbers were used to find the shortest route in a cross-lane type guidance road network. Numerical experiments showed that the improved anisotropic Q-learning method could provide a stable and dynamic solution for AGV path planning.

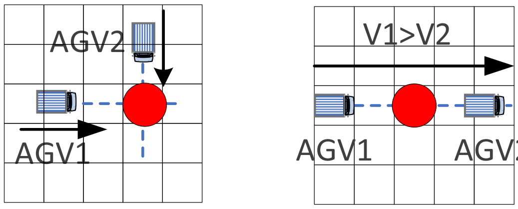
D. Free-Range Path Planning

For the current research of ACT, fixed-layout of multi-AGV path planning is still the mainstream of research. The fixed layout of the road may cause unnecessary vehicle conflicts and congestion under limited space resources, which is not conducive to improving transportation efficiency. Therefore, few scholars also have researched the free-range path planning of multi-AGV. In free-range path planning, the driving route of the vehicle is not along the fixed roads but could be freely planned within the given driving area.

Duinkerken et al. [67] mentioned that free-range path planning has potential applications in the ACT scenario. In their work, a dynamic free-range route selection method based on the microscopic pedestrian behavior model was proposed. The proposed method could comprehensively consider the task arrival time of the AGV, static obstacles and other AGV planned trajectories, and dynamically determine the optimized trajectory. To better realize the free routing planning of multiple AGVs, based on [67], Duinkerken and Lodewijks [49] proposed a control method called DEFT. DEFT can be used to calculate the trajectory of a single AGV based on the current position of the AGV, the destination of the transportation task, the expected time to reach the destination, the planned trajectory of other AGVs, and obstacles. The preliminary experimental results of the scheme showed that the variance of the transportation time could be reduced to a certain extent, but more experiments are needed to be conducted to fully improve the scheme. Daphne [68] integrated the advantages of free-range path planning and traditional path planning, to propose a novel path planning method, namely hybrid path planning. In their work, the traditional path planning method was used in the area near QC to guide the traffic flow of AGV, while the free-range path planning method was used in other areas of the ACT.

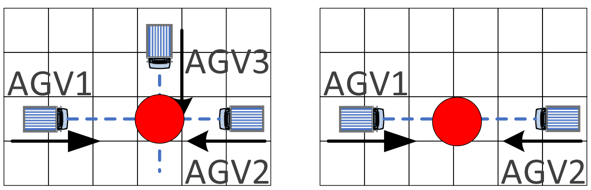
E. Summary

To sum up, as a kind of pre-planning method, static path planning could be used to quickly plan the driving route for AGVs with a relatively fixed driving environment. Since the model of static path planning is relatively simple, it is often used to solve large-scale route problems. However, abnormal events that occur during driving cannot be resolved well by static path planning. The planning process of dynamic path planning is closely related to time, many scholars, therefore, use various time window-based dynamic path planning methods to search the real-time feasible paths. Also, heuristic



a) Conflict at intersection b) Conflict when driving in the same direction

Fig. 3. Conflict situations of AGVs.



a) Multiple AGV deadlock b) Same direction deadlock

Fig. 4. Deadlock situations of AGVs.

algorithms were widely used in the literature to obtain the optimal solution.

Although both static and dynamic path planning take a relatively comprehensive consideration of most aspects of the ACT, and various methods were adopted to avoid or eliminate exceptions such as conflicts and deadlocks, the premise of these methods is that the layout of the ACT is known. But no matter what, under the fixed layout, a lot of potential road resources are sacrificed in exchange for the simplicity of path planning.

To further obtain efficient use of road resources, a few scholars also research free-range path planning. The driving path of AGV is no longer limited to the fixed routes, it could travel freely within a given range area. This kind of path planning makes the differentiated layout of ACT no longer an important constraint of path planning, and thus the AGV has a higher degree of freedom of travel. With the gradual improvement and development of ACTs, considering the flexibility and universality of free-range path planning, it is likely to become a new potential research hotspot.

V. Exception Handling

A. Basic Exception Handling Model of AGV in ACT

Considering the uncertainty of road conditions and the complexity of multi-AGV driving, conflicts or deadlocks often occur. The common conflicts and deadlocks of multi-AGV are shown in Figs. 3 and 4, respectively. Only the conflict occurs, AGVs often fall into the risk of an imminent collision. Only the deadlock occurs, AGVs often stay in place and cannot continue to drive until the deadlock is broken.

Frequent conflicts or deadlocks will greatly reduce the smoothness of AGV operation and affect the on-time completion of tasks. Therefore, reasonable path planning should consider these abnormal situations. If it cannot be completely avoided in path planning, it is necessary to establish an efficient exception-handling mechanism to avoid or reduce the impact of the above exceptions on the smooth operation of multi-AGV as much as possible.

TABLE IV

Definition of Parameters and Decision Variables of Exception Handling

Symbol	Definition	Remark
J	Set of tasks	P
V	Set of AGVs	P
A	Set of divided areas	P
l	Body length of AGV	P
ls	Length of the divided area	P
v_i	Normal driving speed of V_i	P
$Distance_{ij}$	Total traveling distance of V_i to execute J_j	P
T_{ij}^{drive}	Traveling time for V_i to complete J_j	P
T_{ij}^{start}	Departure time of V_i to execute J_j	P
T_{ij}^{arrive}	Arrival time for V_i to execute J_j	P
T_{ij}^{load}	Loading/unloading time for V_i to execute J_j	P
T_j^{due}	Deadline of J_j	P
$Cost_{ij}$	Time left until the deadline that V_i completes J_j	P
T_{ijr}^{in}	Time when V_i executes J_j to reach Area A_r	P
T_{ijr}^{out}	Time when V_i executes J_j to leaves Area A_r	P
T_{ij}^{wait}	Waiting time in the process of V_i executing J_j	D.V.

Based on the common requirements and constraints, the basic model of multi-AGV exception handling is given here as shown below. Before that, the parameters and decision variables of the model are defined as shown in Table IV.

To minimize the impact of conflicts and deadlocks on the horizontal transportation system, set the total task delay time as the objective function of the exception handling problem, as shown in (17):

$$min \sum_{i \in V} \sum_{j \in J} Cost_{ij}. \tag{17}$$

The following constraints are usually considered during the problem-solving process.

When the speed of the AGV is approximately constant, the actual traveling time of the AGV can be shown as (18). The completion time for the AGV to execute the task is shown as (19). The delay or advance time for the AGV to execute the task is shown as (20).

$$T_{ij}^{drive} = \frac{Distance_{ij}}{v_i}, \forall i \in V, \forall j \in J, \tag{18}$$

$$T_{ij}^{arrive} = T_{ij}^{start} + T_{ij}^{drive} + T_{ij}^{wait} + T_{ij}^{load}, \forall i \in V, \forall j \in J, \tag{19}$$

$$Cost_{ij} = T_{ij}^{arrive} - T_j^{due}, \forall i \in V, \forall j \in J. \tag{20}$$

The necessary conditions for the avoidance of exceptional situations can be represented as (21). By adjusting the arrival time of the AGV to the corresponding divided area, it is guaranteed that the AGV could avoid conflicts and deadlocks in time during the driving process. The departure time of the AGV from the corresponding divided area is shown as (22).

$$|T_{ijr}^{in} - T_{mhr}^{in}| \geq \frac{l+ls}{v_i}, \quad \forall i, m \in V, \ \forall j, h \in J, \ \forall r \in A, \tag{21}$$

$$T_{ijr}^{out} = T_{ijr}^{in} + \frac{l+ls}{v_i}, \quad \forall i \in V, \ \forall j \in J, \ \forall r \in A. \tag{22}$$

Considering the actual transportation needs, the start time of the task should be earlier than the deadline. The total traveling

TABLE V
EXCEPTION HANDLING RESEARCH IN THE LITERATURE

Reference	Year	Problem	Scene	Control mode	Solution method	Consideration	Constraint
Smolic-Rocak [60]	2010	Conflict avoidance	Automated warehouse	Centralized	Time window-based dynamic routing method	Number of tasks, task priority	One-direction path
Fan [71]	2017	Conflict avoidance	Automated warehouse	Centralized	Time window-based dynamic routing method		One-direction path
Xin [72]	2020	Conflict avoidance	Manufacturing system	Centralized	Spatiotemporal network model	Task sequence, time and space constraints	Any direction path
Zhang [73]	2017	Conflict avoidance	Automated warehouse	Centralized	Adaptive conflict resolution strategy	Conflict type	Two-direction path
Małopolski [55]	2018	Conflict & deadlock avoidance	Transportation System	Centralized	Chain of reservations	Site size constraint	Two-direction path
Lee [74]	2019	Conflict avoidance	Automated warehouse	Centralized	Time window detection-based cyber-physical system		Two-direction path
Zhong [75]	2020	Conflict & deadlock avoidance	Automated container terminal	Centralized	Speed control strategy	Task priority	One-direction path
Walenta [76]	2017	Conflict avoidance	AGV system	Decentralized	Resource competition strategy	Task priority	Two-direction path
Zheng [77]	2013	Conflict & deadlock avoidance	Manufacturing system	Decentralized	Area Control		One-direction path
Mehdi [78]	2017	Conflict avoidance	Transportation System	Centralized	Speed adjustment strategy	Time constraint	Any direction path
Herrero-Perez [79]	2010	Conflict & deadlock avoidance	Manufacturing system	Mixed	Area Control		Any direction path
M.-S. Yeh [80]	1998	Deadlock avoidance	AGV system	Centralized	Area Control	Layout constraint	One-direction path
Fransen [81]	2020	Deadlock elimination	AGV system	Centralized	Grid-based dynamic path planning		Two-direction path
Qi [82]	2018	Conflict & deadlock avoidance	Automated warehouse	Centralized	Flow control strategy	Capacity constraint	Two-direction path
Perronnet [83]	2019	Conflict & deadlock avoidance	Unmanned vehicle system	Centralized	Intersection management method		Two-direction path

distance of the AGV to execute the task is greater than zero. Also, the start time of AGV to execute the corresponding task is not less than 0. All these are shown in (23), (24), (25).

$$T_j^{due} \geq T_{ij}^{start}, \quad \forall j \in J, \tag{23}$$

$$Distance_{ij} \geq 0, \quad \forall i \in V, \ \forall j \in J, \tag{24}$$

$$T_{ij}^{start} \geq 0, \quad \forall i \in V, \ \forall j \in J. \tag{25}$$

Exception-handling research is universal. Except for the ACT scene, multi-AGV exception handling issues widely exist in manufacturing systems, warehouse management, transportation, etc. To make this part of the survey more enlightening, we will jump out of the limitations of the ACT scenes in the following discussion. Based on the given common model, the following focuses on the problem of multi-AGV exception handling to sort out the research points of different scholars on this problem. Table V gives the typical and representative pieces of literature on exception handling of multiple AGVs and analyzes the different factors considered by different scholars for different research points, as well as the solution methods for corresponding problems.

B. Category of Exception Handling

During the operation of multiple AGVs in the ACT, the conflicts and deadlocks of multiple AGVs that occur from time to time, many ACTs established intelligent transportation systems for unified management and control of AGVs. Taking into account the communication characteristics of AGVs, some scholars have researched the control mode of AGVs.

The exception handling of multiple AGVs can be divided into two types: centralized control and decentralized control. In centralized control, the central controller knows the location and tasks of all AGVs. The central control system is responsible for collecting all information and performing unified planning and control. Since the central control system could obtain all AGV operations information, it has the potential to globally optimize the AGV operations and find the optimal solution for the AGV group. However, the scalability of centralized control is often limited. For example, the response time to changes in environmental factors is long, and the calculation for dynamic large-scale AGV groups is very time-consuming, which causes a certain degree of delay for dynamic event handling.

Considering that centralized control could better manage all AGVs, many scholars have studied the optimization of centralized control of multiple AGVs to avoid possible AGV conflicts or deadlocks [72], [73], [82], [83]. Gerrits et al. [83] proposed a comprehensive and universal multi-agent system for the multi-AGV control of ACT. Zhong et al. [73] introduced a novel plan planning model for the ACT. Lee et al. [72] used the centralized control system to control and coordinate the movement of the robot in real time.

Compared with centralized control, the control communication of decentralized control favors the interactive communication of AGVs. During the task execution, the AGV could coordinate with neighboring devices or other AGVs to obtain more local information for exercise planning. Since the AGV uses local information to calculate and plan locally, this kind of motion coordination method is more flexible and expandable than that of centralized control. However, in decentralized control, the optimization process of all individuals is relatively more about their own goal optimization. It is difficult to achieve global optimization for overall planning. Therefore, for small-scale systems, in general, although the decentralized method could guarantee higher flexibility and robustness, the overall objective optimization is not as ideal as the centralized architecture.

However, with the gradual development of intelligent capability for AGV, some scholars have begun to shift from centralized control to more flexible decentralized control in recent years. Zheng et al. [84] studied the use of collaborative decentralized control to control the AGVs to complete the specified terminal transportation plan. Zheng et al. [75] proposed a decentralized control mechanism for the conflicts and deadlocks of multiple AGVs. The zone controllers in different areas circumvent the possible conflicts and deadlocks of AGVs through mutual information transmission. Walenta et al. [74] proposed a decentralized control system architecture for the coordinated control of multiple AGVs in material transportation tasks based on mobile robot solutions. AGVs compete with each other based on priority before using zone resources to avoid possible collisions.

C. Conflict and Deadlock Avoidance

The conflict and deadlock avoidance of large-scale AGV operating systems are currently one of the key issues in the research of multi-AGV operation control. Many scholars use different methods to try to avoid or reduce the possible AGV operation conflicts and deadlocks [85]. The most common optimization and control methods of conflict and deadlock avoidance could be roughly divided into three categories: time window-based conflict and deadlock avoidance, zone control-based conflict and deadlock avoidance, and rule-based conflict and deadlock avoidance.

1) Time Window-Based Conflict and Deadlock Avoidance: The occurrence of conflict and deadlock during the operation of the AGV is closely related to the vehicle's driving time and location. By arranging and adjusting the time windows of different AGV driving routes, it could guarantee the conflict-free driving of different AGVs in the same area.

Fan et al. [69] proposed a heuristic algorithm to search for the idle time window in the path selected by each AGV and select the path with the earliest arrival time window as its planned path. The research is ideal. In a dynamic environment, the calculation of the time window is affected by many factors, such as the acceleration and deceleration time of the AGV, external obstacles, etc., which makes the accurate calculation of the time window more difficult. Incorrect time windows and external obstacles may lead to unpredictability collision. Xin et al. [70] proposed a spatiotemporal model and a dedicated algorithm to avoid conflicts while minimizing the cycle time of each AGV's operation task.

Since ACT has some unique characteristics, in combination with the characteristics of multiple AGVs operations in the terminal, many scholars have carried out corresponding research. They fully consider the operation time of the AGV, and add the consideration of time window to the comprehensive scheduling of transportation, using the reasonable arrangement of the time window to avoid the possible conflicts of multiple AGVs. The time window is used in dynamic path planning to avoid conflicts and deadlocks that may occur during the driving of the AGV as much as possible. This part of the literature has been discussed in detail in Section IV-C, not repeated here.

2) Zone Control-Based Conflict and Deadlock Avoidance: The time window-based conflict and deadlock avoidance solutions require high accuracy of time window calculation, which is difficult to be satisfied with the dynamic operation of large-scale fleets. Therefore, many scholars consider the use of zone control methods to avoid vehicle collisions and deadlocks. During the driving of the AGV, the guiding path of the AGV consists of a series of zones. These zones represent workstations, intersections of multiple roads, or straight roads. AGV must obtain permission from the central controller to enter the corresponding zone to avoid collision and deadlock [86]. Based on the chain of reservations, Małopolski et al. [54] proposed a novel method to prevent AGV collision and deadlock. This method allows to AGVs dynamically add reservations at any time. After adding a reservation to the queue, AGV could immediately start its transportation task. Qi et al. [80] proposed two effective traffic control strategies with polynomial time complexity. It uses authorization-based point control strategies to avoid conflicts.

Considering a large number of AGVs operations simultaneously in the ACT and the large-scale size of the terminal, some work has also explored the application of the zone control methods in the terminal scenario. Kim et al. [87] proposed a method for detecting and preventing deadlocks for the traffic control of multiple AGVs in the ACT. In their work, AGV makes a reservation for the zones to avoid collisions and deadlocks while the priority table is used to maintain priority consistency between zones. Li et al. [88] proposed an extended area control model, which relaxes the area size limit based on the conventional area control model. It improves the utilization of the zone. Besides, through the emergency traffic control scheme, the guiding path for the failed AGV is re-planned in time to ensure the conflict-free operation of multiple AGVs.

3) Rule-Based Conflict and Deadlock Avoidance: Unlike the above two conflict and deadlock avoidance methods, the rule-based method is strongly related to the application scenario. The following are several typical rule-based studies of multi-AGV conflict and deadlock in ACT scenarios. Cao and Zhu [89] classified the conflict types of AGVs in the multi-AGV system and then formulated corresponding collision avoidance rules for different situations. Liu et al. [90] resolved different types of conflicts through corresponding control logic and protocol.

D. Deadlock Elimination

In view of the conflict and deadlock that may occur during the driving of multiple AGVs, many scholars use the time window-based method, zone control-based method, or specific rules to avoid collisions or deadlocks as much as possible. However, considering that the driving process of the AGV is complicated, the multi-vehicle deadlock may still occur due to changes in road conditions and vehicle driving conditions. Some scholars also have researched the deadlock elimination of multiple AGVs.

Qi et al. [80] proposed two control strategies for multi-AGV deadlocks: (1) deadlock detection and recovery; (2) deadlock avoidance and secondary deadlock recovery. Fransen et al. [79] proposed a dynamic path planning method for grid-based systems. The initial update function included in the method could recover from deadlock situations without detection. Moorthy et al. [91] studied an effective deadlock prediction algorithm with a complexity of $O(V^2)$, where V is the number of AGVs. The algorithm makes it possible to predict the deadlock in each short decision cycle when a new AGV movement command is issued.

Also, to ensure the operations of AGV in the ACT, some studies combined the characteristics of the terminal to achieve timely avoidance of terminal deadlocks through graph theory, classification detection, or other methods.

Lehmann et al. [92] introduced two deadlock detection methods. The first one is based on the matrix representation of the terminal system, and the second one directly tracks the request for the individual resource. Three different procedures are proposed to modify the sequence of handling operations or to assign them to alternative resources to resolve conflicts between concurrent processes. Park et al. [93] proposed a graph-based deadlock detection method for the deadlock of multiple AGVs in the ACT. The vehicle deadlock could be prevented by imposing constraints on vehicle movement. Bae et al. [94] considered the AGV turning problem. They adopted a more flexible AGV flow line to divide the grid and controlled the travel time of AGVs through the occupancy area reservation (OAR) table to avoid deadlock. Gerrits et al. [83] marked the deadlock-prone areas in the ACT. When the vehicle enters the deadlock-prone area, the rerouting algorithm was used to plan a new passable path for the AGV to avoid the deadlock.

E. Summary

The core of handling exception events during the AGV driving process is to avoid collisions or deadlocks. Therefore, most scholars used time windows, zone control, or corresponding detection rules to detect vehicle exception events in time and then adjust the motion plan of AGVs to avoid the occurrence of exception events in real time.

Taking into account the comprehensiveness and completeness of the collected information, for traffic control of the multi-AGV system, centralized control methods are widely used. In recent years, with the continuous development of communication technology (such as NB-IoT, 5G) and equipment, decentralized control has begun gradually gaining wider applications due to its flexibility. The use of decentralized control methods that allow AGVs to have higher autonomous decision-making rights to flexibly avoid conflicts during the driving process will be one of the directions worthy of attention in the future.

VI. Vehicle Management

As the core transportation equipment of ACTs, AGV is directly related to the efficiency of terminal operations. Ensuring the normal operation of AGVs is one of the necessary businesses requirement of the ACT. Here, the two main issues of AGV management in ACTs are discussed, including vehicle quantity and type selection and vehicle maintenance.

A. Vehicle Quantity and Type Selection

The quantity of AGV in operations is directly related to the operational efficiency and costs of the ACT. For the optimization of the quantity of AGVs, many scholars have adopted different analysis methods to conduct research. Pjevcevic et al. [95] proposed a data envelopment analysis (DEA)-based decision-making method for container loading and unloading. Based on the average service time of ships, and the average utilization rate of QCs and AGVs, the number of AGVs used in the ACT could be determined. The study showed that DEA is a useful method for the efficiency assessment of AGV fleet size and ACT operation. Roy et al. [96] proposed a closed queuing network model based on traffic flow to characterize the impact of the number of AGVs on the throughput of the ACT. The results showed that AGV congestion will cause a throughput drop of 85%. In addition, the proposed queuing network model also can be used to determine the number of AGVs for a given port throughput. Liu et al. [90] considered the impact of the yard layout on the deployment of AGVs and adopted the multi-attribute decision-making (MADM) method to determine the number of AGVs in different scenarios. The simulation results showed that different numbers of AGVs will affect the loading and unloading performance. The layout yard will have a significant impact on the decision of the number of AGVs. Besides, Vis et al. [97] also proposed a minimum flow algorithm to determine the number of AGVs required by ACTs. Holly et al. [98] used different machine learning methods to predict the number of AGVs used in ports to achieve flexible scheduling of AGVs.

Type selection of the vehicle not only needs to weigh the investment and operating costs of the ACT but also needs to match the operation mode and degree of the ACT. AGV and the automated lifting vehicle (ALV) are mainly two kinds of vehicles that are used in the transportation system in the ACT. From the perspective of investment and operating costs, Vis et al. [99] pointed out that the cost of AGV is 38% higher than that of ALV. From the perspective of transportation performance, The simulation experiments conducted by Bae et al. [100] showed that ALV requires fewer vehicles under the same productivity level. Once when the number of vehicles is large enough, the performance of AGV will eventually catch up with that of ALV. Kumawat et al. [101] developed a semi-open queueing network model to compare AGV and ALV and pointed out that replacing AGV with ALV can increase container unloading throughput by 16%. However, their research also showed that when the arrival rate of the container is low, the throughput performance of AGV will be higher than that of ALV.

B. Vehicle Maintenance

As transportation equipment is driven by electric power, the operations of AGV should consider environmental factors and time factors. After a period of operation, the main body of the vehicle, tires, and other components will experience varying degrees of wear and tear. The necessary maintenance or replacement operation needs to be carried out in time. Besides, the battery of AGVs also needs to adopt certain strategies to replace or supplement power to ensure the normal operation of the AGV. The common maintenance mode of the multi-AGV could be divided into preventive maintenance, corrective maintenance, and predictive maintenance [102].

Different scholars adopted various maintenance strategies and reliability calculation methods to carry out maintenance management on the multi-AGV system to ensure the smooth progress of transportation tasks.

Regarding the management of AGV batteries, most scholars focus on the study of AGV charging strategies. Xiang et al. [103] considered the two battery charging strategies of battery insertion and battery exchange, and then proposed a nested semi-open queueing network model to estimate the performance of ACT in the case of battery management. Ma et al. [104] proposed two battery charging strategies: conservative policy and progressive policy. Their research illustrated the use of different charging strategies will have a certain impact on the overall transportation efficiency of the system.

C. Summary

In general, for the management of multiple AGVs in the ACT, the current research is mainly biased toward the quantity management and battery management of AGVs. Most scholars studied the optimization of the number of AGVs to improve the overall transportation efficiency of the terminal and reduce the operational cost of the terminal. Considering that AGVs are driven by electricity, many scholars have also studied the battery charging strategy to optimize the battery management of AGVs. Besides, as the high-intensity operation equipment of the ACT, the topic of the prognostics and health management of AGV also has begun to appear in pieces of literature. Timely maintenance is the key to ensuring the normal operations of AGVs. When we conducted our review of the literature, we found that the prognostics and health management of AGV in the terminal are relatively rare. However, the topic is worthy of in-depth research. Therefore, we believe that preventive and predictive maintenance research on the terminal AGV (even more equipment in the ACT) to ensure the normal operations of equipment and reduce the long-term operational cost of the terminal will be a direction worthy of further exploration.

VII. Discussion of Status and Gap

Container terminals are transforming and upgrading to ACTs. The research on the transportation system of ACTs has widely drawn the attention of scholars. Due to the limitations of the current AGV control method, operations strategy, terminal environment, and other factors, the transportation system of the actual terminal still has much room to be improved and optimized to promote overall transportation efficiency and reduce the comprehensive operational costs. optimized to promote ov

The current adopted transportation system of the ACT is composed of multiple sub-systems. According to the operational function of sub-systems, it can be roughly divided into four sub-systems: equipment scheduling, path planning, exception handling, and vehicle management. The port operation status of the corresponding sub-systems is shown as follows.

For equipment scheduling, less consideration is given to the coordinated scheduling of multi-equipment. Most systems assign tasks to corresponding equipment based on limited information such as the destination of the container and the location of the AGV. There are a few considerations about other state information of the AGV, such as the remaining power of the AGV, running time of the equipment, the health degree of the equipment, etc. Therefore, when assigning tasks, there is no guarantee that the assignment strategy is optimal.

For multi-AGV path planning and exception handling, the existing schemes mainly consider how to find the shortest distance path for a single AGV in the space dimension and lack considerations of possible vehicle conflicts. Once a vehicle conflict problem occurs, the AGV only can rely on its collision avoidance mechanism to solve it. In other words, when the AGV detects an obstacle ahead, it will stall until the obstacle is removed. However, this method will cause unnecessary starting and braking of the AGV. It not only accelerates the loss of AGV but also affects the efficiency of terminal operations. Besides, when multiple AGVs stop to avoid collisions, the deadlock problem may also occur.

For vehicle management, the existing terminal has less consideration for the optimization of AGV number and the maintenance of equipment. For the charging strategy of multiple AGVs, the replacement station is currently used for rapid battery replacement, and there is no special replacement strategy. Further research in the management of multiple AGVs is needed.

VIII. Conclusion and Future Directions

Compared with the traditional terminal, ACT not only significantly improves transportation efficiency but also greatly reduces the cost of resources such as manpower and material resources. The automation and intelligentization of ACT, therefore, is currently a key direction for the terminals in the world.

In order to improve the efficiency of terminal transportation and reduce operating costs, plenty of articles have conducted comprehensive research on the functional sub-systems of the terminal transportation system. According to the survey of the literature, we find that the following directions are still worthy of further exploration for the ACT.

1) Multi-equipment, large-scale integrated operations scheduling optimization: The current equipment scheduling in the ACT mainly focuses on single-type equipment. Since the actual equipment operation scheduling is a comprehensive process involving multi-equipment from QC, AGV to ASC, joint or integrated operations scheduling of the multi-type and large quantity of the equipment needs to be considered to efficiently respond to large-scale terminal operations requirements.

2) Multi-AGV dynamic path planning under free-range terminal layout: Current research on path planning of AGVs is mostly based on the fixed layout. Also, the research scope of vehicle scale is relatively small, which is usually no more than 20 AGVs. However, there are often more than 50 AGVs running simultaneously in the actual terminal. Therefore, flexible and efficient dynamic path planning methods for large-scale AGVs under the free-range terminal layout are expected to be further explored.

3) Multi-AGV exception handling under decentralized control: With the further development of intelligent interconnection of equipment, the traffic control of AGVs has begun to change from the traditional centralized control to the more flexible and free decentralized control. Through the exploration of the combination of complex network theory and the generation conditions of the conflict and deadlocks, achieving the rule-based efficient conflict and deadlocks avoidance methods under the distributed control mode may be one valuable research point in this field.

4) Prognostics and health management for the life cycle of the ACT equipment: Most of the current literature paid less attention to prognostics and health management of ACT equipment. In view of the large-scale use of equipment such as AGV, QC, and ASC in the terminal are equipped with smart sensors, it provides a potential opportunity for the operation and maintenance personnel to perform remote predictive maintenance of equipment. Therefore, there is much room worth further exploring in this field.

In our cooperation with terminal operators, we found that two important future research projects are worthy of follow-up. (1) Considering the actual construction needs of different ACTs, how to design and improve the ACT transportation system is still a critical engineering problem. Based on the panoramic map for the main research topics in transportation systems provided by the paper, projects on transportation system design for the new ACT and the function improvement for the existing ACT can be further conducted. (2) Due to the introduction of a large number of dynamic AGVs, the transportation system of ACT constitutes a complex system. How to carry out operations management and performance evaluation for this complex system is the key to terminal operations and continuous optimization. Therefore, referring to the performance evaluation objectives involved in the four research topics of this paper, and then forming a multi-dimensional comprehensive transportation system operations management evaluation system will be the other important project worthy of development in the future.

In general, this paper reviews the research on vehicle transportation of the ACT in the recent 25 years. Our survey defines the four main research topics in vehicle transportation of the ACT including equipment scheduling, path planning, exception handling, and vehicle management. In each topic, the works in the literature are summarized and several research opportunities for possible follow-up research directions in different fields are proposed. We expect our survey could not only provide references for more scholars on the research of operation and management of terminals, but also provide guidance for system evaluation and improvement for terminal system engineers and operation managers.

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Article

A Hybrid Dynamic Method for Conflict-Free Integrated Schedule Optimization in U-Shaped Automated Container Terminals

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Abstract: Automated guided vehicles (AGVs) in the U-shaped automated container terminal travel longer and more complex paths. The conflicts among AGVs are trickier. The scheduling strategy of the traditional automated container terminal is difficult to be applied to the U-shaped automated container terminal. In order to minimize the handling time of all tasks and avoid AGV conflicts simultaneously in the U-shaped automated container terminal, this paper establishes a hybrid programming model for conflict-free integrated scheduling of quay cranes, AGVs, and double-cantilever rail cranes in the unloading process. It consists of a discrete event dynamic model and a continuous time dynamic model. An improved genetic seagull optimization algorithm (GSOA) is designed. A series of numerical experiments are conducted to verify the effectiveness and the efficiency of the model and the algorithm. The results show that the proposed method can simultaneously realize the AGVs collision avoidance and multi-equipment integrated scheduling optimization in the U-shaped automated container terminal.

Keywords: U-shaped automated container terminal; bi-level programming; AGV path planning; integrated scheduling optimization; genetic seagull optimization algorithm

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1. Introduction

As the connection point between land transportation and sea transportation, container terminals play important roles in commodity transportation. With the development of economic globalization and the growth of vessels, the throughputs of container terminals are constantly increasing. Multiple partners in the port and shipping supply chain put forward higher requirements for the handling efficiency and automation level of facilities in container terminals. A traditional automated container terminal usually has a vertical layout. Its construction cost is high. It usually adopts the end handling, and automated guided vehicles (AGVs) and external trucks only need to drive into the seaside and landside ends of the blocks in the yard, respectively. Non-cantilever rail cranes are the main yard equipment. They have to travel a long distance with containers to complete the handling. It results in high energy consumption and low efficiency. However, the emerging U-shaped automated container terminal (as shown in Figure 1) adopts side handling. The container handling points are longitudinally set on both sides of the blocks. AGVs and external trucks can travel into the yard. Double-cantilever rail cranes in the yard interact directly with AGVs or external trucks. A U-shaped automated container terminal hahas the advantages of a high efficiency and low cost, which is the transformation direction of traditional container terminals.

Nowadays, multi-equipment integrated scheduling and AGV path planning have become the main research topics in container terminals. During the actual operation, uncertain environments may cause collision and congestion problems in AGV path planning.

In the U-shaped automated container terminal, AGVs need to travel longer distances for loading and unloading in the yard. This leads to the problem of mutual waiting between the AGV and double-cantilever rail crane, which affects the overall handling efficiency in the U-shaped automated container terminal. In order to solve these problems and improve the loading and unloading efficiency of the U-shaped automated container terminal, this paper takes the unloading process of the U-shaped automated container terminal as the research object. We establish a hybrid dynamic model for multi-equipment integrated scheduling based on bi-level programming. It is composed of a discrete event dynamic model and a continuous time dynamic model.

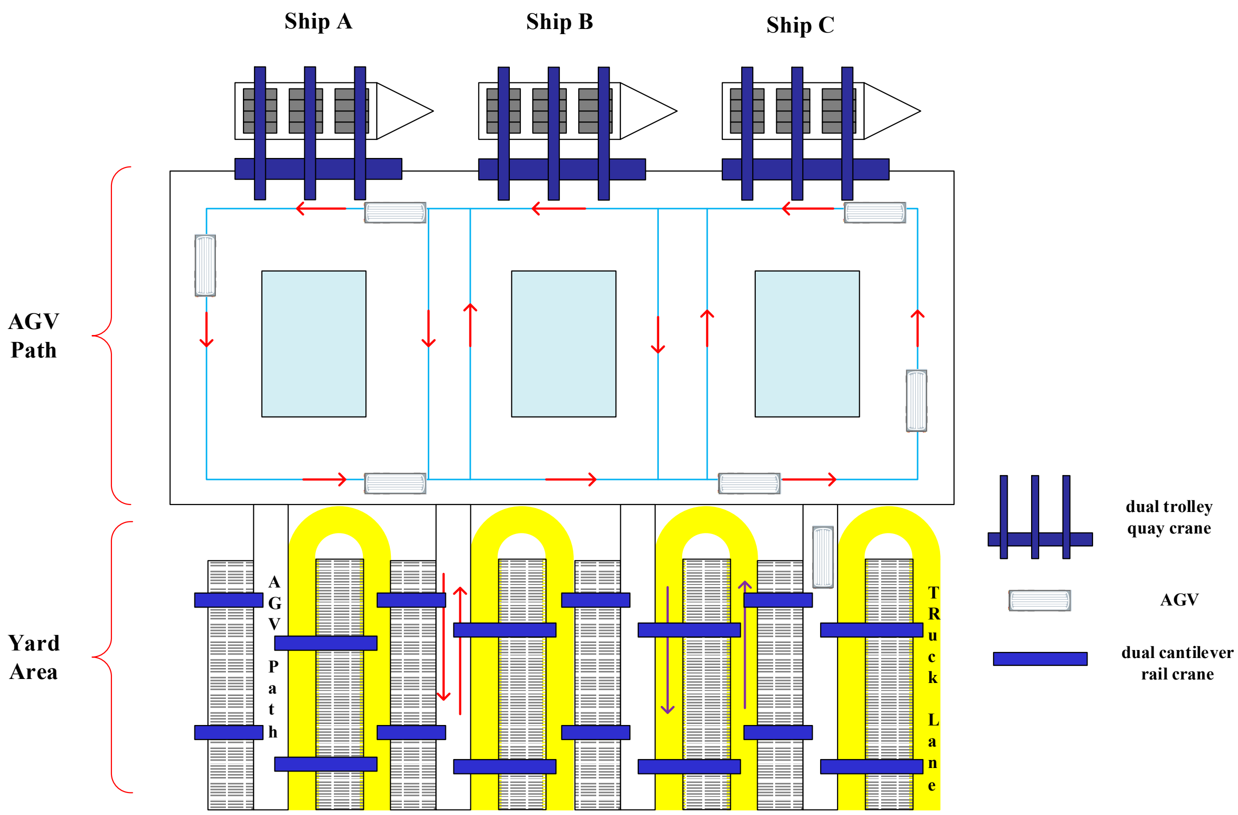


Figure 1. The layout of a U-shaped automated container terminal.

This paper has three main contributions:

(1) According to the actual operational needs, this paper considers AGVs' conflict-free path planning and multi-equipment integrated scheduling simultaneously instead of studying them separately.
(2) This paper establishes a bi-level programming-based hybrid dynamic model composed of a discrete event dynamic model and a continuous time dynamic model. It minimizes the handling time of all tasks and avoids AGV conflicts simultaneously.
(3) This paper designs an improved genetic seagull optimization algorithm to solve the model. By comparison with the adaptive genetic algorithm and bi-level genetic algorithm, the proposed method is validated on small-sized and large-sized problems.

The remaining subsections of this paper are as follows: Section 2 reviews related research on AGV path planning and integrated scheduling of automated container terminals. Section 3 further analyzes the problem and builds the model. Section 4 presents a genetic seagull algorithm. Section 5 conducts small-scale and large-scale example experiments. Section 6 concludes the article and points out future research directions.

2. Literature Review

In recent years, there have been many studies on multi-equipment integrated scheduling and AGV path planning in automated container terminals, and significant research results have been achieved.

Integrated scheduling of different equipment is an inevitable and very important subject to improve the efficiency of automated container terminals. Zhong et al. [1] studied the integrated scheduling problem of quay cranes (QCs), AGVs, and yard cranes in the automated container terminal. Li et al. [2] considered that loading and unloading processes occurred simultaneously and the high correlations between devices. They established a new mixed integer programming model to analyze the allocation and integrated scheduling of terminal equipment. Chen et al. [3] transformed the integrated scheduling problem of the automated container terminal into a multi-equipment collaborative scheduling problem. They established a commodity network traffic model with traffic balance constraints of a yard crane and AGV. Luo et al. [4] studied the multi-equipment integrated scheduling problem in an automated container terminal. They built a mixed integer programming model with the goal of minimizing the berthing time of the ship according to the loading process and discussed the work efficiency of the single cycle and double cycle mode. They created an adaptive genetic algorithm (AGA) to solve this model. Zhen et al. [5] studied the integrated scheduling of quay cranes and container trucks in container terminals, proved that the integrated scheduling problem is NP-hard, and proposed some features to greatly reduce the computational complexity. Koster et al. [6] established new integrated stochastic models in which they analyzed the performance of overlapping loading and unloading operations. They captured the complex stochastic interactions among quayside, horizontal transportation, and stackside processes. Zhao et al. [7] studied the multi-equipment scheduling problem of QCs and AGVs in automated container terminals, considering the capacity limitation of the quay crane transfer platform, and carried out data experiments with Qingdao port as an example. Jamrus et al. [8] applied the flexible job shop scheduling problem to a semiconductor manufacturing system and constructed a particle swarm optimization algorithm based on the Cauchy distribution and operator. However, there are few studies on three types of equipment, and few studies have considered the waiting time between equipment. In addition, AGV is the key piece of equipment in automated container terminals. When studying the integrated scheduling problem, the conflicts among AGVs have not been considered.

AGVs are the main piece of equipment connecting QCs and yard cranes (YCs) in automated container terminals. There are a lot of related studies on AGVs in automated container terminals [9–14]. Ma et al. [9] proposed a shuffled frog leaping algorithm with a mutant process for AGV path planning in automated container terminals, which could increase the diversity of the population and improve the convergence speed. Waldemar [10] used square topology to describe the transportation network and proposed an AGV collision and deadlock prevention method based on the reserved chain. Xu et al. [11] considered the conflict of AGVs in automated container terminals and avoided conflicts by controlling the speed of AGVs. Yang et al. [12] established a bi-level programming model, which could avoid AGV conflicts and proposed a bi-level genetic algorithm (BGA). Keisuke Murakami [13] studied the scheduling and conflict-free path planning of AGVs in a flexible manufacturing system. He used a spatiotemporal network to simulate the discrete fractional linear programming problem and expressed it as a mixed integer linear programming problem. In addition, he also proposed an effective inequality to speed up the calculation. Zhong et al. [14] studied multi-AGV conflict-free path planning in integrated scheduling of automated container terminals. They established a mixed integer programming model to solve the AGV conflict and deadlock problems effectively. Tomas et al. [15] studied the energy consumption of trucks in container terminals. They evaluated the energy consumption according to the dynamic characteristics of trucks and different routes, and finally proposed a new control strategy.

At present, there are many studies on multi-equipment integrated scheduling in automated container terminals but few studies on the integrated scheduling of quay cranes, AGVs, and double-cantilever rail cranes under the layout of a U-shaped automated container terminal [16–18]. Li et al. [19] conducted detailed simulation research on different types of layout design to compare their terminal performance. Li et al. [20] studied hybrid scheduling of yard cranes, AGVs, and external trucks under the layout of a U-shaped automated container terminal. Additionally, few studies have considered AGV conflict-free path planning in the process of multi-equipment integrated scheduling optimization [20–22]. The presented studies usually study AGV conflict-free path planning and multi-equipment integrated scheduling optimization separately, which limits practical applications of the research results. In practice, these two problems are interactively coupled. In the U-shaped automated container terminal, AGVs need to travel a long distance to reach the target bay, which will create a mutual waiting between the AGV and double-cantilever rail crane. Additionally, their paths are obviously different from those of the traditional automated container terminal. Accordingly, conflicts among AGVs are becoming trickier. These unique characteristics of these U-shaped automated container terminal mean that the models for traditional automated container terminals cannot be directly applied to U-shaped automated container terminals, so our integrated scheduling optimization of quay cranes, AGVs, and double-cantilever rail cranes considering the conflict-free path planning of AGVs in the U-shaped automated container terminal is important and timely. It helps to improve the operation efficiency and reduce the transportation cost of the U-shaped automated container terminal.

3. Model Formulation

This paper focuses on the unloading process, and the research objective is to minimize the handling time of all tasks in U-shaped automated container terminals. This problem includes more complex discrete event dynamic programming and continuous time dynamic programming. Discrete events occur during container handling between different equipment while the dynamic handling status (such as speed, displacement) of continuous time occurs in discrete events. Therefore, the bi-level programming model composed of a discrete event dynamic model and continuous time dynamic model is established. The dynamic characteristics mainly involve the time when AGV arrives at each node, the strategy to avoid conflicts, and the process of handling containers. This model is divided into two parts: one is the integrated scheduling model, and the other is the AGVs path planning model.

3.1. Assumptions

(1) The AGV lane is unidirectional.
(2) AGV runs at an average speed, considering the impact of acceleration, deceleration, turning, empty, and load.
(3) A safe distance can be maintained among AGVs.
(4) Multiple AGVs serve multiple quay cranes and they do not fixedly serve a certain quay crane.
(5) The maximum carrying capacity of each AGV is two twenty-foot equivalent unit (TEU). The QC and double-cantilever rail crane can each handle up to 2 TEU at a time.

3.2. Model Parameters

$N = \{1, 2, 3 \ldots, u, p\}$: set of all containers.
$V = \{1, 2, 3 \ldots, c\}$: set of all AGVs.
$Q = \{1, 2, 3 \ldots, a, b\}$: set of all QCs.
$Y = \{1, 2, 3, \ldots, m\}$: set of all double cantilever rail cranes
B_{mn}: set of all bays, where m represents yard and n represents bay.
N_a: set of containers handled by quay crane a.
S: a dummy starting quay crane.

F: a dummy ending quay crane.

O_s : $Q \cup S$, set of all quay cranes plus the dummy starting quay crane.

O_F : $Q \cup F$, set of all quay cranes plus the dummy ending quay crane.

O : $Q \cup F \cup S$, set, including all quay cranes.

$G = \{1, 2, 3 \ldots, g\}$: set of nodes in the path network, where g represents the number of nodes.

$E = \{e_{21}, e_{18}, \ldots, e_{ij}\}$: set of links in a path network, $e_{ij} = \{i \to j : i, j \in G\}$ represents the distance between node i and node j, also represents the link between node i and node j.

$W = \{w_{1,21}, w_{2,18}, \ldots, w_{u,ij}\}$: set of travel time, $w_{u,ij}$ represents the time when task u pass e_{ij}.

D: set of shortest paths and alternative paths that need to be sorted.

$T_w = \left[T_{w_1,ij}, T_{w_2,ij}, \ldots, T_{w_{u,ij}}\right]^T$: set of time window function.

$t_{in,ij} = \left[t_{in,1,ij}, t_{in,2,ij}, \ldots, t_{in,u,ij}\right]^T$: set of the time of AGV entering link e_{ij}.

$t_{out,ij} = \left[t_{out,1,ij}, t_{out,2,ij}, \ldots, t_{out,u,ij}\right]^T$: set of the time of AGV leaving link e_{ij}.

v: the speed of AGVs.

M: a very large positive number.

T_1: the time when portal trolley of the quay crane takes the container from the transfer platform to the AGV.

T_3: the time when the double cantilever rail crane takes the container from the AGV to the target bay.

P: the number of turns in one path.

n_d: the number of links of path d.

k_{ua}: the time when the QC a starts to handle the container u.

T_{ua}: the time when the main trolley of QC a takes the container u from the ship to the transfer platform.

r_{ua}: the time when portal trolley of QC a put the container u from the transfer platform to the AGV.

h_{ua}: the time when AGV transports the container u to the designated bay.

q_{ua}: the time when the double cantilever rail crane reaches the designated bay of the container u.

θ_{um}: the target bay of the container u which handled by double cantilever rail crane m.

f_{ua}: the finish time of container u.

x_{uapb}: if AGV handles the container p of quay crane b after completing the container u of quay crane a, it is 1; otherwise, it is 0.

β_{uac}: if the AGV c handles the container u of quay crane a, it is 1; otherwise, it is 0.

α_{uamn}: if the target bay of the container u is bay n in the yard m, it is 1; otherwise, it is 0.

y_{ijc}: if AGV c passes through node i and node j in turn, it is 1; otherwise, it is 0.

z_{ij}: if AGV c selects the link from node i to node j, it is 1; otherwise, it is 0.

3.3. Design of the Upper-Layer Model

$$\min T = \max_{u \in N_a} f_{ua} - \min_{u \in Na} k_{ua}, \forall a \in O \quad (1)$$

In this paper, the multi-equipment scheduling system is regarded as a discrete event dynamic system [22,23]. Equation (1) is the objective function of the model, which aims to minimize the handling time difference between completing the last container and starting the first container, which represents the total completion time of tasks:

$$k_{ua} + T_{ua} + T_1 \le r_{ua}, \forall u \in N_a, \forall a \in O \quad (2)$$

$$r_{ua} + \sum_{c \in V} w_{i,j} \cdot \beta_{uac} \le h_{ua}, \forall u \in N_a, \forall a \in O, \forall i \in O, j \in B_{mn} \quad (3)$$

$$\max\{h_{ua}, q_{ua}\} + T_3 \sum_{m,n \in B_{mn}} \alpha_{uamn} \le f_{ua}, \forall u \in N_a, \forall a \in O \tag{4}$$

$$\begin{aligned} &\max\{h_{ua}, q_{ua}\} + \textstyle\sum_{c \in V} w_{i,j} \cdot \beta_{uac} \le r_{pb} + M\left(1 - x_{uapb}\right), \\ &\forall u \in N_a, \forall p \in N_b, \forall a \in O_S, \forall b \in O_F, \forall i \in B_{mn}, \forall j \in Q \end{aligned} \tag{5}$$

$$q_{um} + \frac{\left|\theta_{(u+1)m} - \theta_{um}\right|}{v'} \le q_{(u+1)m}, \forall u \in N, \forall m \in Y \tag{6}$$

$$k_{(u+1)a} - k_{ua} = T_{ua} + T_{(u+1)a}, \forall u \in N_a, \forall a \in O \tag{7}$$

Constraint (2) means the connection between the time when the QC starts to unload the container from the ship and the time when the portal trolley of QC puts the container on the AGV. Constraint (3) means the connection between the time AGV starts from the quay crane and the time AGV reaches the bay. Constraint (4) means the connection between the time when the AGV or double-cantilever rail crane reach the target bay and the ending time of the task. Constraint (5) means the connection between the time when the same AGV accomplishes the current task and the starting time of the next task. Constraint (6) means the time connection between two consecutive tasks unloaded by the same double-cantilever rail crane. Constraint (7) means the time connection between two consecutive tasks unloaded by the same quay crane:

$$\sum_{b \in O_F} \sum_{u \in N} x_{uapb} = 1, \forall a \in O_S \tag{8}$$

$$\sum_{u \in N} \beta_{uac} = 1, \forall a \in O, \forall c \in V \tag{9}$$

$$k_{ua}, r_{ua}, h_{ua}, f_{ua}, T_{ua} > 0, \forall u \in N, \forall a \in O \tag{10}$$

Constraint (8) ensures that after the same AGV completes the current task, there is only one next task. Constraint (9) ensures that one AGV can only transport one container. Constraint (10) represents the ranges of the time parameters.

3.4. Design of the Lower-Layer Model

Firstly, this paper determines the path between the quay cranes and the blocks according to the terminal road network and tasks assignment and uses the Dijkstra algorithm to obtain the shortest paths. When there are several shortest paths, the better path will be selected according to the principle of fewer turns. Then, the time window of each link will be calculated according to the shortest path. If there is no time window overlap in each link, there is no conflict among AGVs, and the path planning is completed. If there is overlap between time windows, we adjust the time when AGV enters the link and update the time window of subsequent links. Finally, the time window overlap is detected until there is no overlapping time window.

The following objective function is to obtain the shortest AGV transportation time in the path planning model:

$$\min W_1 = \frac{\left(\sum_{i \in G} z_{qi} e_{qi} + \sum_{i,j \in G} z_{ij} e_{ij} + \sum_{j \in G} z_{jb} e_{jb}\right)}{v}, \forall q \in Q, \forall b \in B_{mn} \tag{11}$$

$$\sum_{i \in G} z_{qi} = \sum_{j \in G} z_{jb}, \forall q \in Q, \forall b \in B_{mn} \tag{12}$$

$$z_{ij} \le y_{ijc}, \forall i, j \in G, \forall c \in V \tag{13}$$

$$\sum_{i,j \in G} y_{ijc} \le g - 1, \forall c \in V \tag{14}$$

Equation (11) is the objective function, which represents the shortest time for AGVs to complete the transportation tasks. Constraint (12) represents that each path has a starting and ending node. The starting or ending node is the point where the quay crane or the bay of the yard is. Constraint (13) represents that e_{ij} can be selected only when it exists. Constraint (14) indicates the elimination of the subloops:

$$T_{w_{u,ij}} = \left(c, u, l_{u,e_{ij}}, t_{in,u,ij}, t_{out,u,ij}\right) \tag{15}$$

$$w_{u,ij} = t_{out,u,ij} - t_{in,u,ij} \tag{16}$$

$$C = arg\min_{u'}\left\{t_{in,u',ij}\middle|\left[t_{in,(u'+1),ij} - \max\left(t_{out,u',ij}, t_{out,(l_{u,e_{ij}}-1)}\right)\right] > w_{ij}, u' = 1,2,\ldots,u''\right\} \tag{17}$$

$$t_{in,u,ij} = \max\left(t_{out,(u'+1),ij}, t_{out,(l_{u,e_{ij}}-1)}\right) \tag{18}$$

$$t_{out,u,ij} = \max\left(t_{in,u,ij} + w_{u,ij}, t_{in,(l_{u,e_{ij}}+1)}\right) \tag{19}$$

$$\left\{t_{in,u',ij}\middle|\left[t_{in,(u'+1),ij} - t_{out,u',ij}\right] < 0, u' = 1,2,\ldots,u''\right\} = \varnothing \tag{20}$$

Equation (15) is the time window function, where $l_{u,e_{ij}}$ represents the sequence number of e_{ij} in the shortest link when handling the task u. Equation (17) represents that when there are u'' tasks occupying link e_{ij}, the time window gap that can be inserted into link e_{ij} should satisfy this formula. Equation (18) represents the time when task u entries link e_{ij}. Equation (19) represents the time when task u leaves link e_{ij}. Equation (20) is used to check whether there is an overlapping time window. If this equation is satisfied, there is no overlapping time window, and there is no conflict among AGVs, the path planning is completed. If Equation (20) is not satisfied, Equations (17)–(19) are repeated for adjustment until there is no overlapping time window.

The alternative path is obtained by the path search method, which meets the following mathematical model:

$$W_2 = \underset{d}{\operatorname{argmin}} P_d \tag{21}$$

$$\mu = \arg_{\eta}\left\{\left[\sum_{i,i\in G} j(z_{ij}(\eta)_d) - \sum_{t=1}^{n_d}\sum_{i,j\in G} i(z_{ij}(\eta)_d)\right] = 0, \forall\eta \in (1,2,\ldots,n_d), \forall d \in D\right\} \tag{22}$$

$$\left\{t_{(z_{ij}(\mu)_d)}\middle|\left[\left|i(z_{ij}(\mu)_d) - j(z_{ij}(\mu)_d)\right| - \left|i(z_{ij}(\mu+1)_d) - j(z_{ij}(\mu+1)_d)\right| \neq 0\right]\right\} = 1, \forall i,j \in \tag{23}$$

$$P_d = \sum_{k=1}^{n_d} t_{(z_{ij}(\mu)_d)}, \forall d \in D \tag{24}$$

Equation (21) is the objective function, which represents the path with the least turning numbers in a group of paths with the same length. Equation (22) represents whether three nodes on a path are continuous. Equation (23) represents that the equation holds once and path turning number add once, where $t_{(z_{ij}(\mu)_d)} = 1$ represents that there is one turning in the node j of link μ on path d. Equation (24) represents the total turning numbers of a path. After selecting the alternative path, the above time window overlap detection and time window adjustment are carried out.

This section establishes the integrated scheduling model of the U-shaped automated container terminal and the AGV conflict-free path planning model. Specifically, for a set of assigned tasks, the upper-layer model generates the time when AGV leaves the quay crane and transmits the time to the lower-layer model. Then, the lower-layer model generates the conflict-free path of AGVs and the time when AGV reaches the target bay of the yard, and feeds back to the upper-layer model. Then, the upper-layer model calculates the waiting time between the AGV and the double-cantilever rail crane, and feeds back the time to the lower-layer model. Finally, the upper-layer model calculates the completion time of this task. When the next task starts, this bi-level programming model enters the next iteration until all unloading tasks are completed.

4. Improved Hybrid Genetic Seagull Optimization Algorithm

The solutions of bi-level programming problems are mainly divided into two categories: analytical methods and heuristic algorithms. The analytical method is to directly obtain its exact solution by the standard solvers. This kind of method is usually suitable for a simple logical relationship and penalty function. It can transform bi-level programming into single-layer programming. However, the proposed bi-level programming model in this paper has many constraints, interactional decision variables, and dynamic characteristics. In addition, there are complex logical relations for multi machining features, task allocations of processes, AGV routes, and container handling sequences. It cannot be solved by the analytical method. The genetic algorithm is used by a large number of scholars to solve the integrated scheduling models of automated container terminals due to its strong universality and fast convergence speed. However, the genetic algorithm has the disadvantages of being premature, and it is easy to fall into a local optimization solution. This paper introduces the seagull optimization algorithm. The seagull optimization algorithm is a new swarm intelligence optimization algorithm proposed by Gaurav Dhiman and Vijay Kumar [24] in 2019, which simulates seagull migration and foraging behaviors in nature. This algorithm has the ability of global search and local search, in which migration behavior has the ability of global search and foraging behavior has the abilities of local search. The excellent global search ability effectively makes up for the shortcomings of GA and avoids falling into the local optimal solution. In addition, preliminary studies have suggested that the hybrid meta-heuristic algorithm achieved a better performance than single algorithms [25–27]. This paper combines the genetic algorithm with the seagull optimization algorithm and proposes an improved hybrid genetic seagull optimization algorithm (GSOA).

4.1. Coding and Decoding

It is assumed that there are nine unloading tasks, three quay cranes, three AGVs, and two blocks. Each block is equipped with two-dual cantilever rail cranes. The chromosome coding diagram is shown in Figure 2. The first line represents the number of container tasks, the second line represents the number of quay cranes, the third line represents the number of AGVs, the fourth line represents the number of blocks, and the fifth line represents the target bay of the container in the block.

Decoding the chromosome, the path of AGV 1 is: quay crane 2 → yard 2 (Task 2) → quay crane 1 → yard 1 (task 3) → quay crane 2 → yard 2 (task 4). The paths of AGV 2 and AGV 3 can also be obtained.

Container Task	2	8	1	3	5	7	4	9	6
Quay Crane	2	1	1	1	3	1	2	3	2
AGV	1	2	3	1	2	3	1	2	3
Block	2	2	1	1	1	2	2	1	1
Bay	117	105	115	109	109	111	105	103	115

Figure 2. Chromosome representation example for tasks.

4.2. Crossover Based on the Seagull Optimization Algorithm

The seagull optimization algorithm simulates seagulls' migration and foraging behaviors in nature. During migration, seagulls travel in groups. In order to avoid collisions, each seagull is in a different position during migration. In a group, seagulls can move towards the best position and change their positions. In addition, seagulls often make spiral movements to attack other migratory birds.

During migration, the algorithm simulates how seagulls move from one location to another. At this stage, seagulls should meet three conditions [15]:

(I). Collision avoidance: in order to avoid collisions among seagulls, the algorithm uses the additional variable A to calculate the new position of seagulls:

$$C_s(t) = A \cdot \eta_s(t) \tag{25}$$

$$A = \lambda_c - \left(gen \cdot \left(\frac{\lambda_c}{Maxiter} \right) \right) \tag{26}$$

where $C_s(t)$ represents a new position that does not conflict with other seagulls. $\eta_s(t)$ represents the current position of the seagull; gen represents the current number of iterations; A represents the motion behavior of the seagull in a given search space, λ_c can control the frequency of A, where its value decreases linearly from 2 to 0; and $maxiter$ is the maximum number of iterations.

(II). Best position direction: after avoiding overlapping with the positions of other seagulls, seagulls will move to the direction of the best position:

$$\delta_s(t) = \mu \cdot (\eta_{bs}(t) - \eta_s(t)) \tag{27}$$

$$\mu = 2 \cdot A^2 \cdot \varepsilon_d \tag{28}$$

where $\delta_s(t)$ represents the direction of the best position, μ is the random number responsible for balancing the global and local search, and ε_d is a random number in the range [0, 1].

(III). Close to the best position: after the seagull moves to the position where it does not collide with other seagulls, it moves towards the direction of the best position to reach a new position:

$$\zeta_s(t) = |C_s(t) + \delta_s(t)| \tag{29}$$

where $\zeta_s(t)$ represents the new position of the seagull.

Seagulls can constantly change their attack angle and speed during migration. They use their wings and weights to maintain height. When attacking prey, they spiral in the air. The motion behavior in the x, y, and z planes are described as follows [24]:

$$x = \varepsilon \cdot \cos(\theta) \tag{30}$$

$$y = \varepsilon \cdot \sin(\theta) \tag{31}$$

$$z = \varepsilon \cdot \theta \tag{32}$$

$$\varepsilon = u' \cdot e^{\theta v'} \tag{33}$$

where ε is the radius of each helix, θ is the random angle value in the range of [0,2π], u' and v' are the correlation constants of the spiral shape, and e is the base of the natural logarithm. Therefore, the attack position of the seagull is as follows:

$$\eta_s(t) = \zeta_s(t) \cdot x \cdot y \cdot z + \eta_{bs}(t) \tag{34}$$

where $\eta_s(t)$ is the attack position of the seagull.

In this paper, the update strategy of the seagull optimization algorithm is introduced into the crossover part of the genetic algorithm, as shown in Figure 3. Aiming at the task number of the first layer of the chromosome, the container task in the chromosome is operated as follows. Firstly, each gene is updated according to the position update formula of the seagull optimization algorithm, as shown in Equations (25)–(34). Then, the elements in each locus are rounded, and the same elements are set to 0. Finally, the individual in the original population is randomly selected and compared with the updated individuals. The “0” elements in the latter individual are replaced by the elements contained in the randomly selected original individual rather than in the updated individual. The second, fourth, and fifth layers of chromosomes follow the first layer to ensure that the starting quay crane, target block, and bay of each task are consistent. Since AGV can perform any task, there is no need to operate on the third layer.

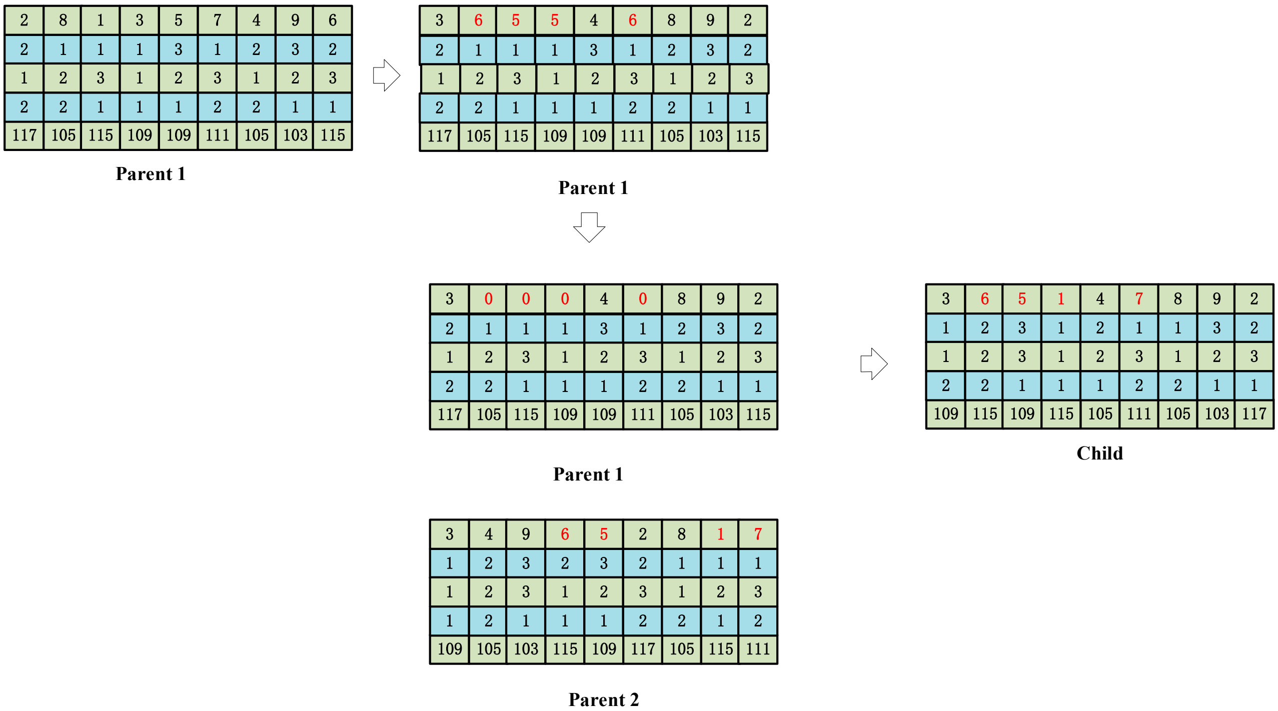


Figure 3. An illustration of crossover for the chromosome.

4.3. Mutation

The mutation in this paper adopts a reverse order operation, where two points are randomly selected on the chromosome and the tasks between the two points are arranged in reverse order. The mutation probability adopts the adaptive mutation probability, which is automatically adjusted according to the evolutionary generation [28], as shown in Equation (35):

$$p_m = p_{max} - \frac{(p_{max} - p_{min}) \cdot iter}{Maxgen} \tag{35}$$

where p_{max} is the maximum variation probability. p_{min} is the minimum mutation probability. *iter* is the evolutionary generation. *Maxgen* is the maximum evolutionary generation. Figure 4. is a illustration of Mutation for the chromosome.

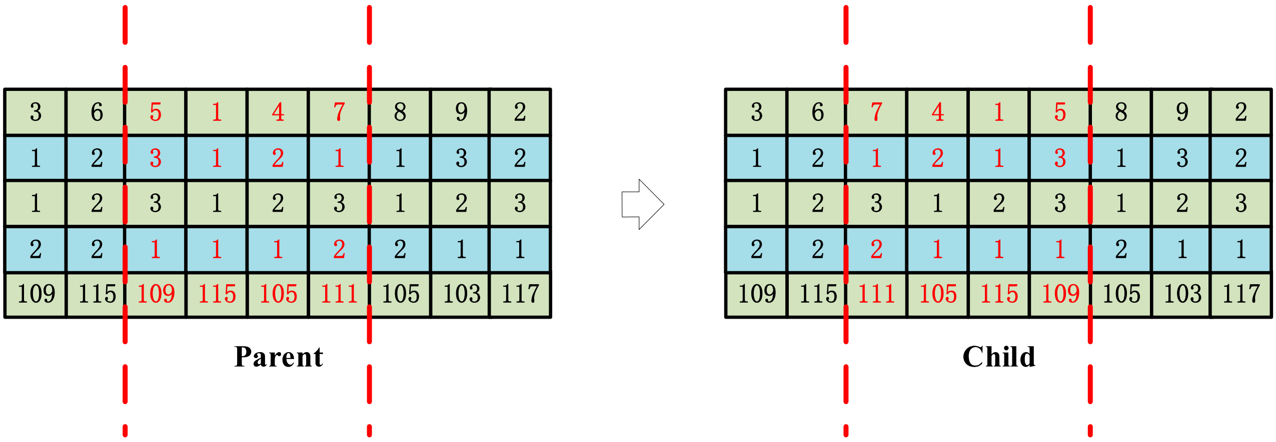


Figure 4. An illustration of mutation for the chromosome.

4.4. Algorithm Flow

The flow chart is shown in Figure 5.

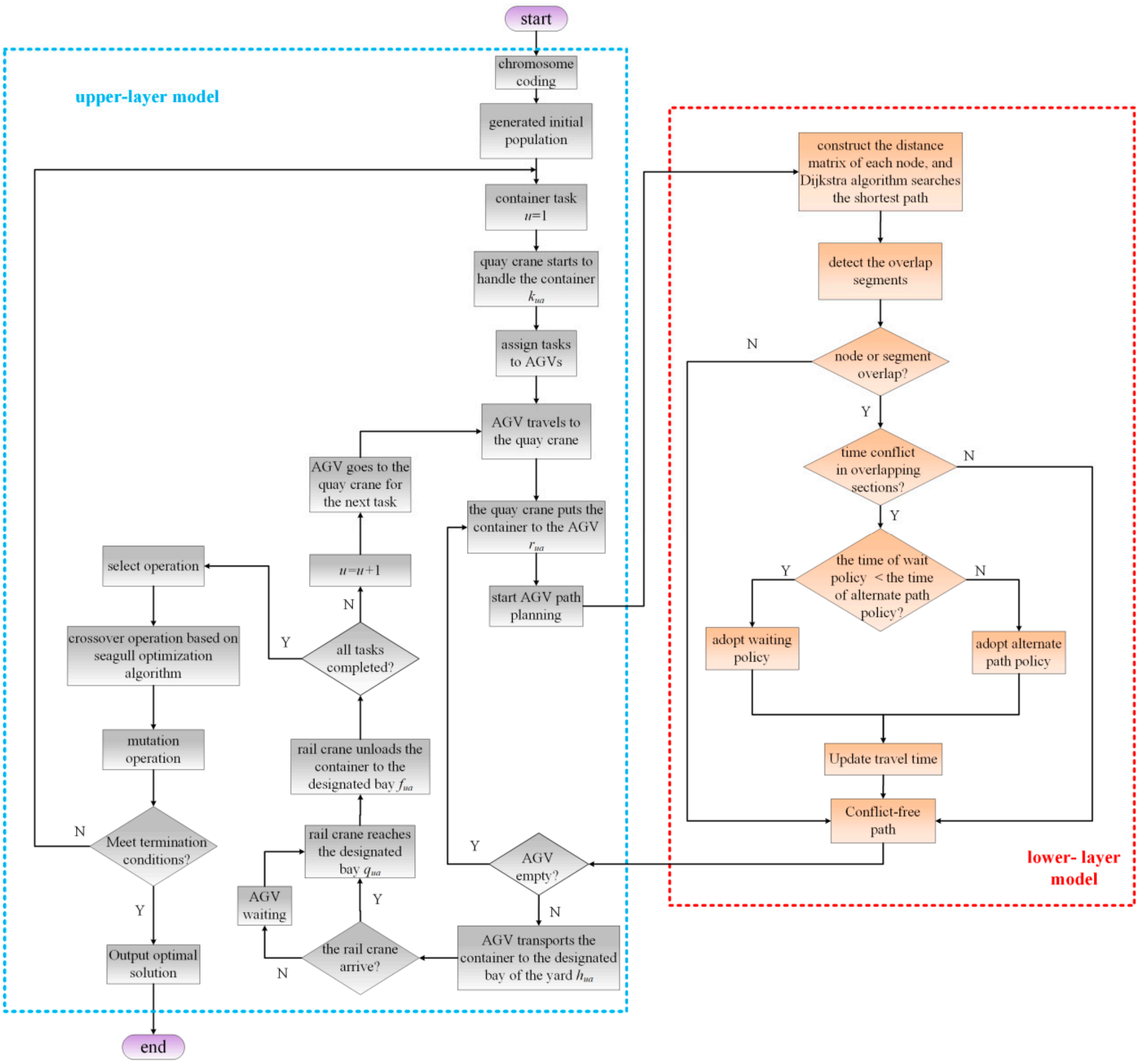


Figure 5. The flowchart of GSOA.

5. Numerical Experiments

These experiments were implemented in MATLAB 2018b, and all the simulations were performed on a computer with Intel(R) Core(TM)i7-8750H CPU@2.20GHz and 16 GB RAM under a Windows operating system.

5.1. AGV Path Network

The navigation and positioning of AGVs in the automated container terminal is based on the magnetic nails buried underground [11] as shown in Figure 6. The locations of the magnetic nails are the nodes of the AGV path network.

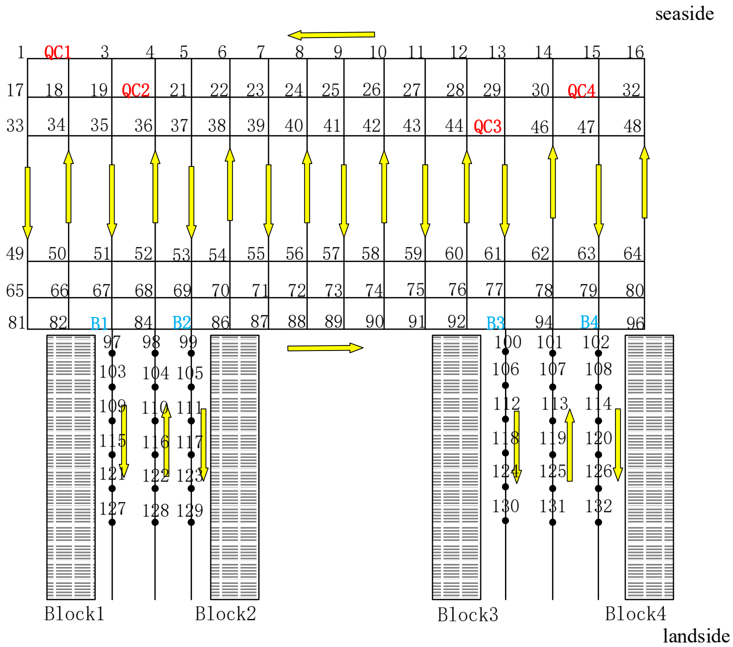


Figure 6. AGV path network of the U-shaped automated container terminal.

In Figure 6, different colors denote the work areas of different equipment. QC 1, QC2, QC3 and QC4 represent the work areas of 4 Quay Cranes. There are 132 nodes to simulate the magnetic nails. The nodes for AGVs to enter the yard are B1, B2, B3, and B4. The nodes for AGV to leave the yard are 84 and 94. The yellow arrows represent the directions of AGVs' travel.

5.2. Parameter Setting

This paper focuses on the unloading mode in a U-shaped automated container terminal. The layout of the terminal is shown in Figure 1. In the horizontal transportation area, the length is 300 m and the width is 120 m. The length of one bay in the storage yard is 20 m, and there are 20 bays in each storage yard area. There are four quay cranes, four blocks, and eight dual-cantilever rail cranes. The AGV speed is 5 m/s and the double-cantilever rail crane speed is 2 m/s. The time for the QC to handle the container to the AGV is 30 s, and the time for the cantilever to handle the container from the AGV to the target bay is 30 s [4,29–31]. The algorithm parameters [23,24] are shown in Table 1.

Table 1. The values of the algorithm parameters.

Algorithm Parameters	Value
$popsiz$	50
$Maxgen$	200
f_c	2
u	1
v	1
p_c	0.5
p_{max}	0.8
p_{min}	0.1

$popsizMaxgenf_c uvp_c p_{max} p_{min}$

5.3. Results for Small-Sized Problems

There are nine unloading tasks. The starting and ending points of the tasks are known. The specific task allocation is shown in Table 2.

Table 2. The AGV task allocation.

AGVs	Container Tasks	Starting Points—Ending Points
1	3, 6, 8	QC1-109-QC2-115-QC1-105
2	4, 5, 1	QC2-105-QC3-109-QC1-115
3	9, 2, 7	QC3-103-QC2-117-QC1-111

Table 2 shows the task allocation of AGVs. "AGVs" represents the serial numbers of AGVs. "Container tasks" represents the serial numbers of container tasks. "Starting points—Ending points" represents the starting points and the ending points of AGVs. AGV 1 completes three unloading tasks in sequence according to the assignment, and the task numbers are 3, 6, and 8, respectively. The starting and ending points of task 3 are both QC1-109. The starting and ending points of task 6 are both QC2-115. The starting and ending points of task 8 are both QC1-105. Therefore, the path of AGV 1 is QC1-109-QC2-115-QC1-105.

The integer programming model and the path search method are used to determine the path from the starting point to the ending point. Then, the shortest path is determined according to the path length and the number of turns. According to the AGV task allocation in Table 2, the shortest paths and the optimized alternative paths for AGV 1 are shown in Table 3. Similarly, the shortest paths and the optimized alternative paths for AGV 2 and AGV 3 can be obtained.

Table 3. The paths of the AGV 1 to complete the task.

Starting Points—Ending Points	Shortest Path	Best Optimal Alternative Path
QC1-109	QC1-1-17-33-49-65-81-82-B1-97-103-109	QC1-1-17-33-49-50-51-67-B1-97-103-109
109-QC2	109-110-104-98-84-68-52-36-QC2	109-110-104-98-84-B2-86-70-54-38-22-21-QC2
QC2-115	QC2-19-35-51-67-B1-97-103-109-115	QC2-19-18-17-33-49-65-81-82-B1-97-103-109-115
115-QC1	115-116-110-104-98-84-68-52-36-QC2-4-3-QC1	115-116-110-104-98-84-B2-86-70-54-38-22-6-5-4-3-QC1
QC1-105	QC1-1-17-33-49-65-81-82-B1-84-B2-99-105	QC1-1-17-33-49-50-51-52-53-69-B2-99-105

In order to verify the effectiveness of the AGV path planning method, experiments were carried out on the AGV path network in Figure 6. The task arrangement is shown in Table 2. Table 3 represents the shortest path and best optimal alternative path of AGV

1 obtained by the lower-layer model. According to the real port operation data, the time for the double-cantilever rail crane to unload a container is assumed to be 30 s. According to the path planning of the lower-layer model, the time point when AGV reaches the designated bay of the block can be obtained. Then, the lower-layer model feeds back the arrival time to the upper-layer model to obtain the waiting time between the AGV and the double-cantilever rail crane. Then, the upper-layer model adds the waiting time to gain the completion time of this task. Finally, the completion time of all unloading tasks can be obtained by performing this operation for each task. Figure 7 is the time window distribution of AGV 1 to AGV 3 under the shortest path. There are conflicts on the paths, and the conflict time windows are marked with a green box in Figure 7. The conflict time window data is shown in Table 4. The conflict object represents the serial number of the conflicting AGVs. The conflict link represents the conflicting road section. The starting time of the conflict link/s represents the time when AGV conflict starts. The ending time of the conflict link/s represents the time when AGV conflict ends.

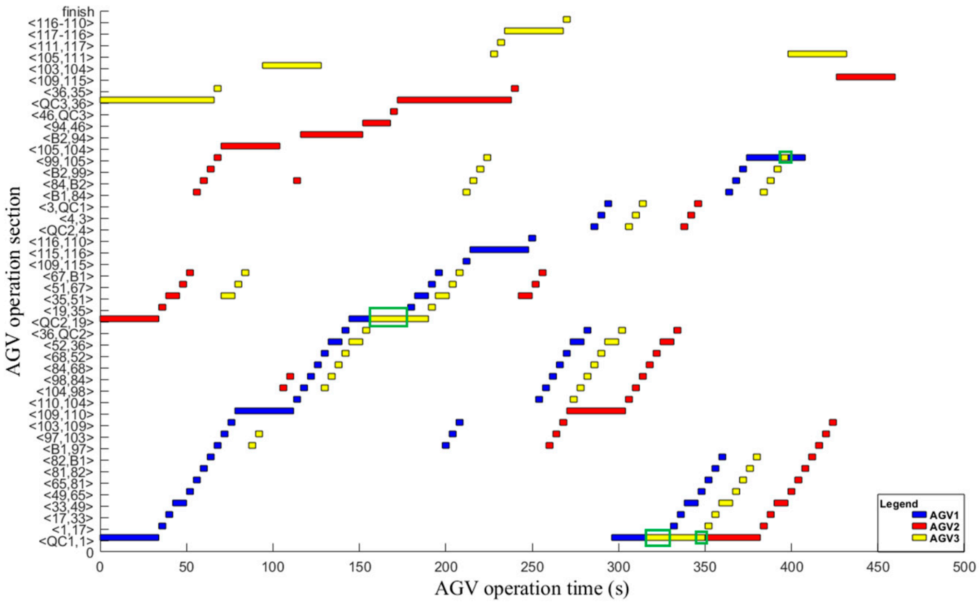


Figure 7. The time window distribution of AGV 1 to AGV 3.

Table 4. The time window of conflict links.

Conflict Object	Conflict Link	The Starting Time of Conflict Link/s	The Ending Time of Conflict Link/s
AGV 1—AGV 3	<QC2,19>	156	178
AGV 1—AGV 3	<QC1,1>	316	330
AGV 1—AGV 3	<99,105>	394	398
AGV 2—AGV 3	<QC1,1>	426	350

When two AGVs conflict, a hybrid policy of a delay and alternative path is adopted. For each conflict, the delay and alternative path policies are adopted, respectively. After comparing the time of the two policies, the policy with a shorter time is selected for adjustment. The results are shown in Figure 8.

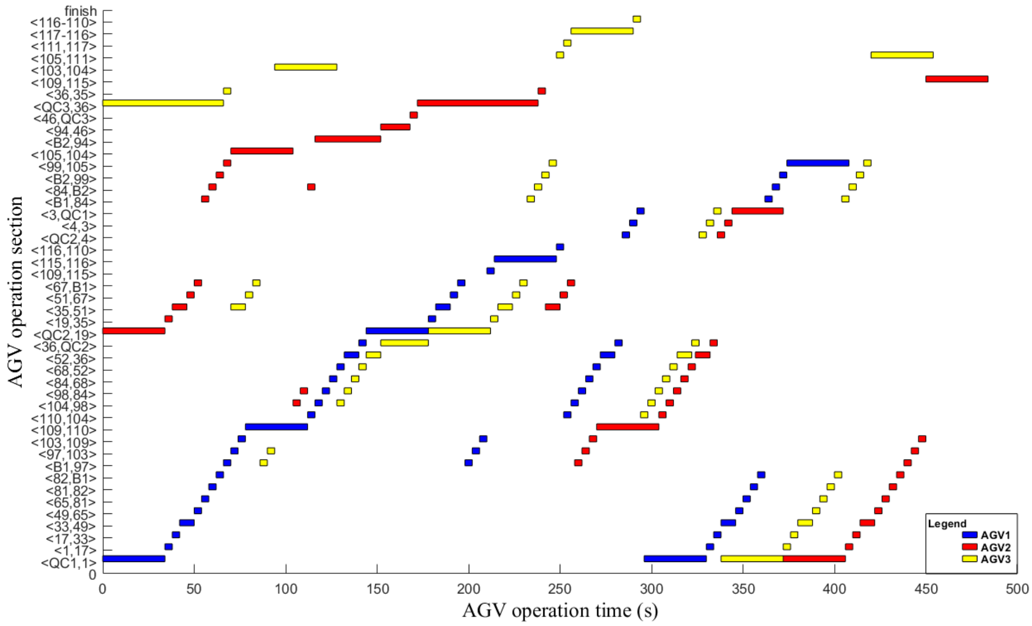


Figure 8. The time window distribution of AGV conflict-free path planning.

By calling the solution results of the lower AGV conflict-free path planning model, the upper task sequence can be optimized repeatedly. The initial task sequence generated by the upper-layer model is shown in Figure 2. After multiple iterations of the solution results of the bi-level model, the optimization task sequence is shown in Figure 9. The unloading time windows are shown in Figure 10. The mark (372,108) after the first time window represents that the unloading time of container task 1 is 372 s, and it takes 108 s to complete the task. The meaning of the marks after other time windows is similar to that of the first time window, and the final completion time is 480 s.

Container Task	3	4	9	6	5	2	8	1	7
Quay Crane	1	2	3	2	3	2	1	1	1
AGV	1	2	3	1	2	3	1	2	3
Storage Yard	1	2	1	1	1	2	2	1	2
Bay	109	105	103	115	109	117	105	115	111

Figure 9. The optimization task sequence.

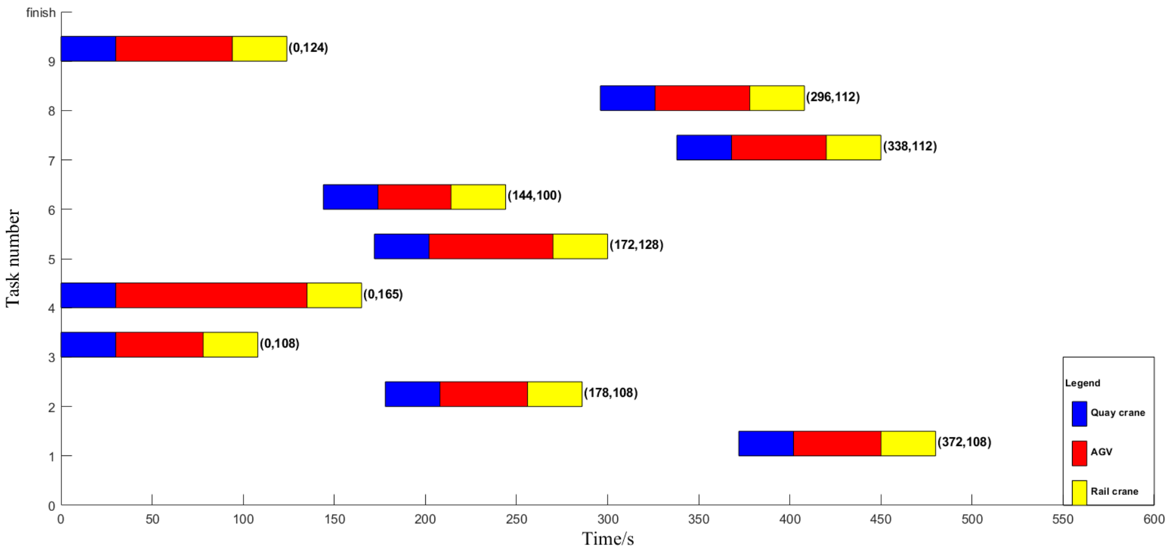


Figure 10. Time windows of the small-sized problem.

5.4. Results for Large-Sized Problems

In order to verify the effectiveness of the proposed model and algorithm, 15 groups of comparative experiments were carried out using AGA [4], BGA [12], and GSOA. In this paper, each group of instances ran for 30 times, and the target value is the maximum (MAX) and average (AVE), and the running time is the average value. The results are shown in Table 5.

Table 5. Results of large-sized problems.

			GSOA		AGA		BGA	
No.	Containers	AGV	OFV/s MAX/AVE	CPU/s	OFV/s MAX/AVE	CPU/s	OFV/s MAX/AVE	CPU/s
1	40	10	382/363	11	468/447	36	503/486	46
2	80	10	759/725	45	967/950	85	1096/986	76
3	120	10	1120/1080	53	1523/1326	116	1424/1354	126
4	120	20	657/630	31	855/722	135	884/769	154
5	200	20	1089/1034	54	1312/1155	385	1326/1203	425
6	200	50	555/535	67	967/823	399	1066/862	362
7	400	20	1923/1813	329	2551/2336	497	2352/2246	457
8	400	40	1023/962	148	1599/1356	451	1597/1356	489
9	640	20	3117/2930	301	3824/3561	556	3923/3653	582
10	640	40	1593/1501	271	2014/1855	550	1926/1795	586
11	800	40	2007/1873	292	2932/2634	507	2964/2862	487
12	1200	30	3925/3671	327	4725/4423	794	4723/4536	724
13	1200	40	2994/2779	346	3764/3658	780	3961/3782	715
14	2000	40	4806/4558	696	6547/6179	1305	6648/6324	1154
15	2000	50	3952/3709	693	5779/5476	1653	5992/5859	1597

It can be seen from the experimental results in Table 5 that:

(1) In the solving process of GSOA, the hybrid policy of the delay and alternative path can stably obtain the approximately optimal solution of large-sized problems. From examples 13 and 15 in Table 5, when the number of containers is 1200 and the number

of AGVs is 40, the average of the objective function value (OFV) is 2779 s; when the number of AGVs is 50, the average of the objective function value is 3709 s, and the difference between the AVE and the MAX is within the acceptable range, which basically meets the time requirements of automated container terminal operation system scheduling.

(2) As the number of containers increases, the total unloading time of the terminal also increases. With the same number of containers, the increase in the number of AGVs will reduce the total unloading time. Therefore, increasing the number of AGVs to a certain extent can significantly improve the efficiency of handling. Different numbers of tasks and AGVs have significant impacts on the total handling time of the terminal.

Taking 120 container tasks and 20 AGVs as an example, Figure 11 shows the handling time window of the large-sized problem, and the unloading process of the U-shaped automated container terminal is described from three types of time windows: a quay crane handling container, AGV transporting container, and double-cantilever rail crane handling container. In Figure 11, there are 120 three-color line segments representing 120 tasks. Taking task 2 as an example, it is similar to Figure 10. The unloading time of task 2 is 345 s, and 107 s is needed to complete task 2. The other linear time windows are similar to that of task 2. The final completion time is 620 s. From Figure 11, the hybrid policy is effective, and it can successfully realize integrated scheduling optimization in U-shaped automated container terminals.

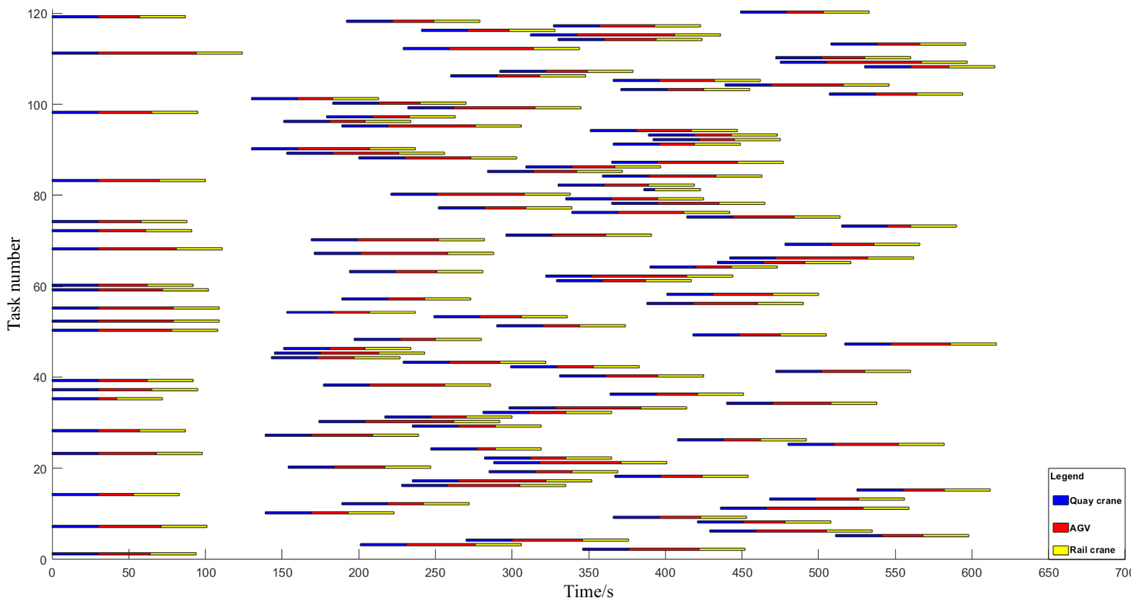
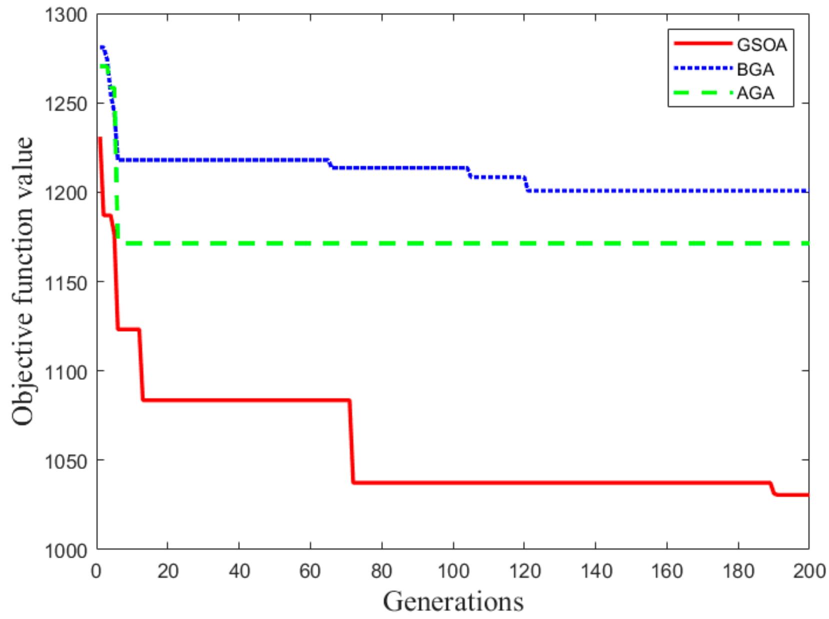
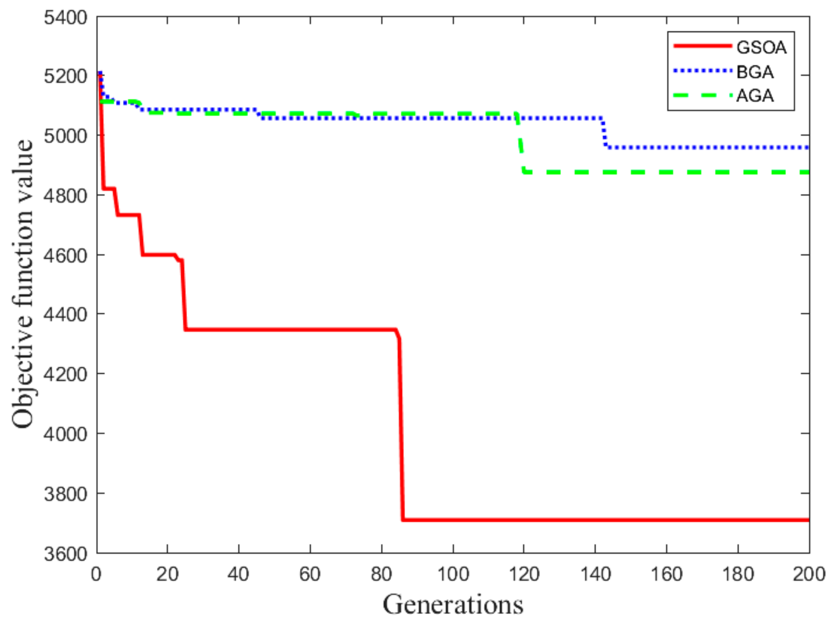


Figure 11. Time windows of the large-sized problem.

To further demonstrate the overall performance comparison of the three algorithms, this paper conducted experiments under the conditions of 200 container tasks and 20 AGVs, as shown in Figure 12a. As can be seen from the Figure 12a, BGA, GSOA, and AGA converge in generation 151, 80, and 122, respectively, and the OFVs are 1155, 1034, and 1203 s, respectively. The convergence efficiency of GSOA is better than the other two algorithms. GSOA converges after 80 iterations, and it also has obvious advantages in its solution quality compared with the other two algorithms. Figure 12b shows the results of the 3 algorithms in 2000 container tasks and 50 AGVs. It can be seen from Figure 12b that GSOA converges when it iterates to about 86 generations, and the OFV is 3709 s. The convergence speed and OFV are obviously better than the other two algorithms, which further verifies the effectiveness of GSOA. From Figure 12a,b, 10× more container tasks are handled while only 2.5× more AGVs are available in the U-shaped automated container terminal. It leads to longer processing times for more container tasks.



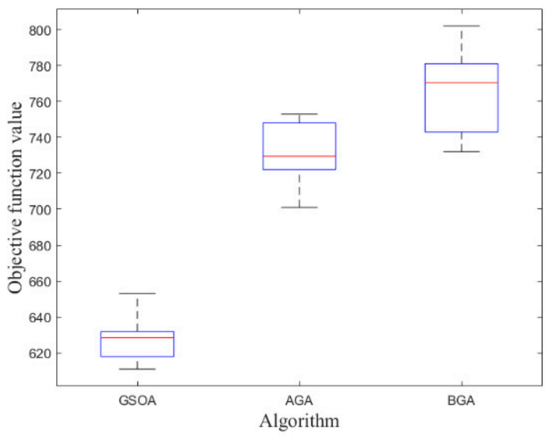
(**a**)



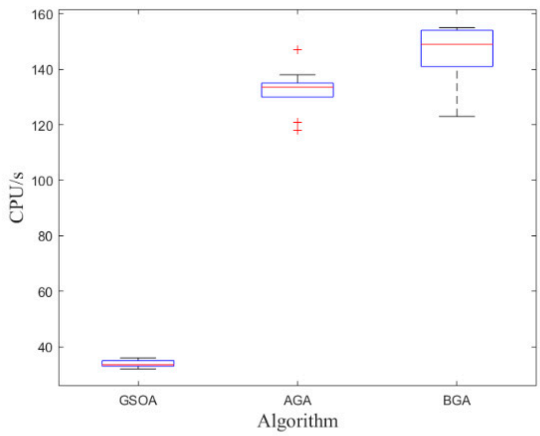
(**b**)

Figure 12. Experimental results of different algorithms. (**a**) Performances of different algorithms with 200 container tasks and 20 AGVs. (**b**) Performances of different algorithms with 2000 container tasks and 50 AGVs.

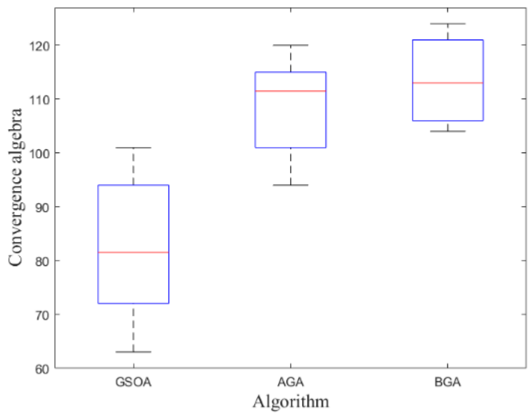
In order to compare the performances of the 3 optimization algorithms in the case of 120 container tasks and 20 AGVs, the 3 algorithms are run 10 times, respectively, to obtain the OFVs, CPU running time, and convergent generations, as shown in Figure 13. As can be seen from Figure 13, the OFV and CPU running time of the GSOA in this paper are significantly better than the other two algorithms. Although the convergent generation varies greatly, the result is significantly better than the other two algorithms.



(a)



(b)



(c)

Figure 13. Box plot comparisons of the algorithm optimization performances. (**a**) Comparison of OFV. (**b**) Comparison of CPU. (**c**) Comparison of convergent generations.

In order to test the stability of the proposed GSOA, this paper considers 30 runs with 200 containers, 20 AGVs, 4 QCs, and 8 dual-cantilever rail cranes, and the parameters are the same each time. Figure 14 shows the result of generation 1–200. Each box represents the variation range of the objective function value in different generations; that is, each box represents the OFVs of the 30 runs in one generation. The central mark is the median of OFVs, the edges of the box are the 25th and 75th percentiles, and the whiskers are the most extreme data points. The data reveal that the OFVs of the algorithm have a wide range in the previous generations. With the superposition of evolutionary generation, the algorithm approaches the approximately optimal solution in each generation. An approximately optimal solution can be found in the 180th generation, and the algorithm gradually converges to stability.

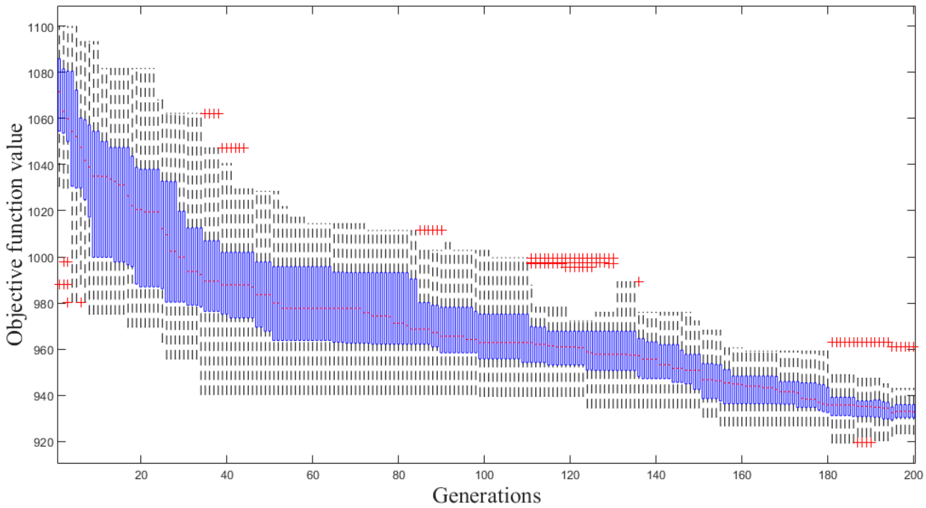


Figure 14. Box plot of GSOA in 30 runs.

6. Conclusions

In this paper, the unloading mode of the U-shaped automated container terminal was considered. Based on the layout of the terminal, a bi-level programming model was established. The upper-layer model is the integrated scheduling model of quay cranes, AGVs, and double-cantilever rail cranes. The lower-layer model is the AGV conflict-free path planning model. The purpose was to minimize the total handling time and improve the efficiency of the terminal. An improved GSOA was designed to solve the model. The GSOA was compared with AGA and BGA to verify the effectiveness of the proposed model and algorithm through large-sized problems. The proposed method was found to be more effective and reliable than AGA and BGA. We experimented with various numbers of containers equipped with different numbers of AGVs to test the GSOA. This process not only revealed reasonable AGV schemes for different quantities of containers but also proved that GSOA obtains favorable solutions within a reasonable amount of time. According to our experiments, the proposed model is practically applicable to the existing U-shaped automated container terminals and may dramatically improve the efficiency.

Integrated scheduling of U-shaped automated container terminals is a complex and interesting problem. Therefore, it can be further studied in future work. The improvements and future research directions are as follows:

(1) Integrated optimization of automated container terminals contains many aspects and we will take berths and external trucks into consideration in the future.
(2) External truck appointment system, carbon emission, and sea rail intermodal transportation can also be considered.
(3) We may also extend the unloading mode into the loading and unloading mode, and the cooperative scheduling problem of the QC, AGV, and double-cantilever rail crane.

Author Contributions: Conceptualization, B.X. and J.L.; methodology, B.X., J.L. and D.J.; validation, B.X., J.L. and D.J.; writing—review and editing, B.X., J.L., D.J., Y.Z., H.W. and H.F.; supervision, B.X. and J.L. All authors have read and agreed to the published version of the manuscript.

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ARTICLES FOR FACULTY MEMBERS

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A probabilistic model of human error assessment for autonomous cargo ships focusing on human–autonomy collaboration

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ABSTRACT

Despite the use of automation technology in the maritime industry, human errors are still the typical navigational risk influencing factors in autonomous ships with the third degree of autonomy. However, there is an urgent need for new human error probability assessment focusing on the autonomous cargo ships with human–autonomy collaboration. Hence, to assess these human errors during the emergency response process, a probabilistic model is proposed in this paper. Firstly, the risk factors are identified and classified by analysing the operational process of the Shore Control Centre (SCC). This is followed by the establishment of an event tree model delivered from human errors using Technique for Human Error Rate Prediction (THERP). Furthermore, Bayesian Networks (BNs) model is utilized for the three stages of perception, decision, and execution. Finally, the human errors probabilities are calculated for the mentioned three stages focusing on human–autonomy collaboration. Moreover, the importance of human error factors is quantified with sensitivity analysis, which can provide flexible references for the theoretical construction of the SCC and training of operators. The process was applied to assess the probabilities of human errors focusing on human–autonomy collaboration under the remote navigation mode of an autonomous cargo ship (test ship) in the city of Wuhan, China.

1. Introduction

With the rapid development of smart ship technology, autonomous ships will inevitably become the main emphasis of innovations by the shipping industry in the near future. For instance, the International Maritime Organization (IMO) at the 98th MSC put the concept of Maritime Autonomous Surface Ship (MASS) forward in 2017. Subsequently, the relevant departments started working on defining applicable laws and regulations from 2018 onwards. Meanwhile, many researchers have come up with preliminary definitions of MASS and established several stages for the development of MASS (IMO, 2018). Specifically, there can be four development stages based on the perspective of autonomy (MSC, 2018) as follows:

- *An automated program can operate ships and provide decision support;*
- *Ships can be controlled remotely with crew on board;*
- *Ships can be controlled remotely without any crew on board;*
- *Ships can be controlled completely autonomously.*

The improvement in automation technology will lead to a reduction in the number of people on board, which can promote the realization of autonomous ship navigation (Burmeister et al., 2014a). Depending on the extent of development in academic communities that the elaboration of MASS with the third degree of autonomy has already settled down. Examples of projects focusing on MASS with the third degree of autonomy include the *Maritime Unmanned Ships through Intelligence in Networks (*MUNIN, 2012*)* and *Advanced Autonomous Waterborne Applications (AAWA)* projects (Jokioinen et al., 2016). Specifically, the navigation mode of MASS with the third degree of autonomy can be divided into four subclasses: 1) ships departing from the harbour manually; 2) fully autonomous navigation mode; 3) remotely manipulated driving by operators of Shore Control Centres (SCCs), and 4) fail-to-safe mode (Burmeister et al., 2014a, 2014b). In the maritime field, until now, a remote-control system for smart ships was tested with

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human-machine interaction in the Delft ship design lab, which is based on the Navigation Brain System designed by WUT (Wang et al., 2020; Yan et al., 2019). An autonomous cargo ship with human–autonomy collaboration was tested in an autonomous ship test area in China.[1] Furthermore, four other autonomous ships have been tested with human–autonomy collaborations (Banda et al., 2019; Schuler, 2018a, 2018b). Accordingly, since humans will not be completely removed from the new marine transportation system, but will rather be reallocated from ships to shore-based control centres, the human factors that influence the decisions and actions of shore-based operators need to be determined, as presented and discussed by Ramos et al. (2018a, 2018b, 2018c), and Fan et al. (2020). Human error analysis and management are also receiving growing interests in industries to reduce the navigational risk associated with human–autonomy collaboration focusing on autonomous ship with the third degree of autonomy. (Noroozi et al., 2014; Abaei et al., 2019; Fan et al., 2020). Therefore, there is an urgent need for new human error assessment methods that are suitable for autonomous cargo ships with human–autonomy collaboration.

Maritime risk assessment considers the research hotspot for both traditional and autonomous ships (Wróbel et al. 2017, 2018; Bačkalov, 2020). Human errors are the main causes of ship accidents in the traditional marine transportation system (Ren et al., 2008; Porathe et al. 2014). Some researchers have argued that the marine safety level could be significantly improved if no crew on-board to operate the ship, similar to the MASS with the third degree of autonomy (Thieme et al., 2018; Fan et al., 2020; Wang et al., 2020). Because humans will not be removed, but will rather be reallocated from ships to shore-based control centres. In fact, if there is no crew operated the ship in real-time, new hazard scenarios can emerge as the crew's presence, mobility, and flexibility in maintenance and emergency occasions are of the essence (Wróbel et al. 2017; Utne et al., 2019). For example, serious accidents are highly likely to occur if there is no crew on board in the presence of equipment failure, such as "shift of cargo", fire or breakdown of the main engine (Banda et al., 2019; Huang et al., 2020). Conversely, these problems can be avoided if the crew detects these issues and resolves them on time (Ahvenjärvi, 2016). Under these circumstances, it is necessary to analyse the role of human errors in the autonomous cargo ships with the third degree of autonomy as they still involve safety risks attached to their operations (Fan et al., 2020; Wróbel et al. 2017). In scientific work, several studies were carried out regarding to the role of human beings in the autonomous cargo ships. Ramos et al. discussed the performance of factors influencing human behavior in autonomous ships. Based on the human cognitive reliability analysis method, these studies first subdivided human factors in autonomous ships into direct/indirect and internal/external factors and subsequently established a decision-making model of factors influencing human behavior. The authors discussed the main factors that influence the operators' decisions and actions while working onshore were pointed out, including four factors: information overload, situation awareness, skill degradation, and boredom in particular. Trudi et al. dubbed the autonomous ship as an "uninhabited" vehicle and argued that it could not be operated without human operators. From a theoretical perspective of macro level, autonomous ships can increase the safety of ships (Fan et al., 2020; Wróbel et al. 2017). Nevertheless, in reality, there are many uncertainties about the safety of autonomous ships due to the lack of first-hand multi-sensory experience. After that, human errors will be transferred to an SCC. Thus, to overcome new challenges that autonomous cargo ships face regarding both safe operation and monitoring, several safety constraints/requirements were proposed, which included communication costs, cybersecurity, information overload, data sharing, human-machine interaction, situational awareness, psychological load, over-reliance on automatic systems, social factors relating to autonomous cargo ships, and requirements for learning new skills. In addition, 23 human-related factors, 12 ship-related factors, 8 environment-related factors, and 12 technology-related factors were defined focusing on the autonomous cargo ship with the third degree of autonomy by Fan et al., 2020. Porathe et al. (2014) analysed the current situation of SCC for autonomous ships under the remote navigation mode and discussed the risks emanating from both ship conditions and human factors that will be faced by the SCC in the near future. These studies observed that maintaining situational awareness in the SCC is much more challenging than creating it. Rather than solely relying on simulated ship bridges, extensive training was needed to maintain situational awareness for real ships. Wróbel et al. (2017) assessed the potential impact of unmanned vessels on maritime transportation safety. Rødseth and Burmeister (2015a, 2015b), and Rødseth and Tjora (2014) analysed and presented the risk-based design methodology applied in the MUNIN project (MUNIN, 2012), which is based on the Formal Safety Assessment (FSA) process of the International Maritime Organization (IMO, 2002). The human factor issues were focused on remote monitoring and controlling of autonomous unmanned vessels (Man et al., 2015, 2016; 2018; Wróbel et al., 2017; Zhou and Zhang, 2019). Previous studies mostly focused on human factors identification from a macro perspective and lacked human error model/ human error probabilistic model that can occur in the emergency response process under the remote control of SCC (Hogg and Ghosh, 2016). In addition, the macro-level or system-level studies of human error factors cannot present the causal relationship, which is difficult to provide the risk control options or improve the SCC design. Thus, consolidation is urgently needed for relevant theoretical models to analyse human error factors and assess the human error probability in emergency response process under the remote navigation mode of SCC.

In scientific work, various human error analysis methods and human error probabilistic assessments have been proposed, including probabilistic risk assessment, the cognitive modelling, and simulations applied to several engineering applications, such as offshore oil and gas (Abbassi et al., 2015; Maya et al., 2019; Islam et al., 2016), and shipping operations (Islam et al., 2020; 2018; 2017; Nikolaos, 2010). The human error quantification techniques are based on two principles: subjective judgment and human error database. The common methods in subjective judgment contain absolute probability judgment (Kent and Lamberts, 2016), paired comparisons (Por and Budescu, 2017), success likelihood index method (Abrishami et al., 2020), and AHP-SLIM methods (Nurdiawati et al., 2018). The major problems associated with the expert judgments are the inconsistencies in the opinions among different experts, which become a challenge to have the required number of judges available who can evaluate the situation adequately. Focusing on human error database, the conventional methods which use the available human error data including human error assessment and reduction technique (Bowo and Furusho, 2018), justified human error data information (Abaei et al., 2019) and technique for human error rate prediction (Shirley et al. 2015). A single assessor could easily implement these techniques. Accordingly, the technique for human error rate prediction is a robust tool to analyse the human error during the emergency response process of autonomous ships at various task levels, and the final human error probability is calculated using an event tree relationship. However, the major problem associated with the mentioned method is the unconsidered uncertainty of the models.

In recent years, Bayesian Network methodology has been developed, and this causal network-based method is able to calculate the probability of events and model uncertainty in a domain or system, and to conduct statistical inference (Banda et al., 2015; Ung, 2019). The mentioned method has the ability to incorporate new observations into the network, the ability to describe inherent causal and associated probabilistic for the systems and the ability to analyse the complex

[1] Remote-control system was applied and tested: http://marsrv.tudelft.nl/dsdl/News; Autonomous cargo ship was tested: http://www.xinhuanet.com/info/2019–10/07/c_138452253.htm.

dependencies among the systematic indicators. In the context of human error probability estimation, that combines Bayesian approach with THERP method. Some research estimates the human error probability in oil tanker collision (Nevalainen et al., 2018; Lu et al., 2019), winter navigation (Ren et al., 2008; Akhtar and Utne, 2014), grounding and collision (Afenyo et al., 2017; Khan et al., 2018), ships stuck risk analysis in ice (Fu et al., 2016, 2018).

Considering the above, this paper aims to model the emergency response process for assessing the human errors probability of operators on the SCC combining the Technique for Human Error Rate Prediction (THERP) and Bayesian Networks (BNs). Specifically, the THERP method is applied to analyse the emergency response process focusing on the autonomous cargo ship with the third degree of autonomy and establish the event tree for human errors. Considering the uncertainties, each node of the event tree is applied to establish the BNs model to assess the human error probability. The process was applied to analyse the probabilities of human errors focusing on human–autonomy collaboration under the remote navigation mode of an autonomous cargo ship (test ship) in the city of Wuhan, China (Yan et al., 2019).

The next section presents the background and definitions of the human emergency operating behaviours during emergency response process of autonomous cargo ships. This is followed by the methodology and the proposed model. The assessment of the probabilistic model of human error assessment is applied in the section thereafter. The discussion and conclusion section presents the findings and identifies gaps in SCC design that need to be addressed in the future, which is followed by concluding remarks, and further work regarding human errors assessment model focus on autonomous cargo ships.

2. Analysis of human emergency operating behavior in the SCC

Under the autonomous navigation mode, autonomous cargo ships are possible facing unfavourable situations caused by risk factors such as external environment, organizational elements, and ship equipment in different task levels. As these situations cannot be handled on-board, the ship and danger warnings will be sent to the SCC to seek assistance from the remote control. In this situation, many researchers have established several decision-making models and control flowcharts corresponding to personnel emergency response processes (Xue et al., 2019; Zhang et al., 2017). The actions taken in the initial minutes of an emergency are critical based on emergency response processes. A prompt warning to operators to percept, make decision or lockdown can keep the ship safe. In this paper, according to the test ship, the emergency response process of the SCC is regarded as the process based on the cognitive behaviours of operators on SCC, namely, risk information perception → judgment decision → execution (Zhang et al., 2015; Yan et al., 2019; Fan et al., 2020). During this process, numerous types of human errors can lead to severe accidents due to the influence of the simulation device, equipment, surrounding environment, operating equipment, and personnel quality. This section analyses and establishes the operator's cognitive emergency response process, as shown in Fig. 1.

The emergency response process of autonomous cargo ships is complex, including various tasks in different situations. For each task, the possible human errors are different in frequency and types. Thus, based on the event tree delivered from the THERP, the BNs model is duplicated in various steps (risk information perception → judgment decision → execution), which has the following advantages:

- The hybrid model is simple and easy to construct, ready for reuse, and analyse from the three aspects for the emergency response process of autonomous cargo ships.
- Compared with the standard Bayesian models, the model is with a simple structure, and easy to be understood and explained (Khan et al., 2018).
- And emergency response process of autonomous cargo ships is a complex system, and the hybrid model can be able to address both the uncertainty and certainty problems.

3. Modeling

3.1. Fundamentals methodology

3.1.1. Technique for human error rate prediction

For human error probabilistic assessment, the THERP is a common tool for analysing daily operations following normal regulars, which is widely used in the quantitative analysis of human reliability, complex systems analysis of routine testing and analysis of maintenance tasks (Islam et al., 2018; 2017; Nikolaos, 2010). The method involves several aspects such as event tree analysis (ETA) (Zhou et al., 2017; Zhang et al., 2019; Ren et al., 2009), factor analysis of personnel performance, and combining quantitative calculation based on human error database (He et al., 2020). The THERP could be used to establish two attitude branch trees for the time sequence of participating events to calculate the error probabilities of all human errors. And the final human error probability is calculated using an event tree relationship. Accordingly, the THERP should consider all kinds of human behaviours in the process of event development, and make accurate quantification based on the type of human error during different operations. To fully understand and identify the key behaviours and related operational details, detailed investigations, and interviews on each human error factors are required for the human error analysis.

For this purpose, the THERP method is applied to analyse the emergency response process and establish the event tree model at various task levels focusing on the autonomous cargo ship with the third degree of autonomy. Furthermore, the engineering application is faced with several problems associated with a complicated analysis process. For example, huge manpower and material inputs, insufficient standardization, and excessive reliance on expert judgment (Chen et al., 2019). To overcome these problems, this paper divides the human error process into three stages based on THERP method and then constructs a BN model for each stage. The model is able to simplify the complicated human error probability modeling through a hierarchical and component-by-component analysis, which is easy to be understood and explained.

3.1.2. Bayesian network

The Bayesian formula given in formula (1) serves as the theoretical basis of the BN. It is principally used to describe the conditional probability inference between two variables (Banda et al., 2015; Ung, 2019).

$$p(A|B) = \frac{p(B|A)p(A)}{p(B)} \tag{1}$$

The formula is made up of prior probability, conditional probability, and posterior probability of the events. The prior probability means the occurrence probability of an event based on historical data or subjective expert judgment. Conditional probability refers to the occurrence probability of random event B when event A has occurred, under the hypothesis that B is a non-zero probability event. The posterior probability refers to the updated probability of an event occurring after taking into consideration prior and conditional probabilities.

$$p(A|B) = \frac{p(B|A)p(A)}{p(B)} \tag{2}$$

The BN is mostly used to model system uncertainties, which are mainly embodied in a Bayesian inference problem. The Bayesian inference problem is a conditional probability reasoning problem, which can be subdivided into two different reasoning models: forwarding reasoning and backward reasoning. Forward reasoning can be viewed

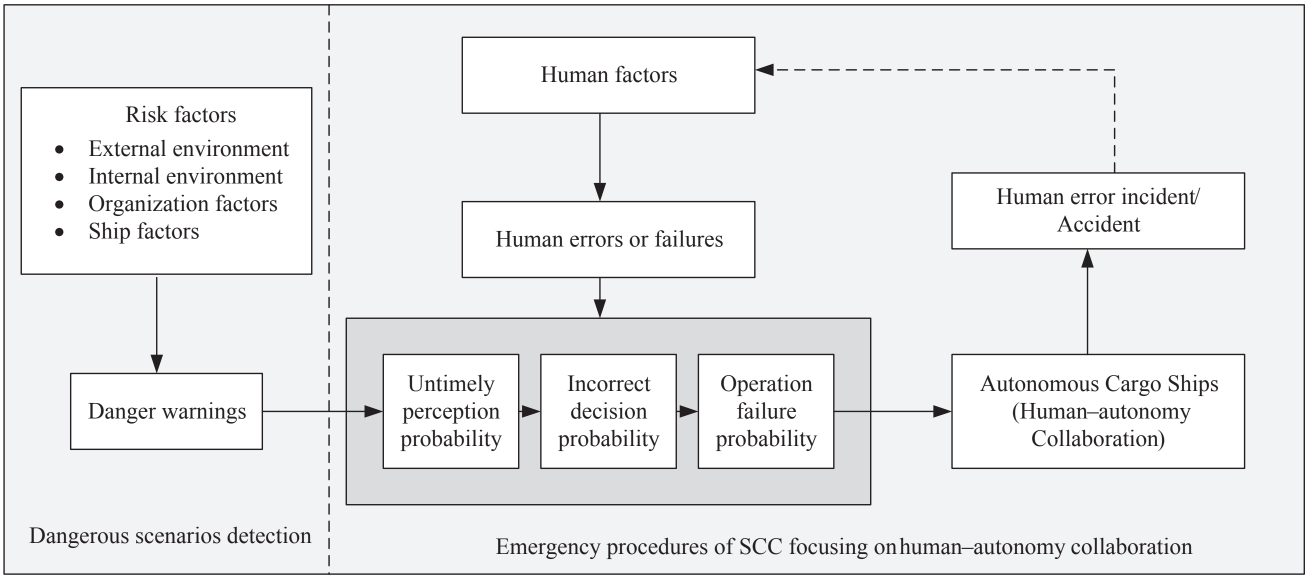

Fig. 1. Human error analysis framework on the SCC under remote navigational mode.

as one type of assessing reasoning. To be specific, it transmits the new explanatory variable information forward to the response variable along the direction of the BN arc, thereby updating the probability of the response variable. And backward reasoning is also known as diagnostic reasoning, which is used to determine the expected value of the response variable firstly. Then, it places this value in the BN and reverse transmits the information to establish the value of the explanatory variable. When a BN contains n nodes, it is usually represented as $\Delta = \{G(V, E), P\}$, where $G(V, E)$ represents an acyclic directed graph G containing n nodes. The node variables in the BN graph are represented by the elements in the set $V = \{V_1,\ldots,V_n\}$, the Bayesian arc E stands for the causal relationship between the variables, and P shows the Conditional Probability Tables (CPTs) of nodes. Suppose that an event $\theta = \{\theta_1,\ldots,\theta_n\}$ has n reference values. When the observed values $X = \{X_1, \ldots, X_n\}$ are available, we can calculate the posterior probability distribution table of θ using (3) as follows, based on the BN:

$$P(\theta| x_1, \ldots,x_n) = \frac{P(x_1, \ldots,x_n |\theta)P(\theta)}{P(x_1, \ldots,x_n)} \tag{3}$$

Accordingly, Fig. 2 is an example route from event A to event B in BNs. Node A impacts node B directly in the network, which means that the former node is determined as the parent of node B, will affect the occurrence probability of event B. The arrow implies node A in the directed acyclic graph points to the directed arc of node B in Fig. 2, which embodies a sub-node relationship between the two events. While conditional probability P(A|B) represents the dependency between events A and B. Noticeably, while the BNs model is constructed, each node can establish a sub-node relationship with the other nodes, but there should be no circular directed model. The closed-loop is prohibited for the model.

However, traditional BNs are difficult to construct, reuse and inflexible for modification. Thus, in the paper, the BNs model is proposed for the three stages: perception, decision, and execution based on the emergency response process on the SCC.

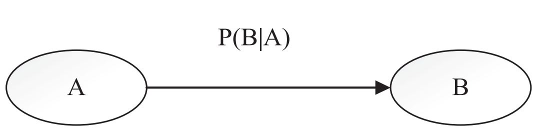

Fig. 2. Graphical representation of the basic elements in BNs.

3.2. Modelling and analysis of THERP-BNs

3.2.1. Emergency response process using THERP

The emergency response process is very essential to enhance the safety for autonomous cargo ships. In the paper, the emergency response process of the SCC is classified into three stages: risk information perception → judgment decision → execution based on the cognitive behaviours of operators on SCC, see in Fig. 1. During this process, numerous types of human errors can lead to severe accidents due to the influence of the simulation device, equipment, surrounding environment, operating equipment, and personnel quality. Accordingly, the emergency response process is assessed based on the time sequence of events using THERP method. According to the emergency response process to be followed by the operators during human–autonomy collaboration, the human error event consists of the following three aspects:

- Untimely perception probability *P1*, which means that the danger warning is not perceived within the controllable time, and consequently, the control of autonomous cargo ship, is not taken over by the SCC in a timely manner.
- Incorrect decision probability *P2*, which refers to the failure of taking effective measures in an emergency to stop the accident.
- Operation failure probability *P3*, which means that the operators took a correct decision, which still leads to an accident.

Furthermore, an event tree of the emergency response process is delivered from THERP analysis, focusing on autonomous ships with the third degree of autonomy during human–autonomy collaboration, shown in Fig. 3.

Therefore, the total human error probability p can be obtained as follows:

$$p = 1 - (1 - p_1)(1 - p_2)(1 - p_3) \tag{4}$$

3.2.2. Human error factors identification and classification

To analyse the human error probability of autonomous cargo ships with the third degree of autonomy focusing on human–autonomy collaboration, the human error factors should be identified and classified into three aspects, which is defined as the variables of the BNs model. And the variables of the BNs model of the human error probability assessment of autonomous cargo ships are mainly reflected in the form

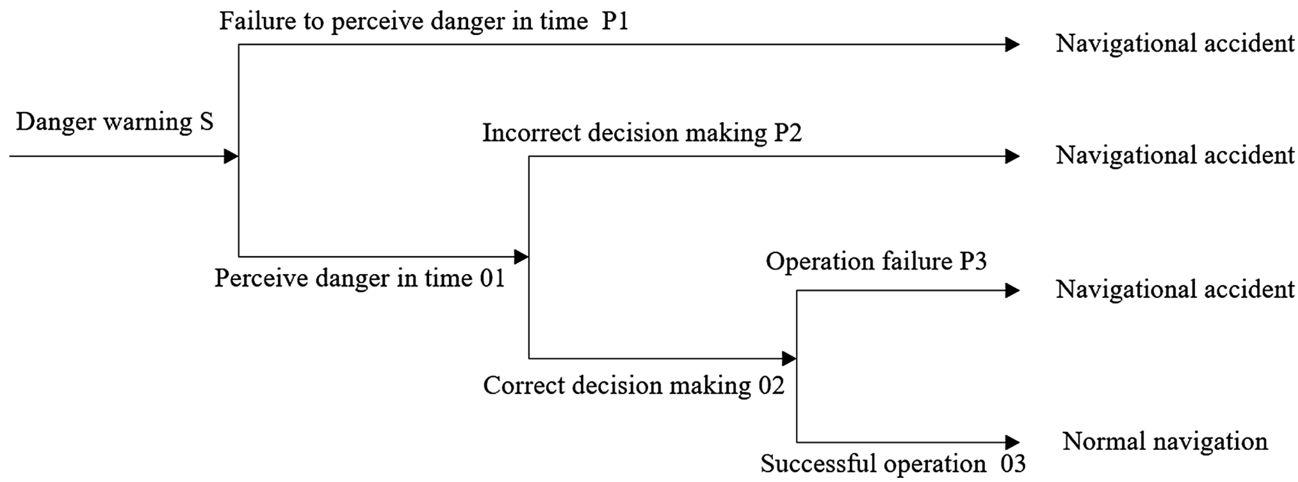

Fig. 3. Event tree model of emergency response process on SCC.

of various nodes in the network. Additionally, the directed edges represent the mutual relationship between these variables, while the conditional probability of the node refers to the strength or degree of dependence of relationships among the nodes. This study strives to establish a Bayesian model of human error for the SCC based on the following steps:

(1) Determination of BNs nodes

In this paper, the human error model of the entire SCC is subdivided into three parts, which include untimely perception, incorrect decision and operation failure. These parts have been used as the output nodes of the three BNs models, respectively. We have identified 16 common human factors that can cause ship accidents, based on literature review and expert investigation of human factors in autonomous ships. In this regard, these 16 factors work as sub-nodes of the BNs and classify them in accordance with the three stages of perception, decision, and execution. To better illustrate the developmental sequence involved in the accident chain of autonomous cargo ships, the classification of these human factors are presented in Table 1.

Based on the mentioned 16 human errors during the emergency response process, the intermediate evens are identified using the mentioned event tree in Section 3.2.2. Namely “untimely perception”, “incorrect decision” and “operation failure”. These additional nodes indicate that the occurrence of a series of factors at each stage leads to the occurrence of relevant nodes at the same stage. Therefore, there are a total of 19 nodes of the BNs model, which are described in Table 2.

These nodes include the human error factors in the entire SCC of the test ship namely, “*Jindouyun 0”* and *“Qiuxinhao*”, which means the *human errors* not limited to only one operator but includes all the staff present in the SCC, i.e., monitoring personnel, helmsmen, cockpit operators, and so on.

(2) Analysis of BNs nodes

The label *A1* refers to the negligence that occurs when one person is monitoring multiple ships. During the navigation of autonomous cargo ships, the responsibilities of the SCC staff are mainly concerned with monitoring the state of motion of the ships in real-time, which means monitoring multiple ships simultaneously during one session (Marilia et al., 2018). During the monitoring process, navigation information should be received continuously from each ship. Accordingly, when the volume of information handled by a staff member reaches a saturation value, known as “information overload” and labelled as *A4*, there is a possibility of negligence. In this context, “information overload” (*A4*) is the parent node of “negligence when one person monitors multiple ships” (*A1*). Insufficient vigilance, labeled as *A2*, refers to the inability to perceive danger warning due to reduced vigilance by the staff present in the SCC towards monitoring of autonomous cargo ships. The “excessive fatigue”, labeled as *A3*, “insufficient sense of responsibility”, labeled as *A5*, and “poor physical and mental conditions”, labeled as *A6*, are all caused by “insufficient vigilance” (*A2*). In addition, the convenience arising due to automation also makes SCC personnel “over-dependent on automation”, labeled as *A7*, thereby reducing personnel

Table 1
Human error factors leading to failure during emergency response process.

Stage	No		Description/explanation
Perception stage	A1	Negligence when one person monitors multiple ships	(Hogg and Ghosh, 2016).
	A2	Insufficient vigilance	(Man et al., 2014).
	A3	Excessive fatigue	(Ramos et al., 2018a, 2018b, 2018c).
	A4	Information overload	(Wahlström et al., 2015).
	A5	Insufficient sense of responsibility	(Fan et al., 2020; Man et al., 2014).
	A6	Poor physical and mental conditions	(Zhou and Zhang, 2019).
	A7	Automation-induced complacency	(Burmeister et al., 2019).
Decision stage	B1	Improper choice in emergency decision-making	(Bowo et al., 2018).
	B2	Lack of experience in emergency disposal	(Man et al., 2015).
	B3	Insufficient understanding of information	(Wahlström et al., 2015).
	B4	No consideration of weather, sea conditions, etc.	(Ahvenjärvi et al., 2016).
Execution stage	C1	Lack of ship perception	(Hogg and Ghosh, 2016).
	C2	Situational awareness defect	(Ramos et al., 2020, 2019; 2018a, 2018b, 2018c).
	C3	Psychological difference	(Burmeister et al., 2019)
	C4	Uncoordinated man-machine interaction	(Wahlström et al., 2015).
	C5	Insufficient training	(Hogg and Ghosh, 2016).

Table 2
Description of the nodes in the proposed BNs model.

	Description		Description
A	Untimely perception	*B2*	Lack of experience in emergency disposal
A1	Negligence when one person monitors multiple ships	*B3*	Insufficient understanding of information
A2	Insufficient vigilance	*B4*	No consideration of weather, sea conditions, etc.
A3	Excessive fatigue	*C*	Operation failure
A4	Information overload	*C1*	Psychological difference
A5	Insufficient sense of responsibility	*C2*	Situational awareness defect
A6	Poor physical and mental conditions	*C3*	Lack of ship perception
A7	Automation-induced complacency	*C4*	Uncoordinated human-machine interaction
B	Decision failure	*C5*	Insufficient training
B1	Inappropriate emergency decision-making		

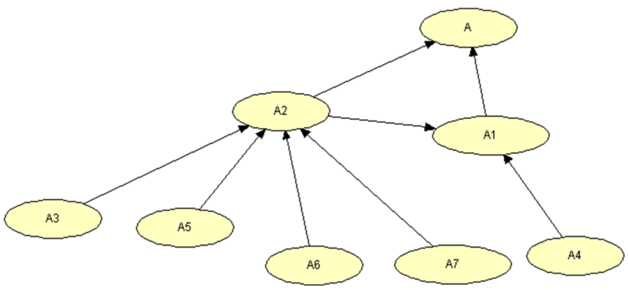

Fig. 4. Bayesian Network model of the perception stage (Notes: *A* - Untimely perception; *A1* - Negligence when one person monitors multiple ships; *A2* - Insufficient vigilance; *A3* - Excessive fatigue; *A4* - Information overload; *A5* - Insufficient sense of responsibility; *A6* - Poor physical and mental conditions; *A7* - Automation-induced complacency).

vigilance. Furthermore, when "insufficient vigilance" (*A2*) occurs among personnel, the above human factors are already included in the node, thus no separate statistics and illustrations will be given for the four nodes corresponding to *A3*, *A5*, *A6* and *A7*.

As for the inappropriate emergency decision-making, labeled as *B1*, when the monitoring personnel receives the danger warning from an autonomous cargo ship, the decision-makers often have "insufficient understanding of information", labeled as *B3*, during the process of emergency decision-making. The reason is due to different locations of the autonomous cargo ship and the personnel, or failure of the personnel to take into account the weather and sea conditions at the time of autonomous cargo ship navigation, which can lead to wrong decisions. When it comes to "lack of experience in emergency disposal", labeled as *B2*, the crew at the SCC need to acquire new skills for remotely managing the emergencies. This training can provide practical experience and help in avoiding incorrect decisions in response to remote emergencies.

The psychological difference is labeled as *C1*. An example of this difference is the inability of the operators in the SCC to acquire the real "ship perception", labeled as *C3* since these operators operate on simulators. Thereby, real immersion in a scene cannot take place because of the simulated scenes, leading to "situational awareness defect", labeled as *C2* (Man et al., 2014). This situation results in a psychological gap for the operator who finds it unable to immerse himself in the scene, known as "uncoordinated man-machine interaction" (*C4*), which leads to operational failure. In terms of "insufficient training" (*C5*), a group of new crews should not only master navigation technology but also software equipment and algorithm-related knowledge. In other words, the requirements for crew quality are becoming stricter. Substandard operation technology is a major cause of shipwrecks. Therefore, the problem of insufficient training will be one of the most important reasons for operation failures in future navigation of autonomous cargo ships. To avoid these failures, the personnel should be required to undergo a gradually increasing amount of training.

3.2.3. Model structure

Furthermore, it can be observed that "insufficient vigilance" (*A2*) in the perception stage serves as the sub-node of four nodes, i.e., "excessive fatigue" (*A3*), "insufficient sense of responsibility" (*A5*), "poor physical and mental conditions" (*A6*), and "automation-induced complacency" (*A7*). Furthermore, it serves as the parent node of "negligence when one person monitors multiple ships" (*A1*) and "untimely perception" (*A*), while "automation-induced complacency" is also the parent node of "negligence when one person monitors multiple ships" (*A1*).

In the decision stage, "inappropriate decision" (*B1*) serves as the sub-node of "insufficient understanding of information" (*B3*) and "no consideration to weather, sea conditions, etc." (*B4*), while both *B1* and "lack of experience in emergency disposal" (*B2*) are the parent nodes of "decision failure" (*B*).

In the operation stage, "psychological difference" (*C1*) serves as the sub-node of "situational awareness defect" (*C2*) and "lack of ship perception" (*C3*). Both *C1* and *C2* are the parent nodes of "uncoordinated man-machine interaction" (*C4*). Meanwhile, *C4* and "insufficient training" (*C5*) are the parent nodes of "operation failure" (*C*). Based on these relationships between children and parent nodes, the three-stage BNs model can be constructed, as shown in Figs. 4–6.

4. Case study

4.1. Data description

As the availability of data related to human factors in the SCCs is limited, expert experience method and test ship, namely "Jindouyun 0"/ "Qiuxinhao" are adopted for analysis of the basic occurrence probability of these factors. On the other hand, the human factors in this study provide theoretical support, risk prevention and control measures for future construction of the SCCs and personnel training. In this section, the expert judgements data are processed by fuzzy triangular numbers. For instance, three well-known experts in the field of

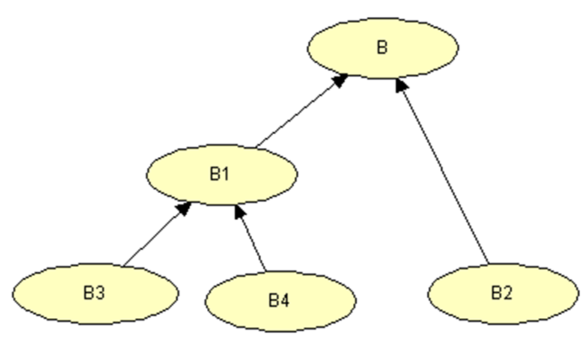

Fig. 5. Bayesian Network model of the decision stage (NOTES: B - Decision failure; B1 - Inappropriate emergency decision-making; B2 - Lack of experience in emergency disposal; B3 - Insufficient understanding of information; B4 - No consideration to weather, sea conditions, etc.)

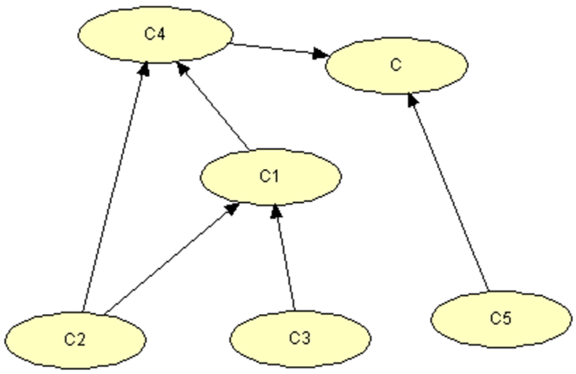

Fig. 6. Bayesian Network model of the operation stage (Notes: C - Operation failure; C1 - Psychological difference; C2 - Situational awareness defect; C3 - Lack of ship perception; C4 - Uncoordinated human-machine interaction; C5 - Insufficient training.)

waterway transportation safety evaluation, three captains having experience for more than 15 years, and two ship designers of test ship were invited to provide evaluation comments on basic event probability of human error in autonomous cargo ship navigation. Considering the rich working experience of the experts, their remarks were deemed as important as other methods described in the following steps:

- Frequency grading

In the process of risk assessment, it is sufficient to only use frequency for event grading (Fu et al., 2016, 2018), such as the grading method provided in Table 3. This frequency can be either a risk assessment indicator or a safety performance indicator. It can be observed based on the standard and definition of the frequency level that the frequency at a level is usually 10 times higher than that in the previous level. According to this definition, the corresponding level number can also be approximated on a logarithmic scale.

- Processing of fuzzy probability

The membership function of the trigonometric function is as follows:

$$f(x) = \begin{cases} 0 x < a \\ \frac{x-a}{m-a} a \leqslant x \leqslant m \\ \frac{b-x}{b-m} m \leqslant x \leqslant b \\ 0 x > b \end{cases} \quad (5)$$

It can be seen from (5) that the triangular number can be represented by three parameters, i.e., a, m and b. In order to generate the experts' score with reference to Table 3, five semantic values shown in Table 4 are specified to represent different fuzzy numbers. The membership function of the corresponding triangular fuzzy number is shown in Fig. 7.

Table 3
Accident frequency level.

Level	Frequency/Year	Description
Very low	10^{-5} ~ 0	Events that are almost impossible
Low	10^{-5} ~ 10^{-3}	Very rare events, not seen in similar projects.
Medium	10^{-3} ~ 10^{-1}	Rare events, people may encounter in their lifetime
High	0.1 ~ 1	An event that has happened, whose reoccurrence in the future is normal
Very high	1 ~ 10	Events expected to happen frequently

Table 4
Semantic values of event occurrence probability and the corresponding triangular fuzzy number.

No.	Semantic value	Triangular fuzzy number
1	Very low	(0,0,0.3)
2	Low	(0,0.3,0.5)
3	Medium	(0.3,0.5,0.7)
4	High	(0.5,0.7,1)
5	Very high	(0.7,0.7,1)

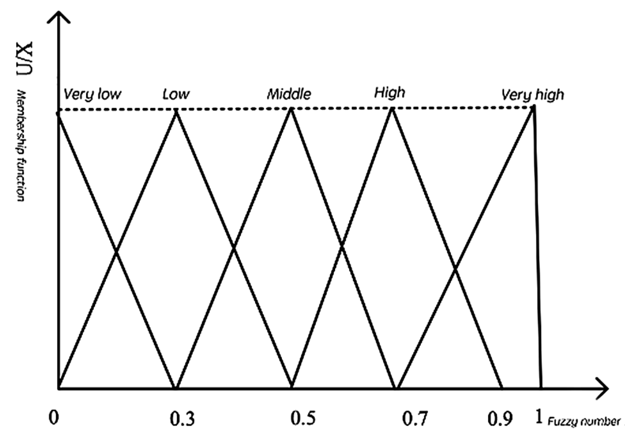

Fig. 7. Membership function of fuzzy triangular numbers.

- Analysis sequences

It is necessary to synthesize the semantic judgments of multiple experts for more accurate characterization of the event occurrence possibility through fuzzy numbers. This paper adopts the fuzzy number synthesis method using a weighted summation and using this method, the comprehensive evaluation of an event i can be expressed as

$$M_i = W_1 F_{1i} + W_2 F_{2i} + \cdots + W_n \quad (6)$$

The weight value of the jth expert (j = 1, 2,…,n) can be represented by W_i, and F_{ji} represents the semantic evaluation fuzzy number of the jth expert for the ith event, (i = 1, 2,…,m).

(1) Deburring

In this paper, the mean area method is used to process fuzzy probability and obtain the exact probability (Swain and Guttmann, 1983). The formula is shown as follows:

$$p_n' = \frac{a_n' + 2m_n' + b_n'}{4} \quad (7)$$

(2) Probability normalization

For each basic event, the sum of the state probabilities must be equal to one. Therefore, the probability given by (4) should be normalized as follows (Abujaafar et al., 2016; Zhang et al., 2013):

$$p_n = \frac{p_n'}{4 \sum_{j=0}^{n-1} p_n'} \quad (8)$$

The final probability of the root node obtained after deburring is shown in Table 5.

4.2. CPT estimation

The conditional probability table for each sub-node can be

Table 5
Basic probability of the root node.

Variable	A3	A5	A6	A7	A4	B2
Probability	1.62e−3	1.64e−3	1.66e−3	1.86e−3	2.64e−3	1.62e−3
Variable	B3	B4	C2	C3	C5	
Probability	1.61e−3	1.75e−3	2.23e−3	2.45e−3	1.62e−3	

determined based on the root node probability. The SCC can face multiple uncertainties during its construction due to lack of available data. This section uses both expert interviews and questionnaires to obtain the conditional probability table for the nodes, where the interview questions are mainly based on probability assignment. Based on the given constraints, the interviewed experts will independently give the corresponding probability values, which are then statistically analysed to obtain an average value.

Taking the sub-node "insufficient vigilance" (*A2*) as an example, as shown in Figs. 4 and 5, there are four parent nodes of A2, including "excessive fatigue" (*A3*), "insufficient sense of responsibility" (*A5*), "poor physical and mental conditions" (*A6*) and "over-reliance on automation" (*A7*), where *A2* can have a value of either zero or one. The former value indicates that the operator is not vigilant enough, while the latter value indicates that the operator is vigilant. Similarly, the four parent nodes of *A2* also have two states, namely zero and one. The conditional probability table of the sub-node "insufficient vigilance" (*A2*) with respect to other states is shown in Table 6.

4.3. Results

Based on the three-stage BNs topology structure of human factors in the SCC, the knowledge of experts is effectively extracted using the calculation method described in the previous sub-section. Subsequently, the conditional probability table of each node is calculated and the probability values are input to the analysis software. The network of the probabilistic model for the three stages is shown in Figs. 8–10 and the human error occurrence probabilities *P1*, *P2*, *P3* in each stage can be obtained using these models.

The emergency response process of autonomous cargo ships is complex, including various tasks in different situations. For each task, the possible human errors are different in frequency and types. The results show that the probability of human errors during risk information perception is higher than the stages of judgment decision and execution, and the probability of human errors during judgment decision is the lowest. Besides, using these probability values in (4), the occurrence probability of ship accident, also called the total human error probability in emergencies, which is calculated as P = 1–0.9961 × 0.9984 × 0.9969 = 8.58e−3, which is slightly higher than that of traditional ships. The negative influence factors affects operator' performance and play an important role in making errors during the emergency response process.

Table 6
Conditional probability of "insufficient vigilance" (*A2*).

A3	A5	A6	A7	A2	
				Y	N
Y	Y	Y	Y	0.0212	0.9788
			N	0.0141	0.9859
		N	Y	0.0196	0.9804
			N	0.0136	0.9864
	N	Y	Y	0.02	0.98
			N	0.0135	0.9865
		N	Y	0.0198	0.9802
			N	0.0137	0.9863
N	Y	Y	Y	0.0178	0.9822
			N	0.0111	0.9889
		N	Y	0.019	0.981
			N	0.0128	0.9872
	N	Y	Y	0.0188	0.9812
			N	0.0123	0.9877
		N	Y	0.01	0.99
			N	0.0038	0.9962

This paper could be observed that when the operators on the SCC has to deal with the emergency disposal of autonomous cargo ships. The human error factors whose posterior probabilities are higher than the prior probability include "negligence when one person monitors multiple ships", "uncoordinated man-machine interaction", "situational awareness defect", "information overload", "lack of experience in emergency disposal", "insufficient vigilance" and "insufficient training", with a combined probability value of greater than 100%. In fact, in the whole system, "negligence when one person monitors multiple ships" and "uncoordinated man-machine interaction" have the two highest node sensitivities, which significantly influence the occurrence of ship accidents. In other words, these two human error factors are highly likely to cause ship accidents due to the failure in personnel emergency disposal, which shows that the results obtained in this paper are in agreement with the actual situation, and can help to understand human errors during emergency response process on the SCC.

Although existing studies focused mainly on human factor identification for autonomous cargo ships, they lacked details about different human error types and their importance in the emergency response process by the SCC. For example, Ramos explored human factors in the navigation process of autonomous cargo ships. This study mainly used the event tree analysis to analyse which human error may occur in the ship control and its degree of impact on consequent accidents, based on the progressive order of events. In addition, other studies figured out that the most important human errors affecting ship navigation include personnel negligence, information overload, situational awareness defect, skill degradation and insufficient vigilance caused by ignorance (Zhou et al., 2017; Ramos et al., 2018a, 2018b, 2018c). The study emphasized the human factors such as monitoring personnel's negligence and situational awareness defect, which is consistent with the human error factor ranking presented in this study.

5. Discussion

As more and more autonomous cargo ships with human–autonomy collaboration are tested in public waters or test waters (Hogg and Ghosh, 2016), consolidation is urgently needed for relevant theoretical models to analyse human error factors and probability in autonomous cargo ships. Hence, this study utilized THERP and Bayesian theory to assess human error probabilities in the emergency response process when the SCC controls a ship remotely. Focusing on the test ship, the findings manifested that the probability of error by the operator on the SCC during the emergency process was 8.58e-3, which is slightly higher than that of traditional ships. Accordingly, it was observed by a study of existing literature that the researchers are not optimistic about the safety of autonomous cargo ships. Even although the human safety is guaranteed when the operators are transferred from the ship to the SCC. However, the probability of error made by the operator on the SCC is higher than seafarers on traditional ships during the emergency response process. Therefore, there is an urgent need for further research on designing the SCC for navigational risk prevention and mitigation.

In order to analyse the influence of each human error factor contributing to the failure of emergency response process, the sensitivity of the proposed BNs model of the emergency response process on the SCC is analysed in this section. First, the occurrence probability of each parent node is assigned the value of one, i.e., $P_{(Cij=1)} = 100\%$,where *i* denotes the node category of the risk factor, and *j* denotes the node number of the risk factor. Then, a full probability variation table of risk events in autonomous cargo ships caused by human errors on the SCC is obtained. Taking the example of node "excessive fatigue" (*A3*), the

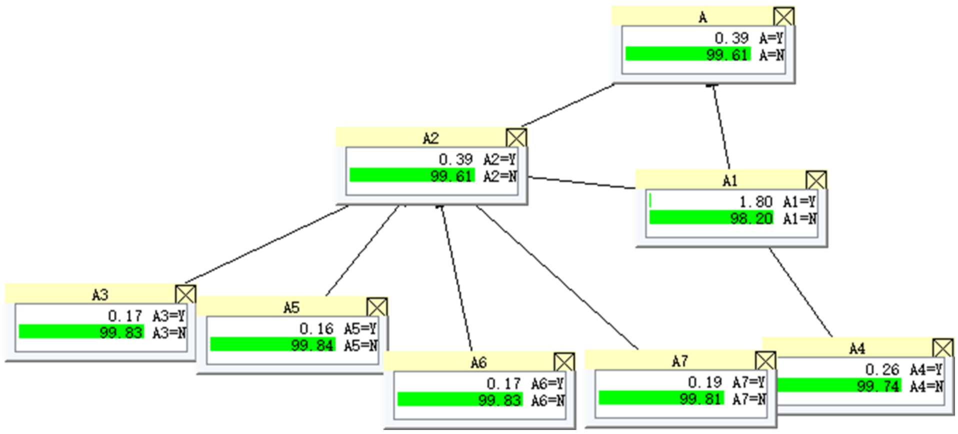

Fig. 8. Topology network in the perception stage.

network topology diagram of the perception stage variations when the monitoring staff is excessively fatigued is shown in Fig. 11.

Based on (4) and Fig. 11, the total occurrence probability of accidents can be calculated as P = 8.68e-3 for the case of "excessive fatigue" (*A3*) in the emergency response process. Similarly, the full occurrence probability of accidents relative to each node variable is assessed, as shown in Table 7.

Table 7 shows the posterior probability of each node. The sensitivity of human factors affecting the autonomous cargo ship navigation accidents is ranked as follows:

A1 > C4 > C2 > A4 > B2 > A2 > C5 > C3 > B1 > A7 > C1 > B3 > B4 > A3 > A5 > A6.

Based on the human factors sensitivity results in case of the emergency response process of autonomous cargo ships, an analysis of eight risk factors having a high sensitivity score was carried out. The analysis revealed that it was necessary to strictly control the "negligence when one person monitors multiple ships" (*A1*). Similarly, the problem of "information overload" (*A4*) should also be avoided. To manage "uncoordinated human-system interaction" (*C4*), "situational awareness defect" (*C2*) and "lack of ship perception" (*C3*), it is necessary to have realistic simulations and training, while an emergency plan system should be improved to deal with "lack of experience in emergency disposal" (*B2*). Finally, crew training should be strengthened to avoid "insufficient vigilance" (*A2*) and "insufficient training" (*C5*).

In summary, there are several points that the clients should pay attention to when constructing or designing the SCCs and training the operators. These points include as follows: "standardize the number of ships monitored by one person", continuously "enhance truthfulness of simulated cabins", strengthening "emergency plan improvement and emergency disposal drills" and mitigating "insufficiency of education and training". These points can provide a theoretical basis and reference opinions, thereby reducing human errors in emergency response process of autonomous cargo ships. Moreover, the human error probability estimated for emergency response process of autonomous cargo ships will help in taking remedial actions to reduce the human error probability and shipping accidents in future.

6. Conclusion and future works

Despite the use of automation technology in the maritime industry, human errors are still the typical risk factors in autonomous ships with the third degree of autonomy focusing on human–autonomy collaboration. Hence, a model based on Technique for Human Error Rate Prediction (THERP) and Bayesian Network methodology is proposed and implemented to analyse the human error probability during the emergency response process of SCC under remote navigation mode. The applicability of the proposed methodology has been demonstrated through a case study of human error analysis, focusing on a test ship. Using the mentioned method is advantageous in such a way that the emergency response process is classified into three stages based on the event tree delivered from THERP, which can easily be combined and extended. The proposed human error assessment model is unique because it has the capability of the following:

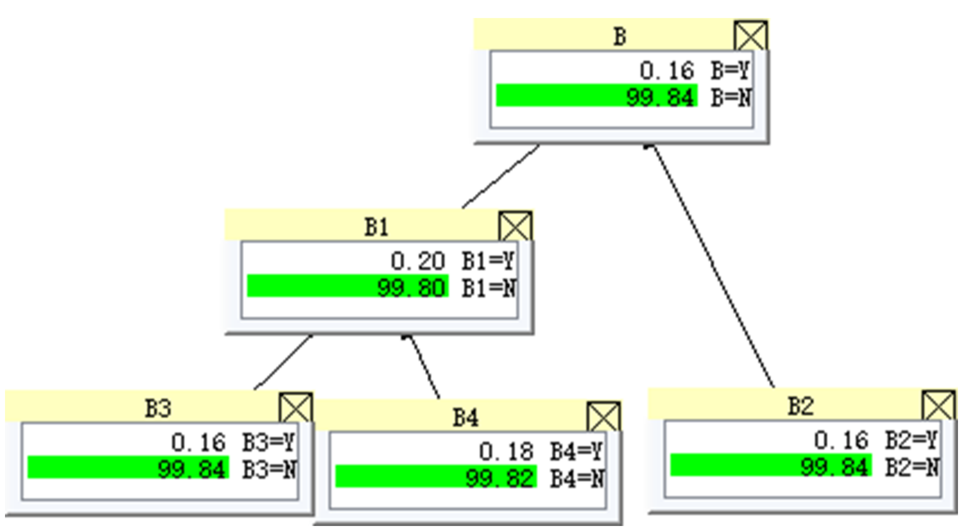

Fig. 9. Topology network in the decision stage.

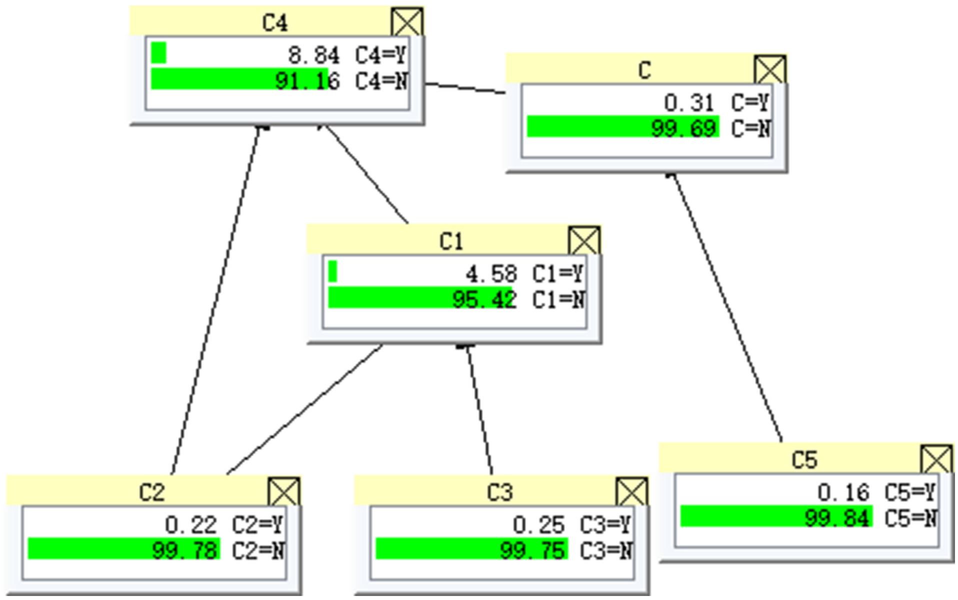

Fig. 10. Topology network in the operation stage.

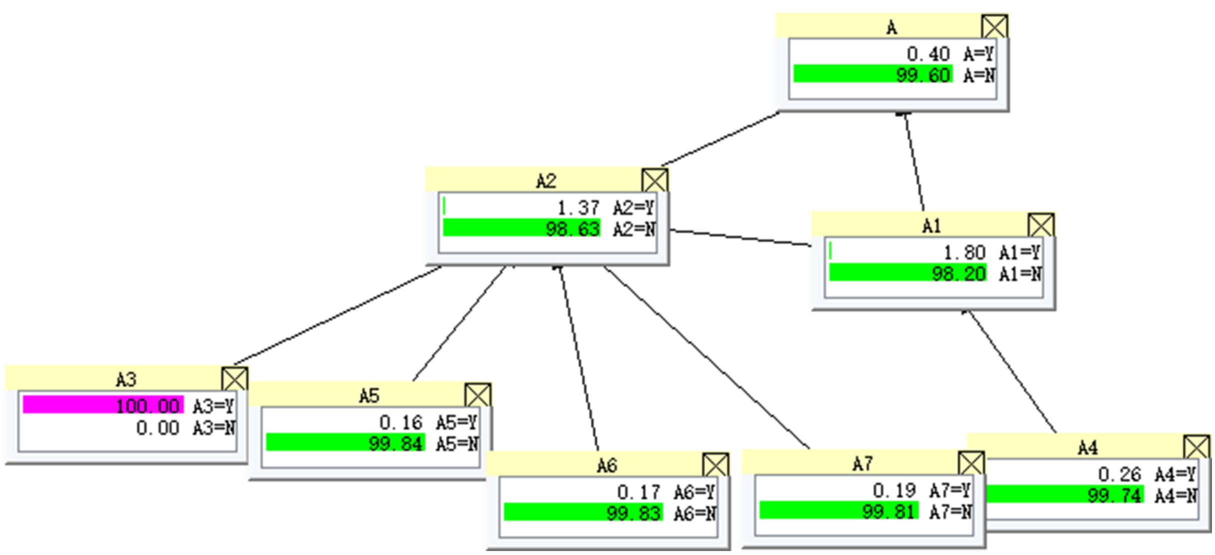

Fig. 11. Schematic diagram of the calculation results of the posterior probability in the perception stage.

Table 7
Sensitivity analysis of human error factors in the SCC.

Variable	Posterior occurrence probability
Negligence when one person monitors multiple ships	2.46e−2
Insufficient vigilance	1.88e−2
Excessive fatigue	8.68e−3
Information overload	1.99e−2
Insufficient sense of responsibility	8.67e−3
Poor physical and mental conditions	8.63e−3
Automation-induced complacency	9.73e−3
Inappropriate emergency decision-making	1.49e−2
Lack of experience in emergency disposal	1.93e−2
Insufficient understanding of information	9.02e−3
No consideration of weather, sea conditions, etc.	8.98e−3
Psychological difference	9.48e−3
Situational awareness defect	2.05e−2
Lack of ship perception	1.80e−2
Uncoordinated human-machine interaction	2.29e−2
Insufficient training	1.81e−2

- The risk factors are identified by analysing the emergency response process of a SCC under remote navigation mode.
- This is followed by the establishment of an event tree model of human errors using THERP during emergency response process on SCC of autonomous ship.
- And a BNs model based on the THERP is proposed for the three stages of perception, decision, and execution, simplifying the complicated human error probability modelling through a hierarchical and component-by-component analysis.

This paper analysed the emergency response process in the SCC of an autonomous cargo ship with the third degree of autonomy focusing on human–autonomy collaboration. This promotes the involvement of different key stakeholders in the safety management for the autonomous vessels and their operating or control systems. However, as the concept of SCC is still in the design or test stage with the third degree of autonomy focusing on human–autonomy collaboration. Moreover, the mode of human-machine interaction and the interactions between conventional and autonomous ships (because of autonomous cargo ships will not replace all maritime vessels in the near future) need more attention in the future to reduce the human error probability. Thus, the human error assessment model for the SCC needs further improvement and analysis with the focus on the available mode of human-machine interaction in ferruginous maritime conditions using systemic theories. Therefore, the assessed human error probability and conclusions in this paper only serve as a reference for designing the SCC for navigational risk prevention and control.

Acknowledgments

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ARTICLES FOR FACULTY MEMBERS

AUTOMATED CONTAINER TERMINAL AND MARITIME CONSTRUCTION RISK

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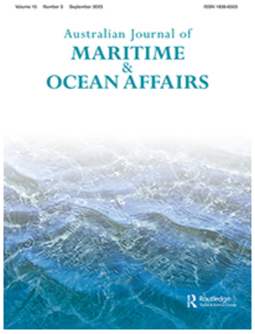

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Automated container terminal: competitive workforce criteria

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ABSTRACT

The global ports are struggling with a manpower shortage, particularly in terms of worker competitiveness. One of the options available to port authorities in these kinds of circumstances is the implementation of fully automated container terminals (ACT). Objectively, the researchers wanted to determine the competitive advantages that the workforce possessed within ACT. As target respondents, ten experts were chosen based on their working experience in semi-automated ports, non-automated ports, shipbuilding firms, and the academic sector. Throughput, the number of ship arrivals, and berthing time were among the quantitative parameters that were considered when selecting the target terminals. The findings demonstrated that the workforce operating at automated container terminals produces higher-quality work. To be a part of the ACT workforce, one must adapt theory to practice, think creatively, be adept at problem-solving, have strong cognitive abilities, and be familiar with automated technology. Additionally, automation is associated with financial benefits, one of which was that the entire terminal profit at the automated container ports was greatly boosted. The result showed that an automated container terminal would need to hire highly skilled workers to maintain its current level of productivity.

KEYWORDS

Automated container terminal; competitive workforce; competitive criteria; artificial intelligence; IR4.0

1. Introduction

The fourth industrial revolution (IR4.0) will bring about widespread digitalisation and automation of employment, both of which will significantly affect the workforce (Hirschi 2018). Digitisation and automation of employment with the exciting possibilities of Artificial Intelligence (AI), distributed ledger systems, crypto currencies, sophisticated materials, and biotechnologies will revolutionise society as well as the patterns of the global economy. Rapid advancements in Artificial Intelligence (AI) and robotics have led to the possibility of human labour being replaced by machines, resulting in employment automation (Arntz, Gregory, and Zierahn 2017). Also, there is a possibility that during the next 10–20 years, the majority of occupations in western developed countries could be replaced by robots (Henriksson 2019; Hervás-Peralta et al. 2019).

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Artificial intelligence (AI) will revolutionise both business and society by enabling faster and more accurate decision-making and the automation of routine tasks. It is possible that as a result of these shifts, thousands of jobs will be lost, and a great deal of the work done today will either become obsolete or undergo significant shifts. On the other hand, new lines of work and the basics of employment are expected to arise (Davenport et al. 2019). The marine industry, and the container terminal business, will undergo significant workplace technological change and workforce skills transformation within the next decade. These changes are expected to take effect as soon as possible (Gekara and Thanh Nguyen 2018). With the introduction of artificial intelligence, the automation of container terminals will be the best example of how technology will affect work, employment, and worker skills.

The lessons learned from history revealed that job losses and unemployment were synonymous with every industrial revolution that occurred throughout the centuries (Gera and Singh 2019). At least half of the professions that exist in the world now face a significant threat of becoming automated within the next ten to twenty years. The top human managers will continue to hold their position since the nature of their jobs calls for a great deal of critical thinking, which is something that artificial intelligence is not yet capable of doing. The human operator of the equipment, such as the crane, the prime mover, and any other machinery that only performs linear functions, will be replaced by the AI. The future of human operators still remained a question and many people are concerned that they might be made redundant. Hence, this study's primary emphasis is placed on the criteria for competition among the human workforce working in automated container ports (ACT). Figure 1 shows the graphical theoretical framework which reflects the essentials of this study.

As such, this study aims to determine the competitive advantages that the workforce possesses within ACT. The structure of this paper can be rendered into the following sections where Section 2 discusses the design of the Systematic Literature Review (SLR) that was incorporated within this study. Section 3 illustrated the design of the qualitative research technique that completed the data collection and analysis part of this study. Section 4 presented the findings that were obtained throughout the data analysis. Section 5 concluded the research paper.

2. Systematic literature review (SLR)

2.1. SLR framework design

The procedures taken by SLR with PRISMA integration to review the papers searched for this study are shown in Figure 2. The approach included the integration of the PRIMA framework with the SLR review process. The framework that was created would give a graphic representation of how the review process was conducted in order to achieve the final findings. In this study, the review question formulated attempts to find out why Conventional Container Terminals would require a competitive workforce. Next, the setting of search criteria will determine the inclusion and rejection of searched studies in literature searching within the third step. Then, the PRISMA stage of identification, screening, eligibility, and inclusion will follow. Finally, the reviewed articles would generate the necessary findings to answer the formulated review questions.

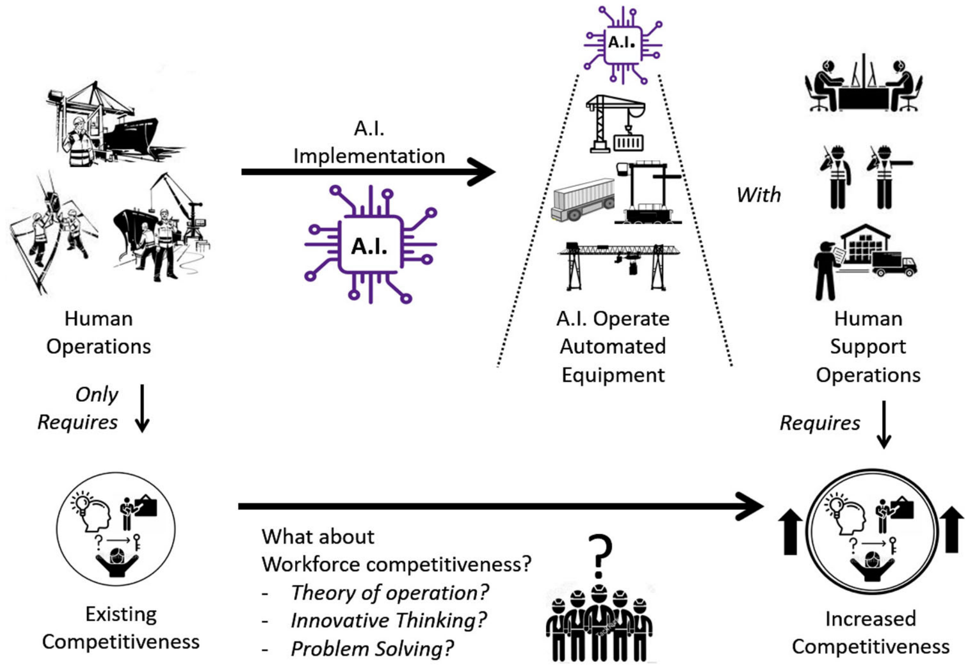

Figure 1. Graphical theoretical framework. Source: Author.

Additionally, Kon et al. (2021) used the PRISMA method to hone the search criteria of the literature obtained, limiting the selection to just articles that were pertinent. The content of the articles that were obtained was analysed using systematic literature reviews to ascertain the journal rankings, study findings, and publication timeline. According to previous research (Sirajuddin and Sunaryo 2019; Yang et al. 2018), container port operators may improve production, cut costs, and preserve the environment by implementing ACT technology. Several academicians (Hanafiah et al. 2022; Rahman et al. 2022; Karim et al. 2022) also find their research of the global ACT trend useful in reviewing the quickly advancing marine technology in ports and shipping.

2.2. SLR Findings

2.2.1. Competitive ACT workforce improved productivity

The use of ACT technology in container terminals would minimise the inefficiency issue that contributed to the delay in container handling processes by decreasing the total travel time of vehicles within container terminals to increase productivity. Additionally, a competitive ACT workforce could improve the efficiency of the port by integrating vehicle scheduling and container yard storage plans to minimise vessel turnover time, which also contributed to the productivity of the container terminal. The implementation of ACT technology in container terminals was rising as a result of the global trade's rapid development, which forces terminal operators to look for solutions that could boost efficiency (Yang et al. 2018). Additionally, the implementation of automated container operations demonstrated the efficacy of the system.

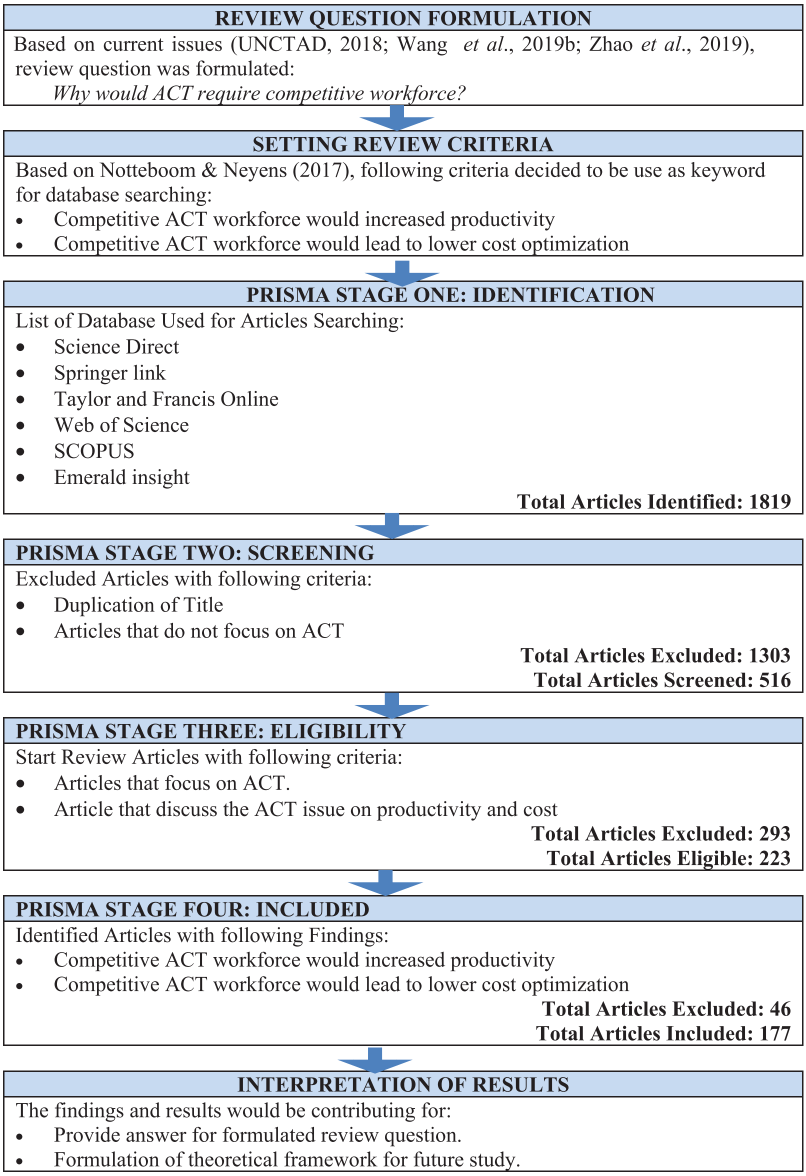

Figure 2. SLR design framework. Source: Authors.

Figure 3 displays the number of articles that demonstrate how an ACT workforce that is competitive produces greater productivity as compared to a traditional container terminal. Prior to 2010, there was a dearth of ACT-related research, which made it difficult to find studies describing how ACT increased port productivity. However, there has been a noticeable surge in publishing since 2010 and forward. As of 2019, there were 18 articles that discussed the findings that an ACT staff that was competitive increased port productivity. Figure 3's trend of rising ACT building since 2010 and the trend of rising article posting were both on the rise at the same time. Therefore, suffice it to say that conventional container terminals must adopt ACT technology to increase the

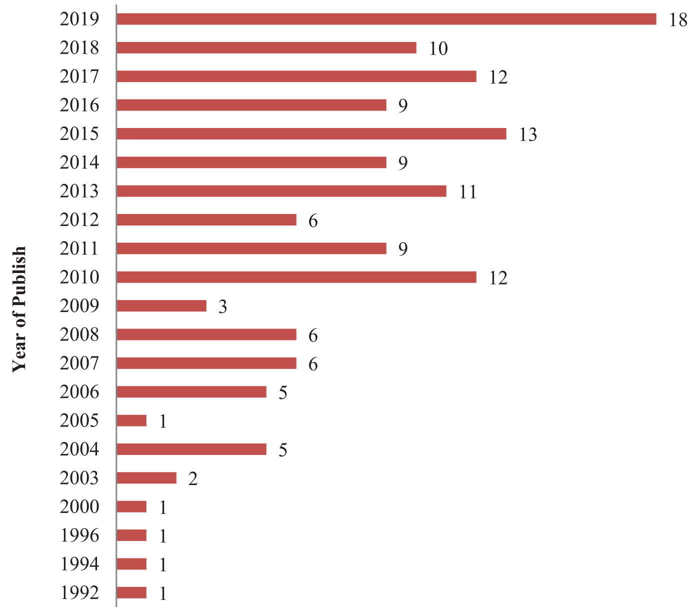

Figure 3. Yearly published articles that supported ACT workforce improved productivity. Source: Authors.

productivity of their workforce in order to remain competitive within the port industry; container terminals that are reluctant to do so would face serious difficulties in competing with other advanced ports around the world in order to survive.

2.2.2. Competitive ACT workforce lowered operation cost

Competitive ACT Workforce significantly decreases labour dependency and labour cost that resulted from epoch effect of automation technology development in container terminal; terminal operators continuously upgrade technology to reduce operating cost that would produce significant profits. The growing rise of international trade, which necessitates terminal operators always seeking out technology that might increase profit by lowering costs, has also contributed to the rising trend of ACT technology adoption (Yang et al. 2018). In order to deliver cost-effective cargo handling services, a competitive ACT Workforce is required. Cargo transporters, terminal operators, shipping corporations, and port authorities are eager to implement cutting-edge technology. Additionally, by using energy more effectively, the competitive ACT workforce might minimise overhead costs for ports and terminals. Energy efficiency utilisation in ACT refers to the ability to maintain service quality while consuming less energy at a lower cost.

Figure 4 displays the papers supporting the claim that the Competitive ACT Workforce reduced operating costs. Prior to 2010, there wasn't a lot of research on the competitive ACT workforce, which is also why there weren't many papers that reported on how this workforce reduced operating costs. The number of publications published on linked themes greatly increased beginning in 2010. The number of articles reporting on how the competitive ACT Workforce reduced operating costs reached 23 publications in 2019 alone. The upward trend in publications may be closely related to the upward

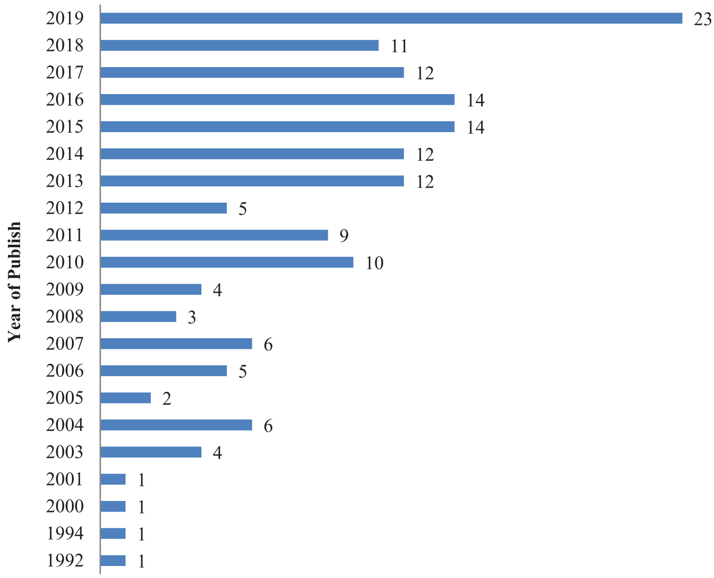

Figure 4. Yearly published articles that supported ACT workforce lowered operation cost. Source: Author.

trend in the number of competitive ACT workers, which began in 2010 and may be referred to in Figure 2. Therefore, it was sufficient to state that ACT's Competitive Workforce technology is necessary to reduce the terminal's operating costs in order to maintain competitiveness over the long run.

2.2. Summary of reviewed literatures

Container terminals that have advanced computerised facilities such as automated quay cranes, automated yard cranes, and autonomous horizontal transport vehicles are examples of what are known as automated container terminals, abbreviated as ACT (Wang et al. 2019). A significant increase in the demand for container terminal services, including loading, unloading, and storage has been seen as a direct result of the expanding worldwide trade as well as technological advancements in the logistics sector (Jeevan et al. 2015). In addition, the research conducted by Yang et al. (2018) discovered that ACT is the one and only rational approach to meet the ever-increasing demand for container terminal operations to attain higher levels of efficiency and productivity. ACT's automated functions have the potential to cut costs associated with human resources as well as emissions produced by the container port (Wang et al. 2019; Yang and Shen 2013). The Europe Container Terminal (ECT) Delta Terminal at the Port of Rotterdam, which is located in the Netherlands, was the first Automated Container Terminal when it opened its doors in 1993. The tendency toward an increase in ACT development occurs most frequently between the years 2014 and 2017. More than 1100 automated cranes were operating across Asia, Europe, the United States, the Middle East, and Australia as of the middle of 2016, with the capacity to handle tens of millions of containers annually (PEMA 2016). The sea side, the land side, and the storage yard make up the three primary areas that make up the automated container terminal (Wang et al. 2019). According to

Günther and Kim (2005), the sea side area consists of a berth, an area for the operation of quay cranes, a buffer zone, a driving lane for automated guided vehicles, and an interchange space on the seaside. On the other hand, the land side consists of a driving lane for trucks, a space for exchanging goods on the land side, and gates that lead to the port. The container blocks are often arranged in the storage yard as a vertical row.

Transferring workers from the dock area into the office is one of the most glaringly evident differences between the ACT and typical container terminals (Sadeghian et al. 2014). Due to the fact that they were working from within an office environment and had access to real-time information, remote operators were able to perform several tasks in a more effective manner (Yang and Li 2017). The operators could take over the duty of resolving exceptions connected to containers abroad the vessel and unmanned processes might be carried out for as much of the operation as was feasible (Henriksson 2019). The transition of knowledge from conventional container terminals to ACT continues because the knowledge is the accumulated experiences and learning outcome of the ACT operators to handle the equipment and manage them simultaneously (María Martín-Soberón et al. 2014). As a result, the role operator with the necessary knowledge should continue actively involved in the industry (Hervás-Peralta et al. 2019).

According to Uȷurlu, Yildirim, and Başar (2015), the most significant factor in the occurrence of accidents within port facilities is the presence of potentially hazardous human factors. These factors include fatigue, carelessness, stress, health, situation awareness, mistakes, insufficient training, and a safety culture. In addition, stressors caused by port policies, port facilities, increased vessel traffic, loading and unloading of cargo, and international policies are being placed on the employees in charge while operations are being carried out (Strauch 2015). Studies have shown that accidents have a far bigger impact on offshore infrastructure than other factors such as fires, engine problems, and hijackings (Hanafiah et al. 2022). In addition, natural disasters such as typhoons, earthquakes, and tidal waves, which are examples of force majeure occurrences, can also be environmental factors that damage port facilities (Tseng and Pilcher 2017).

Many industry professionals anticipated that cyber physical systems would largely be responsible for replacing professions that required fewer skills and were more standardised (Signorelli 2018). Because of their decentralised, integrative, and cross-functional management capabilities, control-based occupations are expected to become increasingly important in the near future (Bonekamp and Sure 2015). Technology for advanced automated control is required to achieve increases in production and decreases in costs (International Federation of Robotics 2017). In addition, Abdul Rahman (2012) note that in order to acquire long-term competitive advantages, it is essential to regularly analyse and review business strategy.

The beginning of a new era, during which artificial intelligence will become increasingly technologically advanced, to the point that it will be possible to work in conjunction with human workers (Liu and Wang 2018). Humans may be about to enter a new era of technological growth, one in which artificial intelligence will work alongside humans in the job. All it takes is a little more knowledge (Seeber et al. 2019). Human labour must spend a substantial amount of effort to succeed in the IR4.0 environment; else, it risks losing its entire competitive edge (Global Port Training 2019). The worker with the lower level of skill will need to obtain extra training and enrol in new courses to be able to operate the ACT. However, this will increase the of human capital resources required (Henriksson 2019). Suppose these workers want to develop their careers within the industry. In that case, they have one more option: to obtain non-automated employment at a container port where they can continue to apply their existing skills (Sirajuddin and Sunaryo 2019). In general, the competitive workforce would be made up of individuals with a high level of expertise and could benefit from IR4.0 technology.

3. Qualitative research

The framework that contains research components that were chosen by the researcher to manage research efficiently and effectively might be regarded as the research design. The research design comprises procedures such as data collecting, analysis, interpretation, and reporting (Creswell and Creswell 2018). Following that, a research design will be established using the plan, which will include numerous methods in order to carry out the research based on the characteristics of the research problem (Leavy 2017). The development of a study design considers the availability of raw data as well as research philosophies, research questions, and research objectives (Richards 2018). Establishing a sampling strategy, formulating a questionnaire, conducting preliminary testing on the questionnaire, collecting data, analysing data, conducting validity and reliability tests, and pre-testing the questionnaire are all part of the qualitative design data collection and analysis technique (Creswell and Creswell 2018).

The techniques known as Grounded Theory aimed to locate data inside a text, such as categories and concepts linked to a study model (Cho and Lee 2014). The Grounded Theory is a set of systematic procedures including data collecting, identifying categories and themes, linking themes, and constructing a theory (Lawrence and Tar 2013). Familiarisation, reflection, open coding, axial coding, and selective coding are the methods of systematic data analysis used in Grounded Theory (Nechully and Pokhriyal 2019). In this study, data collection, analysis, interpretation, and reporting procedures were finished before Grounded Theory was utilised to analyse the data.

In general, the research starts with identification of research problem then follows with the rising of research questions. The designed questionna ire that were based on main research questions were adminstrerd to the respondents for data collection process. Upon the complete of data collection, the analysis or coding of data would commence towards the results of analysis. Finally, the findings of the research would be obtained and discussed. Figure 5 below visualised the summary of research flow.

4. Findings and discussions

This section shall discuss the findings that were based on the analysis results.

4.1. Respondents profile

Respondents from professional background were contacted and provided the answers for the questionnaire within this study. Respondents from the professional world are ideal candidates for qualitative interviews because they are able to give rational answers, which in turn facilitate an easy coding process in the following stages (Aberbach and Rockman 2002). For instances, Video Interview Person No.1 (VIP1) is the senior manager

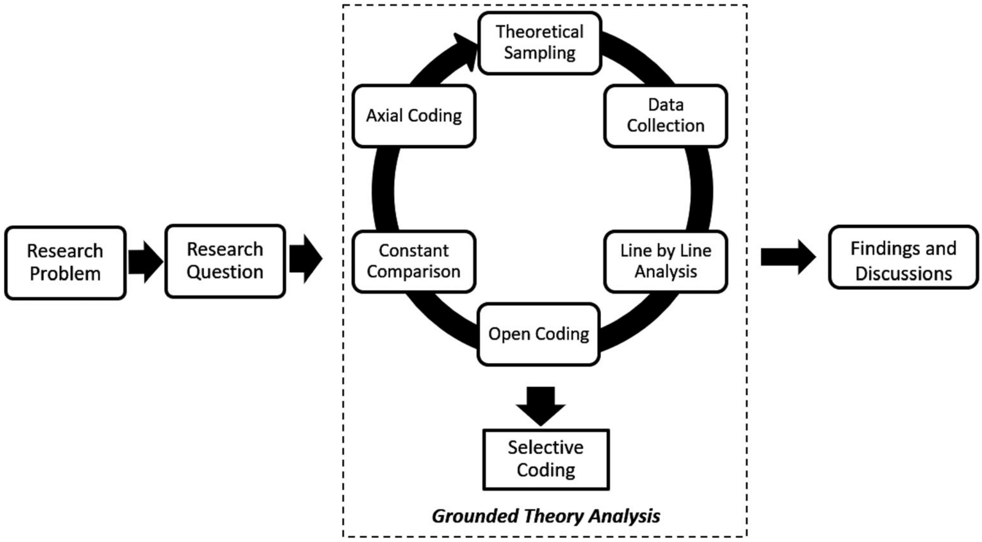

Figure 5. Summary of research flow. Source: Authors.

from container terminal located at East Malaysia with industry experience of 30 years and MBA academic background. Table 1 below shows the profile of every respondent.

The purpose of interview is to select elements within population associated with the research topic to develop a conclusion which is reliable regarding the population and the research topic. Usually, the availability of resources and methods chosen will determine the strategy of the sampling. In order to collect the required data, a sampling unit will be drawn from sampling frame or target population. Hence, the careful selection of sampling unit within sampling frame will determine the reliability and validity of research outcome.

In qualitative research, non-probability sampling will be applied with various sizes of samples based on research question and analysis unit. The main purpose of this sampling technique is to acquire depth and extensive information from sampling unit to address the research questions.

In qualitative sampling, there is one non-probability sampling technique that is known as Convenience Sampling. This kind of sampling technique aims to select qualified participants who are available to be interviewed within the sampling frame voluntarily. It is done by identifying potential respondents who possess the criteria and interview them until the sample size proportion is met.

In this research, the targeted population would be expecting respondent from top level management from the three categories of ACT technology provider, user and promoter. The final sampling list would reveal the potential respondent who are relevant to the research topic and the ease of accessibility. The potential respondent expected to be very knowledgeable about Malaysian container terminal development and familiar with workforce policies related to container terminal.

The findings for questionnaire which asked the respondents about the significant criteria of competitive workforce within ACT. The followings are 3 criteria that were mentioned during interview session (see table 4.11). Moreover, the conditions of the

Table 1. Respondent's profile.

No.	Code	Experience (years)	Rank	Qualification	Duration (min)
1	VIP1	30	Senior Manager	MBA	32
2	VIP2	30	General Manager	MBA	55
3	VIP3	23	Head of Department	Bachelor Degree	32
4	VIP4	28	General Manager	Bachelor Degree	45
5	VIP5	18	Head of Department	Master Degree	45
6	VIP6	30	Head of Department	MBA	84
7	VIP7	40	Professor	PhD	87
8	VIP8	20	Managing Director	MBA	56
9	VIP9	11	Manager	Bachelor Degree	43
10	VIP10	21	General Manager	Bachelor Degree	59
11	VIP11	15	Director	Bachelor Degree	23

Source: Authors.

disruptive emergence of new port operation and services and the rapidly changing work environments necessitate the cultivation of a competitive workforce that is equipped with the essential knowledge and skills in IR4.0. Table 2 shows the response rate from interview.

4.2. Apply theory in operation

In the course of the interviews that were carried out, sixty per cent of the respondents were in agreement with the statement that the staff within ACT needs to be capable of using theory in operation for them to become more competitive. For instance, a number of respondents said that the application of theory in operation, such as being 'acquainted with the system' (VIP1) and 'understanding the equipment' (VIP2), will help the workforce become more competitive. Applying theory inside operations would improve workers' comprehension of their jobs regardless of the areas they are designated to work in, and would also enable those workers to give adequate production levels to the ACT. The respondents believed that an increased level of job comprehension among the labour force could also lead to an increase in ACT production (all VIP). According to the following remark, to be competitive in their field, workers need to have an understanding of their role within the ACT. In this context, a remark made by another one of the participants is noteworthy for expressing this position. In this research, VIP7 expressed his views: *Similarly, the new port technology needs to understand in detail before it can be applied to automate the specific process in the port operation.*

It has been emphasised that the level of workers' understanding concerning their jobs would have a considerable impact on the functioning of the ACT. For instance, one study found that a one per cent increase in the expertise of port workers resulted in a 2.5 per cent increase in port productivity (Global Port Training 2019). A worker who is able to use theory in operation would have better control over their job and deliver acceptable

Table 2. The significant criteria of competitive workforce.

Developed themes	Response rate (%)
Apply theory in operation	60
Innovative thinking	80
Good in problem solving	70
Good cognitive abilities	80
Familiar with automated technologies	90

performance within the ACT. Consequently, the worker would have to play significant role in the ACT performance physically (Chan, Hamid, and Mokhtar 2016). The global ACT is able to continuously improve their workforce's performance because of the manufacturer's commitment to provide them with regular updates on the status of their equipment (KoneCranes 2017). Therefore, applying theory inside operations could improve the ACT container operation and boost the productivity of the container terminal by enhancing worker comprehension regarding their respective jobs (VIP5). In addition, an experienced person would be useful to the ACT in assisting the client in getting additional time and cost benefits. The results of the interview were quite comparable to these findings. For example, VIP4 commented that 'Vessel operators usually prefer terminal with a lesser and shorter port of call to save time and cost because every berthing at the terminal would incur operation cost payable to container terminal operator'.

4.3. Innovative thinking

According to the results of the interview sessions that were carried out, eighty percent of the respondents are in agreement that having a workforce that is capable of innovative thinking is essential for the growth of ACT. For instance, VIP4 explained that 'worker skills such as increased awareness, better creativity, and distinctive innovation are the fundamental necessities for the expansion of the port'. The worker that works within the modern seaport is required to think creatively, in comparison to the worker of the preceding generation (Sirajuddin and Sunaryo 2019). A respondent (VIP6) commented that 'The technology of automated container terminal will need the workforce with skills of innovation and good competencies'.

Additionally, VIP4 stated that 'Technical skills in no longer sufficient to sustain a career in the Port industry; other skills such as innovation, creativity, critical thinking, ability to forecast, problem-solving and multitasking skill are becoming more essential'. Consequently, the future generation of the workforce would have to equip themselves with skills beyond technical for their career sustainability.

The training process should focus on developing not only the operational method and the operating skills of the workforce but also the innovative potential of the workforce. The management not only needs to establish some innovative training bases for the workforce in order to cultivate the innovative spirit and practical ability of the workforce, but they also need to actively adopt various measures to closely link academic and industrial relations. This is necessary in order for the management to successfully cultivate the innovative spirit and practical ability of the workforce. This is done with the goal of building training bases and continuously expanding the career opportunities available to the workforce. It has positive implications for fostering a workforce that is capable of finding solutions to problems, enhancing their ability to innovate and practise, learning the latest technologies, gaining valuable work experience, enhancing their overall job quality, and ensuring that they will have employment in the foreseeable future.

4.4. Good in problem solving

Seventy per cent (70%) of the participants agreed that a competitive worker within ACT would have to be good at problem- solving. The Respondents indicated that good in problem-solving would improve the workflow within the ACT. For instance, VIP5 mentioned that: There will be new areas for *the workforce to explore, such as Artificial Intelligence, LEAN and problem-solving.*

The amount of information an employee has determines whether or not they can utilise the many problem-solving solutions available to them (Li et al. 2011). Therefore, difficulties arise not only in the external task surroundings but also in the representations of the task that are stored in the working memories of the workforce. The goal of the research mentioned in this article was to investigate the use of artificial intelligence (AI) in the ACT industry with regard to the workforce's ability to tackle difficult problems..

The quantity of information a workers has access to is also the primary factor in determining whether or not that worker will be able to utilise any of the options for problem-solving that are now accessible (Gadeyne and Verhamme 2011). As a consequence, problems may appear not only in the shape of the external job surroundings but also as internal representations of the task in the working memory of the workforce members. The objective of the study referred to in this article was to evaluate the application of artificial intelligence (AI) in the ACT industry with reference to the capacity of the workforce to address challenging issues.

4.5. Good cognitive abilities

80% of the respondents agreed that a competitive worker must possess good cognitive abilities. The cognitive abilities have a direct association with their survival within the industry. One of the respondents, VIP6, stated 'So, the cognitive abilities of the worker will determine their competitiveness in the industry where they will have to compete with each other for survival'.

The cognitive capabilities of a worker have been found to have a relevant association with a variety of work areas. According to the research that has been conducted, an individual's level of cognitive ability is an essential component in both the process of explaining and comprehending their managerial practises and job performance (Eglynas et al. 2019). The concluding hypothesis of the research suggested, thus, that the influence of cognitive capacity on the performance of firms is of the utmost importance.

Along these same lines, evidence suggests that a person's cognitive ability has a significant association with the job success they achieve (Li and Burns 2017). According to the facts, a worker with better cognitive ability has the potential to contribute more to the effective operation of a company. The research that has been done in this area also investigates the utility of cognitive capacity in predicting personal achievement in addition to job performance.

4.6. Familiar with automated technologies

90% of the respondents agreed that a competitive ACT worker must be familiar with automated technologies. The cognitive abilities have a direct association with their survival within the industry. One of the respondents, VIP9, stated 'The human operator must be familiar with the remote-control instruments and become efficient at handling it. The truck also will be driverless later'.

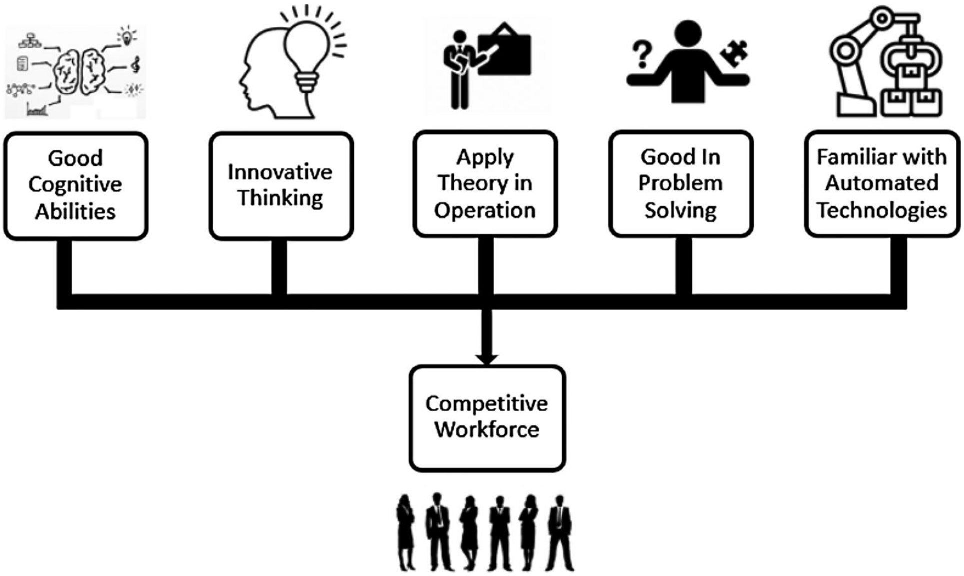

Figure 6. Competitive ACT workforce criteria. Source: Authors.

In most cases, the workforce that already possesses some level of technological expertise is the one that will have the least amount of difficulty obtaining training help (Global Port Training 2019). The employee at ACT may find that using any kind of technology presents a problem for them; hence, they need to continue to become accustomed to the usage of technology or else they will avoid it. Because of this, the worker poses a wide variety of interesting tasks.

Digital awareness among sectors is essential for employees to become familiar with technology. It should be carried out to promote understanding of how automated technology is becoming a necessary and key alternative to acquiring job prospects (Gadeyne and Verhamme 2011). The review of published works also shown that being conversant with technological advances does, in fact, increase the number of career opportunities available to individuals.

4.7. Competitive Workforce within ACT

This section summarises the crucial criteria of a competitive workforce within the ACT. Based on the research findings, the competitive workforce would have Five criteria's which are good cognitive abilities, innovative thinking, applying theory in operation, good in problem solving and familiarity with automated technologies. Figure 6 below depicts the research finding for this section in graphic form.

5. Conclusion

The vast majority of accidents within the port facilities result from potentially hazardous human factors such as weariness, carelessness, stress, health, a lack of situational awareness, errors, insufficient training, and a culture of disrespect for safety. As a consequence, it is of the utmost importance to do research into the opportunities presented by IR4.0, particularly concerning the degree to which businesses are prepared to implement AI technology.

The fundamental weakness that sparked this inquiry was a lack of information on the skills and experience required to run an automated container port. This study was prompted because of this shortcoming. The second weakness in their defence would be a loss of human skills necessary to keep up their competitiveness and continue offering their services in automated container ports. This would be the second hole in their defence. After the automation technology was installed within the container terminal, the final goal was to provide a strategy that would strike a balance between the human workforce and artificial intelligence.

As a consequence of this, it is of the utmost importance to do research into the opportunities presented by IR4.0, particularly with regard to the degree to which businesses are prepared to implement AI technology. Given that the human race may soon be entering a new age of technological growth, one in which artificial intelligence will work alongside humans in the workplace, more in-depth comprehension of the technologies that underpin IR4.0 is absolutely necessary. This is due to the fact that IR4.0 is the fourth iteration of the Internet of Things.

According to the respondents, having information and communication technology skills is an essential component of a well-rounded education in logistics. The people who took part in the interview are aware that a significant number of these abilities are at least partially endogenous and that acquiring new talents in these areas is very challenging. Training programs need to combine 'soft skills' like teamwork and communication in addition to 'hard skills' like information and communication technology (ICT) expertise.

Respondents believed that networked artificial intelligence would increase human performance but also pose a threat to the long-term viability of the human workforce inside the ACT, based on the research findings. It would be necessary to reorganise the current economic and national human resource policy in the direction of the goal of expanding humans' capacities and capabilities in order to enhance human and artificial intelligence collaboration and stop trends that would compromise human relevance in the face of programed intelligence in the future. This would be necessary to heighten human and AI collaboration and stop trends compromising human relevance in the face of programed intelligence. As a result of the enhanced efficiency and other economic benefits offered by computer-based machine intelligence, all aspects of human labour will continue to be changed. These benefits include greater productivity.

The people responsible for making decisions on Malaysia's human capital policy, as well as the stakeholders in the container terminal, have benefited from this study in a number of ways, particularly from an industrial point of view. The outcomes of this research would provide a reference to the policy makers so that they can include ACT in their port development strategy to increase the efficiency and effectiveness of the operation of container terminals.

The purpose of the notion presented in this research was to devise a solution to an issue that business and government leaders may confront in the near future. As the AI deployment at Malaysia Container Terminal is still in its infancy, it is probable that the terminal operator does not yet have a comprehensive grasp of the human tasks that AI will replace. Because this advanced teaching style is still in its infancy, Malaysian educators may be unable to prepare the potential workforce for the impending artificial intelligence trend (AI). The fact that the AI trend in Malaysia is still in its infancy is mostly responsible for the information limitations that surfaced during the investigation.

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Appendix A

Grounded theory coding summary

Familiarisation & reflection	Open coding	Axial coding	Selective coding (final theme)	Response rate
Uncomplicated terminal operation Terminal operation SOP Terminal operation is repetitive	Terminal operation is not complicated	Terminal operation can be theoretical	Apply theory in operation	60% VIP 7, 5, 6, 3, 2, 4
Changes in workforce skills requirement IR4.0 essential abilities	Worker with creative ability Low skill worker will be obsolete	Worker with innovative ability High skill worker will be more essential	Innovative thinking	80% VIP 8, 5, 2, 9, 4, 7, 6, 1
Worker with high competencies.	IT savvy, well trained, highly skilled worker with critical thinking	Worker with high skills who can think critically	Good in problem solving	70% VIP 3, 5, 6, 7, 9, 1, 4
workforce skills requirement changes Industrial revolution 4.0	Worker with fast thinking ability Slow worker will be obsolete	Worker with flexible ability High speed thinking worker will be more essential	Good cognitive abilities	80% VIP 5, 3, 2, 9, 4, 7, 6, 1
Worker with high academic qualification.	Highly skilled worker with critical thinking and computer engineering background	Worker with computer science who can think critically	Familiar with ACT technologies	90% VIP 3, 5, 6, 7, 9, 1, 4, 8, 2

Appendix B

Questionnaire development summary

Phase	Procedure	Output
Development of questionnaire	Section A (RQ1): The Significant Criteria that human workforce must possess in order to remain competitive within Automated Container Terminal - Skills requirement - Knowledge Requirement - Job Parameter - Main Responsibilities Section B (RQ2): The initiatives that could be taken by less competitive human workforce to increase productivity value so that they could remain active in industry - Advices - Awareness	• Theme exploration on human Workforce within ACT • Theme expand on Human Workforce within ACT
Qualitative data collection	• Individual semi-structured Questions formulated in RQ1 • Individual Open-ended Questions formulated in RQ2 • Expected respondents: ➢Technology providers ➢Technology users – container terminal operators, port authorities, and container terminal stakeholders ➢Technology promoters – government agency and private logistics associations.	• Audio recording • Transcribed texts
Qualitative data analysis	• Grounded theory • Manual analysis technique • Within the case theme development • Cross case theme development	• Identified themes based on similar categories • Identified themes based on different categories • Classified themes based on similar categories • Classified themes based on different categories

ARTICLES FOR FACULTY MEMBERS

AUTOMATED CONTAINER TERMINAL AND MARITIME CONSTRUCTION RISK

Title/Author	**Container terminal automation: revealing distinctive terminal characteristics and operating parameters / Knatz, G., Notteboom, T., & Pallis, A. A.**
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ORIGINAL ARTICLE

Container terminal automation: revealing distinctive terminal characteristics and operating parameters

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Abstract

This study focuses on the automation of terminal equipment used to handle containers. A dataset was compiled, which includes 63 fully and semi-automated container terminals in operation around the world, their organizational features, technical dimensions, and the maritime and urban markets they serve. The data analysis focuses on where, when, under which conditions, and to what extent container terminals were automated, and who is responsible for implementing terminal automation. Only 3% of the world's container terminals were found to be either fully or semi-automated. A survey-based analysis of global terminal operators identifies how they implement their automation and the time necessary for terminal operators to start realizing a return on their investment. The results systematically map global automated terminal characteristics. Acknowledging that not all container terminals are candidates for automation of terminal equipment, this paper contributes to extant literature by presenting a systematic review of all global automated terminals in order to substantiate or refute any perceptions that might exist on their characteristics, for example, in terms of minimum cargo volumes needed for automation. The findings can provide some guidance to market actors considering investments in automation and public and private port authority decision makers that might also commit resources to automation.

Keywords Ports · Container terminals · Terminal automation · Port ownership · Automation investment · Return on investment (ROI)

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1 Introduction

Terminal automation is a full or partial substitution of manned terminal operations by automated equipment and processes. Automation is already present in most terminals, at least in its simplest form, using information technologies to manage terminal assets and supplement human activity. For example, modern container terminals use advanced terminal operating systems (TOSs) to control and optimize the movement and storage of containers in and around the terminal. Terminal operations involve various technologies such as RFID, optical character recognition (OCR), and anti-sway systems in cranes. However, automation can also include ship-to-shore cranes, the movement of containers from the berth to the yard, and yard equipment. The focus of this study is on this latter type of automation.

In the past decade, container terminal automation has attracted much attention in business, policy, and, subsequently, academic circles (Kon et al., 2020, Ghiara and Tei 2021, see also Sect. 3). While not all container terminals are candidates for automation of terminal equipment, no systematic review of all global automated terminals exists to shed light on the typical characteristics of these terminals. This study makes a distinction between *fully automated* and *semi-automated* container terminals. In line with earlier works (see, among others: Martín-Soberón et al. 2014; Drewry 2018; McKinsey 2018; Moody's 2019; Camarero Orive et al. 2020; Rodrigue and Notteboom 2021), a semi-automated terminal has automated the vertical movement of containers in the yard, while a fully automated terminal has also automated the horizontal movement of containers from the berth (i.e., the quayside) to the yard (i.e., the container stacking area).

The progressive introduction of semi-automated and fully automated terminal systems is driven, among other reasons, by the need for operations standardization, reduction in manning, increased handling capacity (Zhao et al. 2019), and productivity improvements (McKinsey 2018; Navis 2018; for a literature review see Kon et al. 2020). Nevertheless, as we demonstrate, only 3% of the container terminals are automated. Thus, container terminal automation is still the exception and not the norm (Miller, 2017). Often, a specific physical size of a container terminal or certain operating characteristics, such as a threshold level of TEU handled, is given as necessary to automate a terminal successfully.

This study advances a better understanding of *where*, *when*, under *which conditions*, and to *what extent* container terminals have been automated and *who* is responsible for implementing terminal automation. Our dataset explores the geography of the 63 automated container terminals (62 operating and one under construction), their organizational features, technical dimensions, the type of automation (full or semi), and the maritime and urban markets they serve. A survey of global terminal operators was undertaken to advance the understanding of terminal automation. The survey examined *how* terminal operators brought about their automated facilities (one or multiple suppliers) and *who* integrated the automated equipment with the TOS. Finally, the length of time before a terminal operator received a return on investment (ROI) was identified. This analysis provides data useful for terminal operators and investors considering automation investments and public and private port authority decision makers that might also commit resources to automation.

2 Research design and data collection

The research design addresses the following research questions:

- R1: When and to what extent have container terminals been automated, and who is responsible for their operation?
- R2: Are there any geographic patterns in the global distribution of automated terminals with some port regions more likely to opt for automation of terminal equipment?
- R3: Are there characteristics, such as cargo volume thresholds, or a specific cargo mix between gateway (import/export) and sea–sea transshipment flows that are common to all automated terminals?
- R4: How are terminal operators implementing their automation projects with one or multiple suppliers, and who has integrated the TOSs and equipment?
- R5: How long before a terminal operator realizes a ROI?

The above research questions require a systematic review of all global automated terminals in order to substantiate or refute any perceptions that might exist on the characteristics of these terminals. To answer the above research questions, we first compiled a list of automated terminals, thereby distinguishing between fully and semi-automated terminals. This distinction is made also in order to analyze whether the above characteristics or trends vary between fully and semi-automated terminals. Our review of extant literature and port and terminal company information identifies the precise number and geographical distribution of semi-automated and fully automated container terminals worldwide and their characteristics in terms of technical layout and equipment use, year of automation, and governance-related characteristics, such as type of terminal operator. This exercise resulted in 63 container terminals worldwide that are fully or partially (semi) automated. At the beginning of 2022, 62 automated terminals were in operation, with one more planned to be operational in 2024 (Table 1).

To address research questions R1 to R3, we collected a wide range of characteristics of automated terminals. Fifty-nine different features of a terminal were identified for our database. These were broadly grouped into the following categories: operations, environmental and energy saving, financial and cost savings, social, safety/security and resilience factors, and marketplace position. In addition, a *miscellaneous* category would note special circumstances like a local mandate for zero emissions, port authority funding to help defray costs typically born by terminal operators, equipment supplied by manufacturers for demonstration purposes, etc. Data was collected from port and terminal operator websites, industry journals and publications, and personal communications. Not all information was available for all 62 terminals, so a subset of critical data was identified that would be readily available and relevant to answer R1 to R3. This data subset included:

Table 1 List of 63 automated terminals as of January 2022

Countries	Terminal names	Ports	Type automation
Belgium	Antwerp Gateway*	Antwerp	Semi
China	Xiamen Ocean Gate Terminal*	Xiamen	Full
	Qingdao New Qianwan Container Ter-	Qingdao	Full
	minal*	Tianjin	Full
	Tianjin Port Second Container Terminal*	Tianjin	Full
	Tianjin Port Container Terminal*	Shanghai	Full
	Yang Shan, Phase 4*	Hong Kong	Semi
	Hong Kong International Terminals*		
England	London Gateway*	Stanford-le-Hope	Semi
	Liverpool2 Container Terminal	Liverpool	Semi
Germany	CTB - Container Terminal Burdhardkai*	Hamburg	Semi
	CTA - Container Terminal Altenwerder*	Hamburg	Full
Ireland	Dublin Ferryport Terminal*	Dublin	Semi
	Belfast Container Terminal*	Belfast	Semi
Israel	Bayport Haifa*	Haifa	Semi
	Hadarom Container Terminal	Ashdod	Semi
Italy	APM Vado Ligure*	Vado Ligure	Semi
Japan	Tobishima Container Berth Co., Ltd.*	Nagoya	Full
	Oi Container Terminal (Berth 6)*	Tokyo	Semi
Korea	Pusan Newport International Terminal	Busan	Semi
	(PNIT)*	Busan	Semi
	Busan Newport Container Terminal	Busan	Semi
	(BNCT)*	Busan	Semi
	Pusan New Port Company (PNC)	Busan	Semi
	Hanjin New Port Company (HJNC)	Incheon	Semi
	HMM PSA Newport Terminal (HPNT)		
	Hanjin Incheon Container Terminal		
Indonesia	Tanju Emas Semarang	Java Island	Semi
	Terminal Petikemas	East Java	Semi
Mexico	Tuxpan Port Terminal*	Veracruz	Semi
	APM Lazaro Cardenas*	Lazaro Cardenas	Semi
	New Port Veracruz	Veracruz	Semi
Netherlands	Rotterdam World Gateway*	Rotterdam	Full
	ECT Delta Terminal	Rotterdam	Full
	ECT Euromax Terminal	Rotterdam	Full
Panama	Manzanillo International Terminal*	Colon	Semi
Singapore	PSA Pasir Panjang Terminal, 1–2–3*	Singapore	Semi
	PSA Pasir Panjang Terminal, 4–5–6*	Singapore	Semi
	Tuas Container Terminal Phase I	Singapore	Full
Spain	Barcelona Europe South Terminal	Barcelona	Semi
	(BEST)*	Algeciras	Semi
	Total Terminals International		
United Arab Emirates	DP World Jebel Ali*	Dubai	Semi
	Khalifa-TIL	Abu Dhabi	Semi
	Khalifa-TIL2	Abu Dhabi	Semi (2024)
	Khalifa COSCO	Abu Dhabi	Semi

Table 1 (continued)

Countries	Terminal names	Ports	Type automation
United States	Long Beach Container Terminal*	Long Beach, CA	Full
	TraPac*	Los Angeles, CA	Full
	APM Terminal Pier 400*	Los Angeles, CA	Full
	Norfolk International Terminal*	Virginia	Semi
	Virginia International Gateway*	Virginia	Semi
	Global Container Terminal*	NY/NJ	Semi
Spain	Total Terminals International	Algeciras	Semi
	Barcelona Europe South Terminal*	Barcelona	Semi
Morocco	APM Terminals MedPort Tangier	Ksar es Seghir	Semi
Australia	Brisbane AutoStrad Terminal	Brisbane	Full
	DP World Australia Brisbane Terminal	Brisbane	Semi
	Brisbane Container Terminal	Brisbane	Full
	Victoria International Container Terminal	Melbourne	Full
	Sydney AutoStrad Terminal	Sydney	Full
	Sydney International Container Terminal	Sydney	Semi
New Zealand	Fergusson Container Terminal	Auckland	Semi
Taiwan	Kaohsiung Intercontinental Terminal (Terminal 4)	Kaohsiung	Semi
	Kao Ming Container Terminal	Kaohsiung	Semi
	Taipei Port Container Terminal	Taipei	Semi
Saudi Arabia	Red Sea Gateway Terminal	Jeddah	Semi
India	Vizhinjam	Vizhinjam	Semi

*Completed survey

- *In relation to R1*: fully or semi-automated terminal; the year the terminal opened; the year the terminal was automated; the terminal ownership profile (identifying the single owner or multiple companies having a shareholding in the terminal); and, the name of the terminal operator;
- *In relation to R2*: the location of the terminals in terms of country and port region (North America, Central America, North Europe/Atlantic, the Mediterranean, Pacific Asia and South Asia/Middle East, Oceania);
- *In relation to R3*: the length of berths; the maximum ship size handled; the maximum draft; the terminal capacity in TEU; the transshipment incidence, defined as the share of sea–sea transshipment (unloading of a container plus loading onto another vessel) in the total TEU throughput; and the total container throughput in TEU.

Descriptive statistics analysis was performed to provide a detailed explorative overview of automated terminal technical characteristics, corporate and institutional aspects, and geo-economic characteristics, exploring whether there are differences between fully and semi-automated terminals.

In addition to the data analysis of all terminals, a survey of automated terminals was undertaken by email in February–July 2021, to collect data for answering questions R4 and R5. The survey included questions about how automation was implemented and the (expected) length of time for a ROI. Senior

Table 2 Number of survey responses by region and by type of terminal automation

Region	Total replies		Fully automated		Semi-automated	
	No	% of total	No	% of total	No	% of total
North America	6	100	3	100	3	100
Central America	3	75.0	–	–	3	75.0
North Europe/Atlantic	7	63.6	2	20.0	5	83.3
Mediterranean	3	50.0	–	–	3	50.0
Pacific Asia	12	54.5	6	85.7	6	42.9
South Asia/Middle East	1	14.3			1	14.3
Total	32	50.7	11	61.1	21	46.6

representatives of the terminal operating companies that manage automated container terminals completed the surveys. The survey questionnaire asked terminal operators the following questions:

(1) How long (in months) was the testing period of the automation equipment/system?
(2) How many years will it take to realize (or has it taken to realize) a ROI for your automated system? Response options were: Just months after, 1–2 years, 2–4 years, 5–6 years, or over 6 years.
(3) How was automation implemented (in terms of equipment suppliers and software integration)? The response options were: one supplier as a turnkey project; one supplier with systems integration by the terminal operator; multiple suppliers with system integration by the main supplier; multiple supplies with system integration by the terminal operator or other arrangements (to be specified by the respondent).

More than half of the world's automated terminals participated in the study (51.6%) by returning valid and usable filled-out surveys. Responses came from all automated terminal operators in the United States, China, Germany, and Ireland, along with terminals in Europe, Korea, Japan, and the Middle East ports. Table 1 lists the 63 automated terminals included in this study, using an asterisk to identify the 32 terminals that completed the survey.

Table 2 indicates the regional distribution as well as the number of semi-automated and fully automated terminals that contributed to the survey-based part of the study by region.

Descriptive statistics facilitated an analysis of the technical characteristics of the terminals. Survey results (length of testing period, time for ROI, and how the terminal equipment was integrated) were subjected to correlation analysis. The number of replies, while over 50% of the total, and thus, representative of the actual situation, is at the lower limit of the number of observations needed when considering the application of any advanced statistical methods.

3 Empirical findings

3.1 Fully and semi-automated terminals

A first attribute in answering research question 1 (R1) relates to the nature of the automation of terminal equipment. Eighteen (18) of the 63 automated terminals, or 29% of the total, are fully automated. Automated stacking cranes (ASCs) are widely used in yard operations. ASCs are automated rail-mounted gantry cranes (ARMGs) that are generally aligned perpendicular to the berth. In some cases, such as at the Alterwerder Terminal in Hamburg, two ASCs with different dimensions (allowing one to pass under the other) work together on the same stack. The term ASC covers ARMG, C-ARMG (cantilever ARMG), and ARTG (automated rubber-tired gantry crane). Automated straddle carriers (AutoStrad) are less common. AutoStrads are unmanned straddle carriers used for quay to stack operations and stack to truck loading operations. Examples include Brisbane AutoStrad Terminal and Sydney AutoStrad Terminal, both operated by Patrick Terminals in Australia.

Berth to yard automation typically relies on unmanned automated terminal tractors, automated guided vehicles (AGVs), or runners (low straddle carriers without a driver onboard). Such automated horizontal transfer systems are quite common. Diesel-hydraulic engines powered the first generation of AGVs, and movement was restricted to fixed tracks on the terminal floor. The latest generation of AGVs is guided by GPS technology and is battery powered, resulting in zero CO_2 emission and noise reduction. AGV speed can reach 6 m/s. Some terminals, such as APMT in Rotterdam, use 'lift AGVs' to lift and stack containers.

A few fully automated terminals can also have remotely operated ship-to-shore cranes for the vessel-to-quay transfer. These cranes use single or dual hoist technology. Examples are found in Rotterdam (APMT at Maasvlakte 2), Shanghai (phase 4 of Yang Shan Terminal Complex), and Qingdao (Qingdao New Qianwan Container Terminal or QQCTN). While these remotely operated cranes are still manned, their operators may have different skills and pay scales compared with traditional crane operators on the berth.

Automation can also be achieved in the fourth main functional area of a container terminal, which is the in–out gate function. Automation in this area primarily concerns automated truck gates. However, this type of automation is not considered when distinguishing between fully and semi-automated terminals.

3.2 The number and temporal development of automated container terminals

A second aspect of R1 focuses on the number of automated terminals and their related growth pattern over time. Such an analysis helps to identify any temporal waves in terminal automation and the overall adoption of full- and semi-automation on a global scale. By the end of the twentieth century, the total number of automated container terminals amounted to just two. Full terminal automation was first implemented in 1993: the ECT Delta SeaLand Terminal at Maasvlakte 1 in Rotterdam

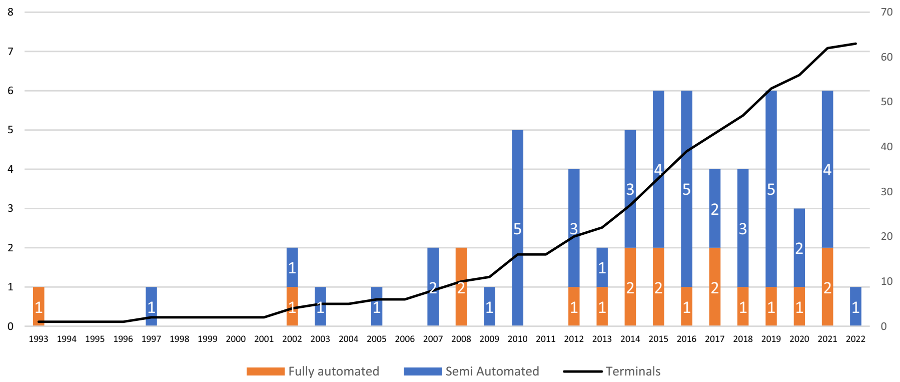

Fig. 1 Cumulative number of automated terminals*. **Note* $N = 63$; as of January 2022

became the first terminal in the world to use AGVs and ASCs. Six years later, in 1999, PSA opened the semi-automated Pasir Panjang Container Terminal 1–2–3 in Singapore. Six more automated container terminals were in operation when the global financial crisis of 2008/2009 hit the port industry. While the crisis changed the port sector in many respects (Pallis and Langen 2010; Notteboom and Rodrigue 2012; Notteboom et al. 2021), the trend toward automation continued. In the period 2008–2012, 12 more terminals were automated.

In early 2022, 62 fully or partially (semi-) automated container terminals were operating worldwide. Forty-seven terminals were automated in the decade 2012–2021 (Fig. 1). The first phase of the Tuas Terminal Complex in Singapore opened in December 2021. The most recent addition in the list, Hadarom Container Terminal at Ashdod Israel, plans to operate as a semi-automated terminal in 2022. Khalifa-TIL2 in Abu Dhabi is planned to become operational in 2024.

The real acceleration of container terminal automation, thus, occurred in the last decade. The development of automated container terminals has been gaining popularity, particularly since 2012. As noted in other reports (PEMA 2016; ITF 2021), most automated terminals developed since the 2010s, after a very gradual uptake in the 1990s and 2000s. The trend seems to continue, as in early 2022, Busan announced the intention to open the first berth of a new semi-automated container terminal (BCT) that will eventually handle more than 2 million TEU with three berths (Wallis 2022).

Still, the number of fully or semi-automated terminals remains relatively small compared to the scale of the global container terminal business. Drewry (2018) identified about 1300 full container terminal facilities worldwide, with just over 3% classed as automated. Moody's (2019) specified 46 semi-automated or fully automated container terminals worldwide. Rodrigue and Notteboom (2021) identified 58 automated terminals globally, of which nine were in a planning phase (see also: Notteboom et al. 2022). Alho (2019) counted 60 automated terminals globally, mainly in Europe and Asia, with forecasts to reach 200 in the next 5 years. Camarero Orive et al. (2020) listed 44 container terminals in the world using automated handling technology. Kon et al. (2020) reported that 54 automated terminals were opened between 1993 and 2020. ITF (2021) reports 53 automated container terminals, representing around 4% of the total global container terminal capacity. Most of them are located in Europe (28%), Asia (32%), Oceania (13%), and the United States (11%), and all of them are included in the list of automated terminals in the present study. The difference between the 63 terminals identified in this study and the number reported in other studies might be explained by differences in the period considered and the applied terminal automation definitions (for example, some studies do not consider terminals that have only automated part of the terminal site).

3.3 Operators that opted to automate terminals

A last aspect of R1 refers to the ownership and operator profile of automated terminals. An analysis of terminal ownership and operators can reveal whether certain ownership configurations and/or terminal operator types are more likely to result in a decision to opt for automation of terminal equipment. In the port operating industry, internationalization shifted from a dominantly regional structure, sometimes focusing on a single port, to several port terminal operators establishing a global portfolio. The terminal operating industry is increasingly complex, with competition, objectives, and entry strategies diverging between heterogeneous terminal operators (Olivier 2005; Olivier et al. 2007; Notteboom and Rodrigue 2012; Parola et al. 2013, Parola et al. 2015) and differences in local market entry conditions (Pallis et al. 2008). Several categorizations of terminal operating companies have been proposed (see: Bichou and Bell 2007; Olivier et al. 2007; Parola and Musso 2007). In this study, terminal operating companies are classified into the following three categories (see also Notteboom and Rodrigue 2012), based on the origins and strategic rationale to invest in the global terminal infrastructure network:

- *Carrier-linked terminal operators.* In recent decades, container shipping lines have developed dedicated terminal capacity to support their core shipping business. The derived benefits involve cost control, operational performance, profitability, and the ability to prioritize their ships during port calls. Excess capacity can go unused in a terminal dedicated only to a particular line or alliance. Other terminals in the same port may be congested, leading to uneven and less efficient asset utilization. Terminal operating companies are separate business units or sister companies with terminal facilities operated on a single-user dedicated base or open to third-party shipping lines. For example, AP Moller-Maersk operates a network of container terminals through its subsidiary APM Terminals, a sister company of Maersk Line. CMA CGM (through a majority shareholding in Terminal Link), MSC (via a majority shareholding in Terminal Investment Limited, TIL), and COSCO (through fully owned COSCO Shipping Ports) are also among the most involved shipping lines in terminal operations.
- *Financial holdings*. Port terminals have attracted several investment banks, retirement funds, and sovereign wealth funds, as an asset class with a potential for revenue generation over long periods (on the financialization of the container terminal industry and the increasing role of such entities since the early 2000s,

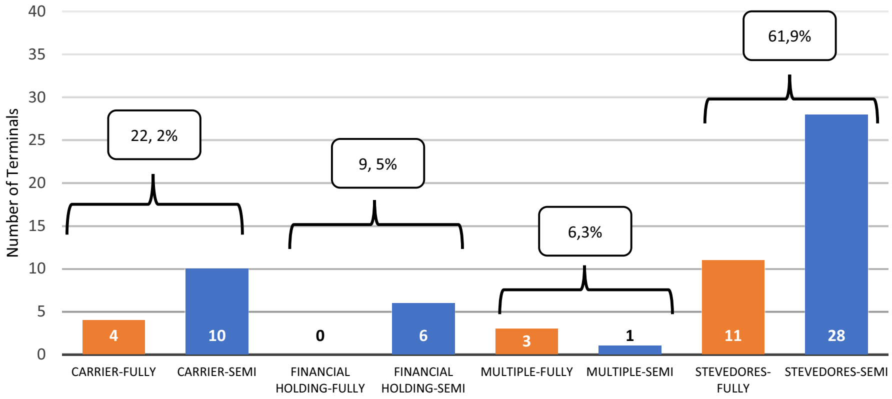

Fig. 2 Automated container terminals per type of operator. $N=63$; as of January 2022

cf. Rodrigue et al. 2011). Most acquire an asset stake and leave operations to the existing operating company. Others directly manage terminal assets through a separate terminal operating company,

- *Pure stevedores*. This group includes independent port terminal operators offering container handling services to a broad customer base. They can be privately owned or part of the port authority, tool port, or public service port portfolio.

The involvement of the above types of terminal operating companies can range from a minority shareholding to full ownership. In quite a few cases, *multiple actors* team up in a joint venture or consortium. For example, stevedores such as Hutchison Ports or PSA mitigate risks through terminal joint ventures with shipping lines, making terminal ownership structures and partnership arrangements increasingly complex.

The results show some spread in operator types, although pure stevedores are by far the most important type, both for full- and semi-automated terminals. Eighteen *pure stevedoring companies* operate 39 automated terminals or 61.9% of all terminals (Fig. 2). Eleven of them are fully automated.[1] Hutchison Ports operates six terminals, more than any other terminal operator. The portfolio of Hutchison Ports spreads in five different regions and includes the 1993-automated ECT Delta Terminal in Rotterdam. PSA is the operator of five automated terminals. These terminals are in two ports in South East Asia, Singapore (three terminals) and Busan (two terminals). One of them, PSA Hyundai Pusan Newport Terminal, is operated by a partnership between PSA and Hyundai. Sixteen other stevedoring companies operate one or two terminals. Stevedoring companies (i.e., D.P. World) and carriers (i.e., COSCO Shipping Ports, APM Terminals) are also involved as partners in one or more of the four automated terminals operated by consortia (6.3% of all automated terminals)—these are the fully automated Rotterdam World Gateway, Tianjin Port

[1] Reference here is to the port operator; in some cases, this might be accompanied by the formation of companies where partners might hold minority equities.

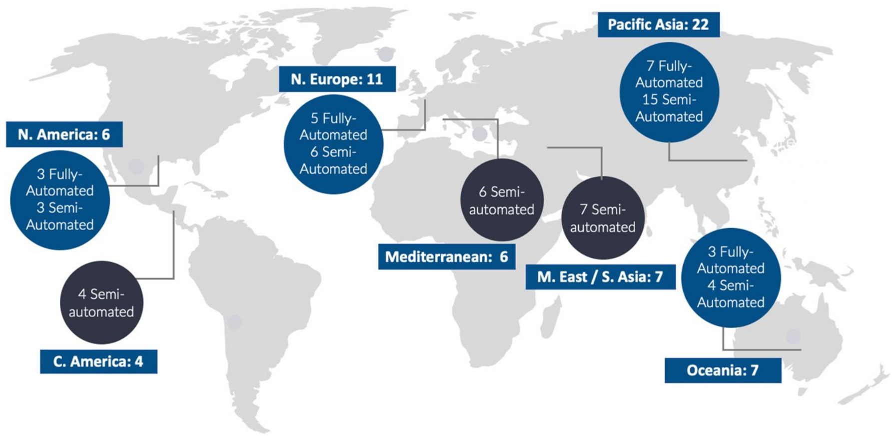

Fig. 3 Geographical distribution of automated container terminals*. *N=63; as of January 2022

Second Container Terminal and the Qingdao New Qianwan Container Terminal, and the semi-automated Antwerp Gateway Terminal.

Carriers who have assumed responsibility to operate container terminals (such as APM Terminals—part of Maersk, Evergreen, MSC (via TIL), COSCO Shipping Ports, MOL, and NYK) operate 10 semi-automated terminals. They also operate four fully automated ones, two of them in Los Angeles, USA (MOL's TraPac Terminal and the APM Terminals in Los Angeles), one in Rotterdam, Europe (the APM Terminals Maasvlakte II), and one in Nagoya, Japan (Tobishima Container Berth). *Financial holding companies* are also engaged in the operation of container terminals. They operate six automated terminals (9.7%) in the UK, Australia, South Korea, and UAE.

3.4 Geographical distribution

Research question 2 (R2) refers to the existence or absence of geographic patterns in the global distribution of automated terminals. The data does not seem to suggest that some port regions are more likely to opt for automation of terminal equipment than others. Semi-automated or fully automated terminals exist in all continents except Africa and Antarctica (Fig. 3). They are located in 23 countries (Fig. 4), evenly distributed between semi-automation and full automation. Australia, China, and the United States each have six terminals. In 20 other countries, the number of automated terminals is smaller. Pacific Asia (22 automated terminals or 35%) and North Europe (11 automated terminals or 17%) are the hotspots for terminal automation in terms of terminal numbers. However, fully automated terminals exist in only four regions; North America (US), Oceania, Pacific Asia, and Europe Atlantic. The geographical distribution of these terminals over time is detailed in Table 3, showing that most regions, with the exceptions of Europe Atlantic and Pacific Asia, are rather late adopters of terminal automation.

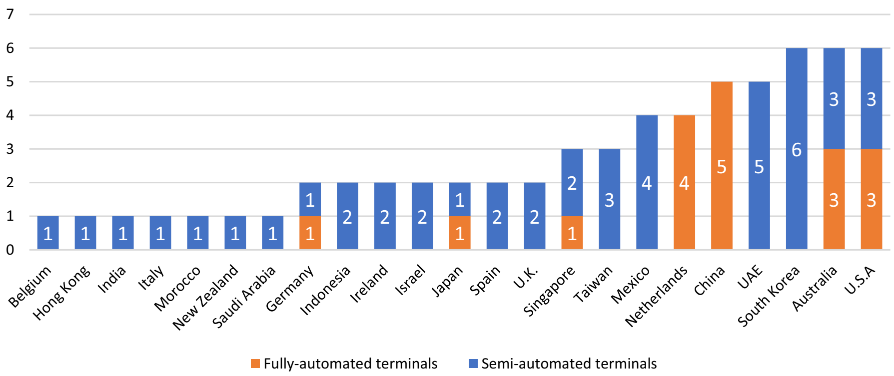

Fig. 4 Distribution of automated container terminals per country. **Notes N*=63; see Table 1 for a complete list of the identified automated terminals

3.5 Terminal throughput

Research question 3 (R3) aims at identifying specific technical and operational thresholds or ranges that might be typical for automated terminals. The first characteristic being analyzed in this regard is terminal throughput (in TEU). Most fully automated terminals handle between 2 and 4 million TEU per year (Fig. 5). Twenty-nine percent of the semi-automated terminals handle between 2 and 3 million TEU per year. However, 11% of the fully automated terminals and 22% of the semi-automated terminals handle between 250,000 and 1 million TEU. These findings demonstrate that terminal automation occurs in all terminal scales, and is not the prerogative of the largest terminal group only.

3.6 Technical characteristics

The second attribute to be analyzed in relation to R3 focuses on terminal dimensions (i.e., quay length and yard acreage) and nautical profile in terms of drafts at berth. Also here, the analysis helps to explore whether automated terminals are concentrated around a specific terminal size or nautical profile. The average acreage of the

Table 3 Evolution of container terminal automation per region

	Total	1993–1999	2000–2007	2008–2012	2013–2022	n.a
North America	6		1		5	
Central America	4				4	
Europe Atlantic	11	1	2	2	6	
Mediterranean	6			2	4	
Pacific Asia	22	1	1	7	12	1
South Asia/Middle East	7			1	5	1
Oceania	7		2		5	
Total	63	2	6	12	41	2

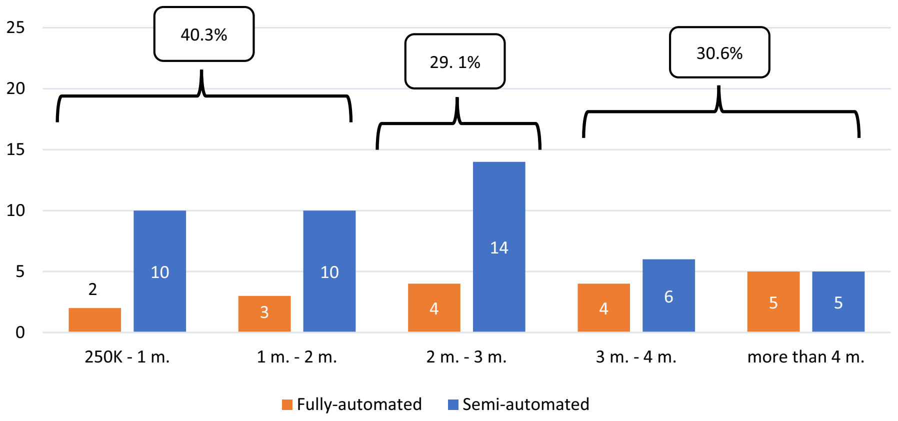

Fig. 5 Scale of fully and semi-automated terminal capacity (TEU)

fully automated terminals (98.6 ha) is 17.2% larger than the respective size of the semi-automated ones (84.1 ha, Table 4). However, the range of terminal size varies significantly for both fully automated terminals (standard deviation = 80.5 m) and semi-automated ones (standard deviation = 69.4 m). In some cases, however, where available land was limited, terminal operators used the space available, resulting in much smaller automated terminals. The semi-automated Pasir Panjang Container Terminal 1–2–3 in Singapore has the largest acreage. The size of 24 terminals—6 fully automated terminals and 18 semi-automated ones—does not exceed 50 ha.

Based on data available for 60 of the 63 terminals, the average quay length is 1480 m, without a difference observed between fully and semi-automated terminals (1506 and 1504 m, respectively).[2] Once more, the standard deviation from this average is substantial for both fully automated (standard deviation 769 m) and semi-automated (standard deviation 1350 m) container terminals. The length of berths in two terminals exceeds 5000 m. There are 10 more automated terminals with berth lengths of 2000 m or longer, and 27 with berth lengths ranging between 1000 and 2000 m. The length of berths in the other 21 terminals for which data are available is less than 1000 m.

The draft at automated terminals ranges from 13.7 to 16 m. However, the situation differs in semi-automated terminals where the draft is as low as nine meters at one terminal in Europe.

The semi-automated operations at a few of the terminals in the dataset only cover a part of the entire terminal surface, as the remaining terminal acreage relies on conventional container terminal equipment. A good example is the Antwerp Gateway Terminal operated by DP World. Since 2006, Antwerp Gateway has operated 20 ASCs on about a third of the terminal acreage. The remaining two thirds of the container yard still rely on manned straddle carriers. These will gradually be phased out

[2] We collected data on number of ship-to-shore cranes but do not know the outreach and technical characteristics of those cranes so we cannot make assumptions on crane density present in the handling of the largest vessels.

Table 4 Technical characteristics of automated container terminals

	Terminal acreage (ha)			Length of berths (m)			Max draft (m)		
	Ave.	Range (Max–Min)	Std Dev	Ave.	Range (Max–Min)	Std Dev	Ave.	Range (Max–Min)	Std Dev
Fully automated	**98.6**	**294.0–26.0**	**80.5**	**1506**	**3600–550**	**769**	**16.8**	**21.0–13.7**	**2.1**
Europe Atlantic	124.6	265.0–80.0	79.2	1840	3600–1000	1016	18.4	19.7–16.6	1.6
North America	82.5	139.0–40.0	60.1	1164	1646–550	560	15.7	16.8–13.7	1.7
Oceania	41.5	63.0–26.0	19.2	907	1400–660	427	14.7	15.2–14.0	0.6
Pacific Asia	113.3	294.0–36.1	102.1	1700	2350–750	651	17.0	21.0–14.8	2.1
Semi-automated	**84.1**	**318.0–13.3**	**69.4**	**1504**	**7772–330**	**1350**	**15.7**	**18.5–9.0**	**1.9**
Central America	43.8	52.0–33.0	8.5	1012	2040–556	691	15.9	16.5–15.0	0.7
Europe Atlantic	83.2	176.0–14.0	72.2	1253	2850–330	915	14.5	17.0–9.0	3.5
Mediterranean	53.8	79.0–19.0	27.8	1192	1600–700	356	16.9	18.5–16.0	1.0
North America	112.7	152.0–68.0	42.3	1348	2020–823	612	15.2	15.2–15.2	0.0
Oceania	38.5	46.0–32.0	6.0	1010	1300–610	309	14.5	16.0–13.2	1.4
Pacific Asia	110.6	318.0–13.3	98.1	2086	7772–380	2079	15.8	18.0–11.0	1.8
South Asia/Middle East	82.4	149.0–50.0	34.2	1322	1862–800	383	16.1	18.0–14.5	1.5
Total	**88.30**	**318.0–13.3**	**73.4**	**1505**	**7772–330**	**1208**	**16.0**	**21.0–9.0**	**2.0**

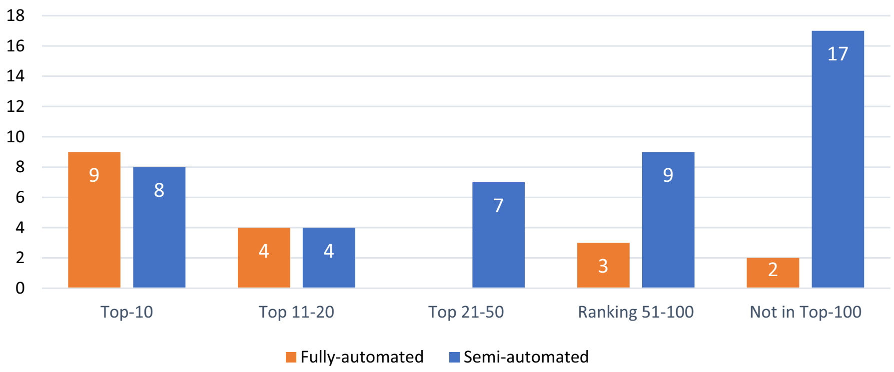

Fig. 6 Automated terminals in the top 100 ranked container ports. *Source* compiled by the authors; $N=63$; based on 2019 throughput; data as detailed in: Lloyd's List top 100 container ports 2020. London: Lloyds List

between 2022 and 2026 and replaced by 34 new ASCs. Other examples of automation covering only a portion of a terminal surface are the two fully automated terminals in Los Angeles, TraPac and APMT.

3.7 Container port scale

The third characteristic associated with R3 considers the scale of the ports in which the fully or semi-automated terminals are located. In particular, we explore the extent to which automated terminals are the prerogative of large container ports only, or alternatively, they can also be found in smaller and second-tier container ports. The 63 automated terminals are located in 43 different container ports. Seventeen of them operate in seven of the top 10 container ports (in terms of throughput). Nine are fully automated (one terminal in Shanghai, Singapore, Qingdao, two in Tianjin, and four in Rotterdam). Seven (two terminals in Singapore, four in Busan, and one in Hong Kong) are semi-automated.

A total of 44 of the 63 automated terminals operate in 27 of the top 100 container ports in terms of annual throughput (Fig. 6). Sixteen of these terminals are fully automated and 28 semi-automated. Fully automated terminals exist in the biggest container ports, with the exceptions being the initiatives by the Chinese government in the case of Xiamen Ocean Gate Container Terminal (fully automated since 2012) and by Hutchison Ports, in the case of Brisbane (fully automated since 2013).

Seventeen semi-automated and 2 fully automated terminals (i.e., 30% of all automated terminals) have been developed in 16 other ports with lower throughput per annum than the top 100 container ports. These are found in different regions of the world, i.e., four in Oceania (three terminals in Australia and one in New Zealand), three in Pacific Asia (in China, Indonesia, and Taiwan, respectively), three in South East Asia (one in India, two in the United Arab Emirates), and three in the Mediterranean Sea (two in Israel, and one in Italy, one in the UK, and three in Mexico). These findings show that while a significant share of automated terminals have been

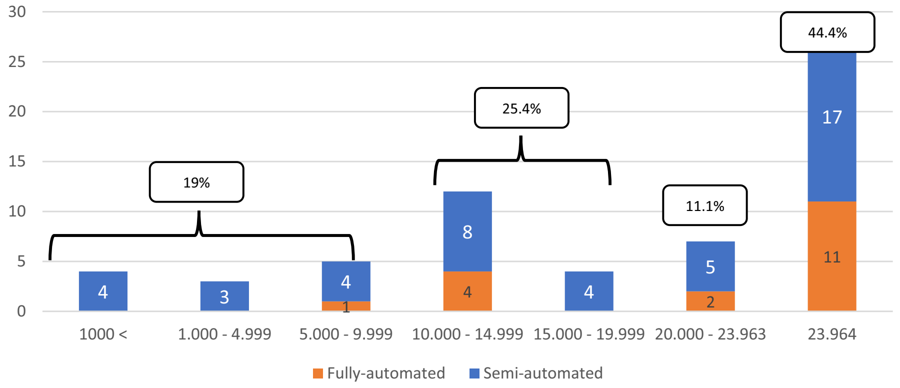

Fig. 7 Size of the biggest vessel calling at world ports hosting automated terminals. At the time of writing, 23,964 TEU was the capacity of the largest container vessel afloat. It concerns HMM Algeciras and sister ships measuring 228,283 gross tonnage (G.T.), 399 m length overall (LOA), 24 containers wide, and 16.52 m draft. We created a separate bar for this vessel size to indicate how many automated terminals received this largest ship size. *Source* compiled by the authors; data of maximum vessel size calling at each port as detailed in UNCTAD Liner Shipping Connectivity Index (LSCI). Geneva: UNCTAD

developed in top-ranked container ports, medium sized and even some smaller container ports are adopting automation as well.

3.8 Largest calling container vessel

The fourth characteristic in relation to R3 deals with the largest vessel scale calling at the automated terminal. An examination of vessel scale data at port and terminal level reveals the extent to which automated terminals are mainly designed to accommodate ultra-large container vessels (ULCCs), or alternatively, might also make sense for ports who are not targeting these ULCCs. Our data shows that automation primarily takes place in terminals on the main East–West trade routes, i.e., Asia–Europe, trans-Pacific and trans-Atlantic. More than half of the automated terminals operate in ports receiving calls of containerships larger than 20,000 TEU (55.6%, Fig. 7). Twenty-eight of these 35 automated terminals (44.4%) exist in ports where the world's largest containerships are deployed. These vessels are primarily deployed on the Asia–North Europe and Asia–Med trade routes. The transpacific trade route has seen a considerable increase in the 20,000 TEU+ vessel class in the past few years, combined with significant increases in call sizes.[3] A further 25.4% of automated terminals are at ports that host calls of containerships exceeding 10,000 TEU capacity. Eleven semi-automated and one fully automated container terminals receive vessels with capacity less than 10,000 TEU. Thus, while automation is not only found in the largest terminals (Sect. 3.7) or the top-ranked world ports (Sect. 3.8), the above analysis indicates automation primarily occurs at terminals that target 10,000 TEU+ vessels.

[3] For example, the MSC Isabella, with a nominal capacity of some 23,000 TEU, broke earlier records when the Pier 400 Terminal unloaded/loaded 34,263 TEU in the port of Los Angeles in June 2020.

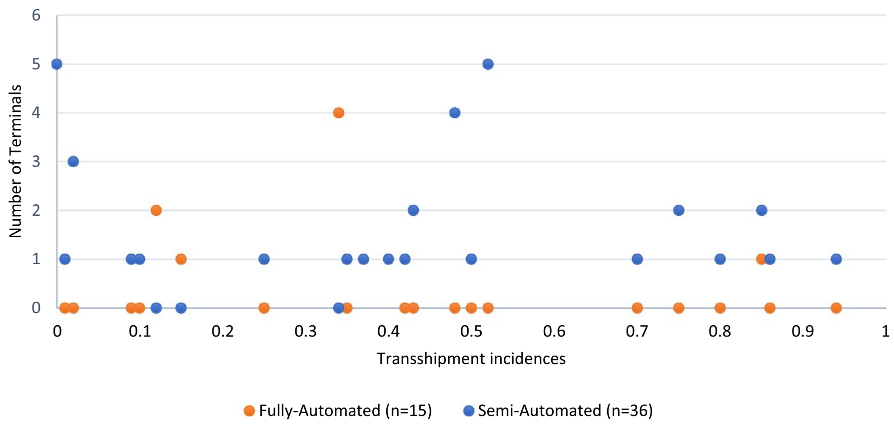

Fig. 8 Trahnsshipment incidence at ports hosting automated terminals. *Source* compilation based on transshipment data collected from port authorities' statistics and Drewry

3.9 The cargo mix

The cargo mix is the last attribute that is analyzed to answer R3. Each container terminal has a specific cargo mix. Most container terminals act as gateways for import and export cargo in relation to their captive or shared hinterlands. Other terminals combine import/export containers with sea–sea transshipment (T/S) flows whereby the containers arrive by vessel and leave on another vessel after a short dwell time at the terminal. The global port system also counts many almost pure transshipment hubs located at key locations in the liner shipping network close to strategic passageways such as the Straits of Gibraltar, the Suez Canal, the Panama Canal, and the Malacca Straits. Examples include Singapore, Freeport (Bahamas), Salalah (Oman), Tanjung Pelepas (Malaysia), Gioia Tauro, Algeciras, Tanger Med, Damietta, and Malta in the Mediterranean. These hubs have a transshipment incidence of 65 to 100% (Notteboom et al. 2019). Some regional markets seem to offer the right conditions for the emergence of several transshipment hubs (e.g., the Med or the Caribbean), such as strategic location within global shipping networks, favorable nautical conditions, land availability and a conducive regulatory framework on cabotage. At the same time, other port systems only feature minimal sea–sea transshipment activity due to unfavorable topological or regulatory conditions. For example, the "Jones Act" (Section 27 of the U.S. Merchant Marine Act of 1920), requiring ships owned and operated by US citizens or permanent residents to transport goods between US ports, is widely considered as one of the reasons behind the absence of a sea–sea transshipment market in the US port system (Brooks 2009).

Transshipment cargo typically has a shorter dwell time than gateway cargo (import/export) which makes yard management easier and results in higher land productivity for a given terminal layout. These factors might pave the way for automation.

Figure 8 shows that *the relation between transshipment incidence and automation* is somewhat spurious. Only one fully automated terminal is located in an

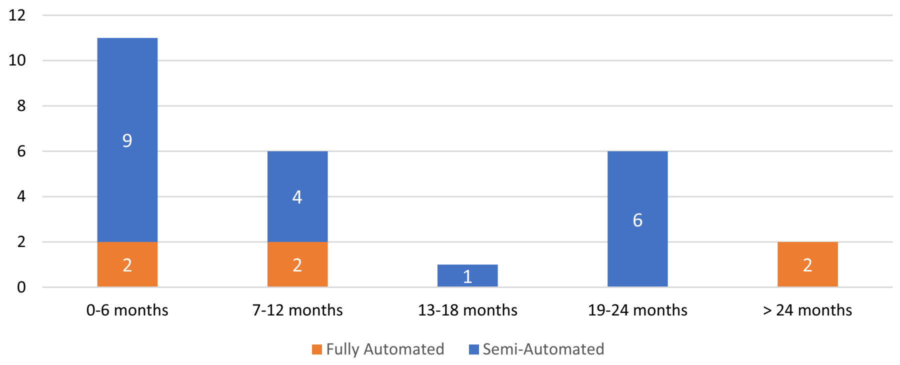

Fig. 9 Length of testing period for automation equipment

almost pure transshipment hub. The other fully automated terminals are found in ports with a mixed profile (i.e., gateway cargo plus transshipment cargo) or gateway ports with a low transshipment incidence. Semi-automated terminals are found in pure transshipment ports (transshipment incidence > 65%), mixed ports (between 25 and 65%), and gateway ports (< 25%), with none of these groups having a dominant presence. Container volumes are more volatile in transshipment terminals, requiring more flexibility (Notteboom et al. 2019). Gateway terminals generally have more captive container volumes—implying less throughput volatility (Wang et al. 2019) and are, thus, better suited to automation.

3.10 Testing and implementation issues

Research question 4 deals with the implementation of automation projects. We particularly analyze whether some approaches to the realization and testing of automated terminals are more common than others. Terminal automation requires advanced approaches to integrated scheduling of handling equipment (Lau and Zhao 2008) to optimize and synchronize the quay, intra-terminal transport, yard, and gate operations (for an overview, see: Stahlbock and Voß 2008; Sha et al. 2021).

A lengthy testing and start-up period can temper the cost reduction potential of automation. Through the survey, terminal operators were asked how many months automated equipment was tested before entire operations began. Twenty-six of the 32 terminals surveyed answered this question (Fig. 9). There was a wide variation in the length of the testing period with no apparent pattern between semi-automated and fully automated terminals. Testing periods ranged from 2 months (a case where the terminal had experience from automating a previous terminal) to 37 months for a fully automated terminal, with multiple suppliers and terminal integration done by the primary equipment supplier. One other terminal reported a testing period of 36 months; in this case, the terminal operator integrated the equipment supplied by multiple vendors. Forty-two percent of the terminals had a testing period of 6 months or less.

Automation requires the complex interaction between different technologies and full synchronization and hardware and software integration in all aspects of terminal operations. The optimization challenges are particularly significant when terminal automation involves a patchwork of traditional and state-of-the-art solutions from different suppliers. Purchasing automation components and equipment from different suppliers can result in expensive and lengthy integration processes. Globally, based on our survey results, 75% of the terminal operators integrated the automated equipment themselves, giving them greater control over the process and the length of the testing period (Table 5). Terminal operators would be anxious to realize the benefits of automation and minimize the testing phase. There were no distinct regional patterns in how terminals were integrated. Integration of the automated equipment by the terminal operator was found around the globe.

The second most common option was using one supplier of automated equipment with the terminal operator doing the integration. This was the case for both semi-automated and fully automated terminals. Less typical was integration by the leading supplier of the equipment. When the lead equipment supplier did the integration, the testing ranged from 6 to 37 months. In the four cases where the lead equipment supplier undertook the integration, the terminals were in Belgium, China, and Hong Kong.

Three terminals (the two Irish and one in China) used one supplier for a turnkey operation. In all three turnkey operations, the length of the testing period was 24 months. There is, however, no correlation between the length of the testing period and whether the automation was implemented by one or more suppliers [Pearson correlation: 0.166; Sig. (2-tailed): 0.525]; or whether the automation was implemented by a terminal operator or a supplier [Pearson correlation: −0.130; Sig. (2-tailed): 0.597, Table 6].

Recognizing the complexity of developing an automated terminal, APM Terminals recently announced an arrangement with ZPMC focused on shifting the relationship between terminal operator and equipment supplier from a transactional one to a partnership that should facilitate the integration process.

3.11 Return on investment

The last research question (R5) targets a key financial aspect of terminal automation, i.e., the ROI. Automated terminals require a significant upfront investment for equipment procurement and the necessary terminal modifications. One survey question asked terminal operators how long before they realized a return on their investment. A total of 31 of the 32 terminals that responded to the survey completed this question (Fig. 10). Sixty-one percent of the terminals indicated that it would take over 6 years to realize a return on the investment. Twenty-nine percent of the terminals realized a ROI between 5 and 6 years.

There was no discernable difference between the lengths of time a fully automated terminal took to realize a ROI compared with a semi-automated terminal.

Table 5 Integration options for automated equipment

Terminals that used	Total* ($n=31$)	Semi-automated terminals ($n=21$)	Fully automated terminals ($n=11$)
Multiple equipment suppliers with integration by terminal operator	19	14	5
Multiple equipment suppliers with the main supplier as integrator	4	2	2
One supplier as a turnkey operation	3	2	1
One supplier with integration by terminal operator	5	2	3

*One terminal indicated another arrangement, unspecified

Table 6 Correlations between length for realizing ROI and supplier(s) involved in implementing automation

	Length of the testing period of the automation equipment/system	Automation implemented by one or more suppliers	Automation implemented by supplier(s) with system integration by terminal operator
Years to realize a ROI for automated system			
Pearson correlation	0.239	−0.031	−0.032
Sig. (2-tailed)	0.250	0.870	0.108
N	31	31	23
Length of the testing period of the automation equipment/system			
Pearson correlation		0.166	−0.130
Sig. (2-tailed)		0.525	0.597
N		31	23

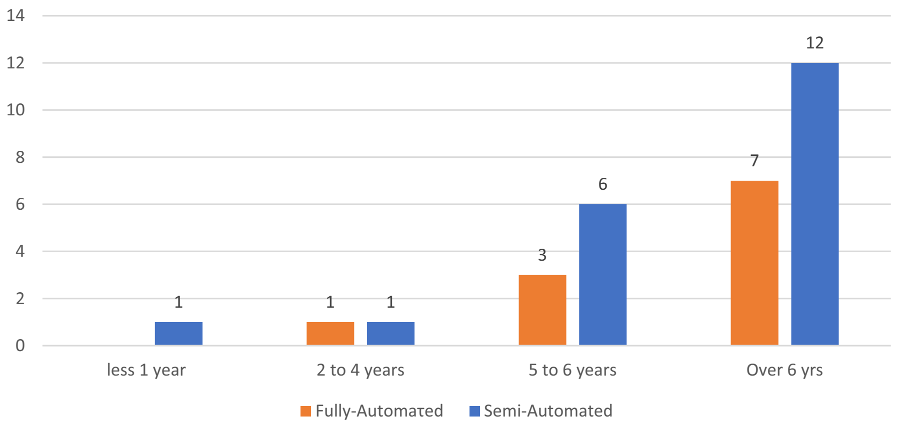

Fig. 10 Years to reach return on investment in automated equipment—raw data

One Pacific Asia terminal reported an unlikely low ROI period of less than 1 year. That is an outlier for which we were unable to find an explanation.

There is also no correlation between the time needed for a ROI and the length of the testing period [Pearson correlation: 0.239; Sig. (2-tailed): 0.250, Table 6]. Moreover, we did not identify any correlation between the time needed for the return of investment and whether the automation was implemented by one or more suppliers [Pearson correlation: – 0.031; Sig. (2-tailed): 0.870] or whether the automation was implemented by a terminal operator or a supplier [Pearson correlation: – 0.0323; Sig. (2-tailed): 0.108].

4 Conclusions

This study provides a deeper understanding of where, when, under which conditions, and to what extent container terminals have been automated and who is responsible for implementing terminal automation. A wide array of temporal, institutional and spatial factors were examined in the context of answering five research questions. The research questions, the analyzed attributes per question and the main findings are summarized in Table 7.

The 63 operating automated terminals are found in 23 countries, in all continents except Africa (and Antarctica). Most of the terminals are located in Pacific Asia and Europe. New automated terminal projects have been proposed for Busan, South Korea (PCN), New Orleans and Long Beach in the US and Chile, while others are under development. Stevedoring companies operate 39 automated terminals, carriers operate 14 terminals, financial holding companies operate 6, and joint ventures or consortia operate 4. Despite the growth in terminal automation, automated terminals still represent a small part of the operators' global terminal portfolios. All top six global/international terminal operators (China COSCO Shipping Ports, PSA

Table 7 Revealing distinctive characteristics of automated terminals in terms of physical, operating, implementation and financial attributes

Research questions	Attributes of automated terminals	Main findings
R1: When and to what extent have container terminals been automated, and who is responsible for their operation?	Full or semi-automated	29% of all automated terminals are fully automated
	Number and temporal development	Accelerated adoption: 76% of all automated terminals opened after 2012; still, they represent only 3% of all container terminals globally
	Type of operator	62% Operated by pure stevedores, 22% by carrier-related operators
R2: Are there any geographic patterns in the global dispersion of automated terminals with some port regions more likely to opt for automation of terminal equipment?	Terminal location (country and region)	Automated terminals exist in all continents except Africa and Antarctica; They are located in 23 countries, evenly distributed between semi-automation and full automation; Europe Atlantic and Pacific Asia are the earliest adopters
R3: Are there characteristics, such as cargo volume thresholds, or a specific cargo mix between gateway (import/export) and sea–sea transshipment flows that are common to all automated terminals?	Terminal throughput (in TEU)	Terminal automation occurs in all terminal scales, and is not the prerogative of 3 million TEU+ terminals (only 30.6% of all automated terminals)
	Quay length	Average = 1480 m (similar for fully and semi-automated terminals). Std Dev = 769 m for fully automated and 1350 m for semi-automated. Upper value of 5000 m. Less than 1000 m for about one third of all automated terminals
	Draft	Ranges from 13.7 to 16 m. Semi-automated terminals: lowest 9 m
	Terminal acreage	Average = 98.6 ha (fully automated); 84.1 ha (semi-automated). Std Dev = 80.5 m (fully automated) and 69.4 m (semi-automated). Less than 50 ha for 39% of terminals
	Container port scale (in TEU)	27% of automated terminals in world's top 10 container ports; 70% in world's top 100 container ports
	Largest container vessel scale	Automation primarily occurs at terminals which target 10,000 TEU+ vessels; 55.6% of terminals operate in ports receiving containerships larger than 20,000 TEU

Table 7 (continued)

Research questions	Attributes of automated terminals	Main findings
	Cargo mix (transshipment incidence)	Relation between transshipment incidence and automation is spurious. Only one fully automated terminal is located in an almost pure transshipment hub. Semi-automated terminals are found in pure transshipment ports, mixed ports, and gateway ports, with none of these groups having a dominant presence
R4: How are terminal operators implementing their automation projects, with one or multiple suppliers, and who has integrated the terminal operating systems and equipment?	Test period	Wide variation in the length of the testing period (2 months to 37 months) with no apparent pattern between semi-automated and fully automated terminals; 43% of terminals had a testing period of 6 months or less
	Automated equipment suppliers	High reliance on multiple equipment suppliers
	Integration of equipment and terminal operating system	75% of the terminal operators integrated the automated equipment by themselves; No correlation between the length of the testing period and whether the automation was implemented by one or more suppliers or whether the automation was implemented by a terminal operator or a supplier
R5: How long before a terminal operator realizes a return on investment?	Return on investment	> 6 years = 61% of terminals; 5–6 years = 29%; no discernable difference between automated and semi-automated terminals

International, APM Terminals, Hutchison Ports, D.P. World and TIL), based on their share in world container port throughput for 2018–2019, (Drewry 2020) are involved in the operation of at least one automated terminal. For example, Hutchison Ports operates 52 container terminals globally, of which only 6 (11.5%) are fully or semi-automated (3 and 3, respectively). APM Terminals has involvement in 59 container terminals, 5 of which are automated terminals (8.5%), 4 fully automated, and 1 semi-automated. Of the 50 terminals controlled by PSA, only 5 (10%) are automated. D.P. World operates six other automated terminals (five semi-automated and one fully automated). TIL is involved in two and China COSCO Shipping in one.

Eighteen of the 63 terminals are fully automated, the rest semi-automated. Although the first automated terminal opened in 1993, the real acceleration has happened in the last decade with 40 terminals automated since 2013. Eleven of those 40 are in the Pacific Asia region. In light of the arrangement between APM Terminals and China's Shanghai Zhenhua Heavy Industries Company (ZPMC), the Pacific Asia region is likely to continue the acceleration toward automation. In October 2021, APM Terminals announced that it was forming a strategic alliance with ZPMC to develop a wide range of automated solutions for its global network of 76 terminals, including automated container handling equipment (APM 2021). This sort of strategic relationships could likely facilitate a more rapid conversion of conventional terminals to automation.

Most automated terminals handle between 2 and 3 million TEU. While many trade publications suggest that automation needs a minimum of 1 million TEU to operate effectively, the results found that twelve automated terminals handle less than 1 million TEU, two of which are fully automated. Thus, terminal automation occurs in all terminal scales, and is not the prerogative of the largest terminal group only. Still, we also found that automation primarily occurs at terminals, small or large, which target 10,000 TEU+ vessels. If gigantism in container shipping, ports, and global logistics (Haralambides 2019) prevails, and the foreseen presence of 25,000 TEU+ ultra-large containerships (ULCS) (Ge et al. 2021) expands, it remains to be seen whether automation will be spread further as a response to the scale diseconomies produced at the port by the use of these larger vessels.

The early 2020s are marked by disruptions in global maritime supply chains, caused by the COVID-19 pandemic (Notteboom et al. 2021; Kent and Haralambides 2022). Against a backdrop of fewer vessel calls and mixed trends in the share of larger vessels calling around the globe, there is a tendency toward bigger call sizes. The foundations of the observed increases in call sizes are driven by the trends in the biggest call sizes, especially those of 6000 TEU or more (Notteboom and Pallis 2022). Record-breaking call sizes in many ports (e.g., Los Angeles, Antwerp, Felxistowe, Singapore) put pressure on yard space, berth availability and quay crane availability and productivity to accommodate such vessels. These are all important parameters in automated terminals. Today, the average size of fully automated terminals is about 100 ha, while the average size of semi-automated terminals is 84 ha. The range of terminal sizes varies significantly for both fully and semi-automated terminals, with 24 being less than 50 ha. The average quay length based on 59 of the 62 terminals is 1480 m without a significant difference between full and semi-automated terminals. Again, variability is high, with two terminals having over 5000 m of berth. All but one terminal have drafts over 14 m, with the maximum draft of automated terminals at 16 m.

Automated terminals allow terminal operators to densify their operations and maximize the use of terminal space. The expectation is that the ability to densify operations in an automated configuration might show that, for a given design capacity, automated terminals could be smaller than conventional terminals. Fully automated terminals are typically 30% larger than semi-automated terminals. Most of the automated terminals developed by the six large global terminal operators have a rather large capacity footprint. However, approximately one third of the existing automated terminals were conversions of existing conventional terminals, particularly in the United States and Europe vis à vis greenfield operations, designed initially with automation. Of the six automated terminals in the US, only one was a greenfield terminal (Virginia International Gateway, originally developed by APM). In addition, several terminals have automated only a part of their existing conventional terminals. For example, AMP Terminal in Los Angeles automated only 40 of its 196 ha. Greenfield terminals are predominately being developed in the Middle East and Asia. These are being developed in phases but their long-range plans show that they are on the larger end of the range of terminal sizes found here.

About 70% of the automated terminals operate in the top 100 container ports in the world but only 17 are found in the top ten container ports. Nine of the top ten container ports based on 2020 volumes are located in the Pacific Asia region (World Shipping Council 2022), already shown here as a hotspot for automation. The expectation is that the percentage of automated terminals in the top 10 container ports will continue to grow over time. There is no strong relationship between transshipment incidence and automation, but expectations based on cargo mix would suggest higher levels of automation in gateway ports and less in transshipment hubs. Only one fully automated terminal is in a transshipment hub, while semi-automated terminals can be found in pure transshipment ports, ports with a mixed cargo mix, and gateway ports.

The decision to automate does not always translate to successful implementation. In two cases, London Thamesport in the UK and the Outer Northern Harbor terminal in Copenhagen, the process of automating the terminals has been canceled for commercial and other reasons. In other parts of the world, intentions and decisions to develop new port infrastructure are associated with automation, but port development advancement is on hold for several reasons. One such case is Mubarak Al Kabeer Port in Kuwait.

While we find a wide variation in technical characteristics among automated terminals there are some operating characteristics that are predominant. There is a clear preference for terminal operators to undertake themselves the integration of a new automated terminal system. One terminal operator indicated on his survey that what was learned during their first terminal integration significantly reduced the time to start their second terminal. Over time, the expectation is that the testing periods will become shorter as terminal operators experience increases. Likewise, ROI results reveal that automation requires a long commitment, with most semi and automated terminals taking over six years to realize a return. The results could have been further refined had an additional response option been available for the terminal operators, such as "over ten years."

Acknowledging that not all container terminals are candidates for automation of their equipment, this paper, therefore, contributes to the extant literature by presenting a systematic review of all global automated terminals in order to substantiate or refute any perceptions that might exist on the characteristics of these terminals, for example in terms of the minimum cargo volume needed. While it is generally believed that only certain terminals will fit the profile where unmanned automated equipment brings added value, the results here reflect a wide variation in automated container terminal features, particularly the size, container volumes, and overall port standing. No specific set of characteristics was identified that must be present for an automated terminal to materialize. Neither physical size nor volume dictates whether or not a terminal can be automated. Rather each locality presents a unique set of circumstances that terminals adapt to. The findings, however, allow a determination of the most likely attribute values of an automated terminal, while acknowledging that wide ranges are reported for automated terminals' physical attributes, because operators have proceeded to automate under a wide variety of local conditions. Nevertheless, the optimum conditions for automation based on the most common characteristics found among the largest number of terminals can be defined. Terminal operators, port authorities and government officials can benchmark their local conditions against the presented list of technical and corporate/governance attributes shown in Table 7. Thus, our findings can provide some guidance to market actors considering automation investments, and to public and private port authority decision makers that might also commit resources to automation.

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ARTICLES FOR FACULTY MEMBERS

AUTOMATED CONTAINER TERMINAL AND MARITIME CONSTRUCTION RISK

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How to control cruise ship disease risk? Inspiration from the research literature

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ABSTRACT

The COVID-19 pandemic once brought the global cruise industry to a standstill. This has led to the realization that the development of viable disease risk management policies and measures will guarantee the sustainability of cruise tourism. The purpose of this study is to identify and develop a framework for risk management of cruise ship disease based on the research literature of cruise diseases in the Web of Science from 1996 to 2019. The study analyzed the characteristics of the literature researchers, the relationships between their research institutions organizations, the main cruise ship disease cases and measures. Based on the discussion of COVID-19 on cruise ships , risk management factors of cruise ship diseases were proposed , which include the port country's epidemic prevention capacity, the mode of disease transmission, the relevant regulations on international public health disposal, the design and construction of cruise ships, the medical and health conditions on cruise ships, and the characteristics of cruise tourism activities. A timeline and system framework for cruise ship disease risk management is proposed. A special "maritime mobile community prevention and control system" should be established, and a cooperation mechanism consisting of the government, non-governmental organizations, trade groups and industry experts should be established. The port should be capable of border isolation, detection and establishment of temporary shelter hospitals. At the same time, big data technologies such as disease tracking, investigation and health data are also important components of the risk management system.

1. Introduction

As the fastest growing sector of the global tourism industry, Cruise tourism has drawn extensive attention. Over the past 40 years, although the global economy has experienced many economic recessions and fluctuations triggered by various factors, the number of cruise passengers has maintained an average growth of about 7%. The cruise industry plays an important role in the global economy, creating 1177,000 jobs, sending out $50.024 billion in payroll and generating $150 billion in global revenue in 2018 [1]. Cruise ships, known as " marine mobile community," are characterized by large passenger capacity, high personnel density, long gathering time, narrow internal environment, relatively concentrated diet and many sailing places, etc. It is more likely to lead to collective outbreaks of infectious diseases than land communities [2].

As of 9:30 a.m. CET on 12 December 2020, 69,521,294 confirmed cases of COVID-19, including 1582,674 deaths, have been reported to WHO worldwide [3]. Although this is the third epidemic caused by coronavirus in the 21st century, the number of people infected now exceeds that of the first two combined [4,5]. The negative impacts of COVID-19 are not limited to human casualties but also include short- and long-term social, economic and political impacts. The International Monetary Fund (IMF) predicts that the global economy could contract by − 3% in 2020, while the loss of GDP due to the epidemic situation could reach around $9 trillion [6]. The UNWTO estimates that the wide-spread of the novel coronavirus has resulted in the loss of about 1.1 billion international tourists, a drop in export earnings of between $91 billion and $1.1 trillion and the loss of between 100 million and 120 million jobs [7]. This is more serious than the global impact of the 2003 SARS epidemic and has severely affected the economic growth and prosperity of some countries [8,9].

Accordingly, the threat to global public health posed by international tourism during the COVID-19 pandemic should also be fully recognized [10]. Farzanegan et al. (2020) found that there was a positive correlation between international tourism and the cumulative level of COVID-19 confirmed cases and deaths by April 30, 2020 [11]. Cruise

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tourism, which is highly dependent on global mobility, has exacerbated this situation. Major cruise companies such as Carnival, Royal Caribbean and Norwegian have witnessed a rapid increase in COVID-19 cases among passengers and crew members [11]. The market value of a number of cruise companies has shrunk dramatically. Among them, the stocks of Royal Caribbean Cruises, Carnival and Norway's three major cruise companies have fallen by an average of 84.2% in 62 days [12], leaving the global cruise industry to a standstill.

Since the worldwide suspension of cruises, the international cruise industry has carefully reflected on the lessons of the infection incidents of cruise tourists in Yokohama, Japan in the early stages of the epidemic [13], and has actively studied safety and health measures and risk prevention mechanisms for the resumption of cruises. The Health Program of European Union has developed guidelines for the resumption of cruise ships called Healthy Gateways [14]. The Health Sail Panel has formulated 74 anti-epidemic recommendations for the resumption of cruise ships in North America, called "Recommendations from the Healthy Sail Panel" [15]. Some countries and regions around the world have resumed cruise ships [16]. However, among the cruise ships that have resumed sailing around the world, some cruise ships have been suspended due to the epidemic [16].

In the "Research Report on Restart of Chinese Cruise Industry", It is argued that the "cruise safety bubble" is a strategy for resuming sailings in other countries and regions of the world where the outbreak has not been controlled and is still in a high and medium risk environment [17]. "The strategy is to create a small, secure and enclosed environment that is decoupled from the general environment [17]. However, the research on epidemic risk management around the world still needs to be strengthened [18]. Wang et al. (2020) discussed the risk management measures of COVID-19 in Chinese universities [19]. McAleer (2020) concluded that prevention is better than cure for the C0VID-19 epidemic [18]. The critical importance of diagnostic tests in emergency situations is determined [20]. It seems sensible to conduct more tests and target more patients, and meanwhile it is also necessary to consider the cost issue [18]. There is mounting evidence that patients with mild symptoms or even no symptoms can transmit the disease [21,22]. However, there are few papers on risk management from the perspective of cruise ships. Chinese scholars Liu and Zhang, taking COVID-19 as an example, propose short-term countermeasures and long-term epidemic prevention mechanisms for cruise ships [2]. At present, the research on risk management of cruise ship diseases is still worth discussing.

Tracking and reviewing the evolution of knowledge and trends allows us to understand the past, analyze the present and anticipate the future [23,24]. To that end, this study aims to comprehensively analyze the global references related to cruise diseases in the WOS database from 1996 to 2019. Specifically, this systematic review research intends to:

1) examine the trends of cruise diseases research;
2) analyze previous cruise diseases studies in terms of study contexts, organizations, authorship status, and keywords;
3) explore the themes of cruise diseases research over the last 24 decades;
4) present the factors of cruise diseases risk management, propose a framework of cruise diseases risk management and provide reference for in-depth research.

2. Methodology and data sources

2.1. Methodology

The developments of information technology and bibliometrics have provided the basis for generating visual software [25,26]. This paper chooses VOSviewer 1.6.10, ArcGIS 10.6, UCINET 6 as measurement and visualization software, and chooses STATA and Excel as auxiliary measurement tools [26]. This method enabled us to identify current profitable countries, authors, co-cited references, keywords and other information, so as to summarize the current status and results of previous research.

2.2. Data sources

The source of literature data is Web of Science Core Collection. The WOS Core Collection is a collection of authoritative and influential academic journals from around the world, covering a wide range of disciplines, and is characterized by high quality, large quantity and time span, and complete documentation [27]. The data retrieval is carried out by using the fields of "TI = cruise ship*\cruise*\cruise line*\illness*\epidemic*, etc." In order to ensure the representativeness of documents, set "Document Types = ARTICLE OR REVIEW" to refine, remove articles unrelated to cruise diseases, and finally obtain 69 valid documents between 1996 and 2019. The above search was conducted before January 1, 2020.

A list of 437 documents that meet the search criteria [TI = cruise ship*\cruise*, etc. AND TS = cruise ship*\cruise*, etc.] between 1996 and 2019 was obtained according to the above operations. Extracting keywords and listing the top 10 keywords with high frequency and strong centrality (Table 1), we found that disease outbreak is one of the top ten keywords in the cruise field, but the number of valid documents is only 69, accounting for 16% of the total number of valid articles, indicating that the number of documents in the field of cruise diseases is small and the research attention is not high.

3. Characteristics of literature publication and authors

3.1. Publication trend

Fig. 1 shows a regression model of the number of publications from 1996 to 2019 using the STATA software. The model shows that the number of articles published in the field of cruise diseases has not increased significantly, and the time series of articles published in WOS has been adjusted by 17.39%. In addition, the scattered points on the graph show that the number of published articles is highly volatile, with the highest value of 6 articles / year and the lowest value of 0 articles / year, and the average annual number of articles is less than 5, indicating that most scholars pay little attention to cruise diseases.

3.2. Publication output

In order to quickly identify publications with higher contributions, Table 2 lists the top 10 source titles, organizations, authors and countries of 69 publications.

In Table 2, the organizations with a total percentage of 3% are Atlanta Res Educ Fdn, Chinese center for disease control prevention, European Centre for Disease Prevention Control, Instituto Adolfo Lutz, Minist Hlth, Netherlands National Institute for Public Health and the Environment, Purdue University and University of Zurich.

Table 1
Top 10 key words in cruise research sorted by frequency and centrality in 1996–2019.

Ranking	Keywords	Frequency	Ranking	Keywords	Centrality
1	cruise ship	97	1	ship	0.43
2	tourism	67	2	emission	0.40
3	cruise tourism	61	3	intention	0.37
4	satisfaction	56	4	flow	0.36
5	model	55	5	luxury cruise	0.24
6	impact	39	6	china	0.23
7	experience	38	7	impact	0.22
8	port	30	8	service quality	0.21
9	passenger	29	9	outbreak	0.20
10	outbreak	22	10	disease	0.20

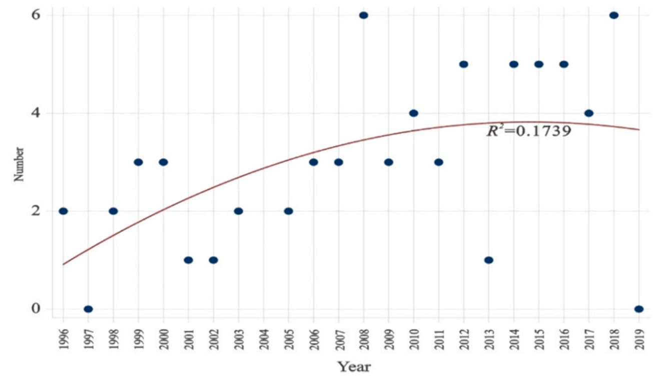


Fig. 1. The number of articles on cruise diseases published in 1996–2019.

3.3. Regional distribution of publications

A total of 396 authors published articles in 21 countries between from 1996 to 2019, with contributions ranging from 36 articles (52.0%) to 1 article (1%). With regard to the regional distribution of research publications (Fig. 2) , Europe becomes the leading region of cruise diseases research constituting 42.7% followed by North America 38.8% and Asia and the Australasia 5.8%. South America obtains only 2.9% of the entire research outcomes. There is no cruise diseases research documented both in Africa and the Middle East. This is related to the market phenomenon of the global cruise industry. Europe is the second leading cruise destination of the world next to North America, and Italy and the UK are the leading cruise ship destinations in Europe [28]. On the other hand, Asia and Australasia are the most rapidly growing cruise destinations of the globe [28].

3.4. The intensity of organizational collaboration

The Table 3 records the top 4 organizations in terms of total link strength. The total link strength of the organization is not related to the number of documents and citations, and is connected to the cooperation groups. From 1996–2019, there were 150 organizations involved in cruise ship disease research. However, only a small number of organizations where the links exist are shown on Fig. 3a. Fig. 3b shows the organizations with more than 2 research records in this field in the WOS.

Table 2
Top 10 more productive sources, organization and countries among 69 publications.

Ranking	Source Titles		Organizations-Enhanced		Authors		Countries	
	ST[a]	TP[b]	Organizations	TP	Authors	TP	Countries	TP
Top 1	Journal of travel medicine	17%	Centers for disease control prevention USA	26%	Cramer EH	10%	USA	52%
Top 2	Emerging infectious diseases	9%	University of Thessaly	9%	Hadjichristodoulou C	9%	England	13%
Top 3	Clinical infectious diseases	7%	Health protection agency	7%	Mouchtouri VA	6%	Italy	12%
Top 4	Epidemiology and infection	6%	Istituto Superiore di Sanita	6%	Vaughan GH	6%	Greece	10%
Top 5	Eurosurveillance	6%	National Kapodistrian University of Athens	6%	Kremastinou J	4%	Australia	9%
Top 6	Food and environmental virology	4%	Cleveland clinic foundation	4%	Nichols G	4%	Germany	9%
Top 7	American journal of preventive medicine	3%	Robert Koch institute	4%	Armstrong P	3%	Peoples r china	9%
Top 8	Annals of emergency medicine	3%	University of California system	4%	Asher CR	3%	Canada	6%
Top 9	Bmc public health	3%	Atlanta Res Educ Fdn	3%	Blanton CJ	3%	Brazil	4%
Top 10	Journal of infectious diseases/Travel medicine and infectious disease[c]	3%	Chinese center for disease control prevention, etc[c]	3%	Bush HS, etc[c]	3%	Denmark/France/ Luxembourg/ Netherlands/ Sweden/ Switzerland[c]	3%

[a] ST: source titles;
[b] TP: total percentage;
[c] both 3%

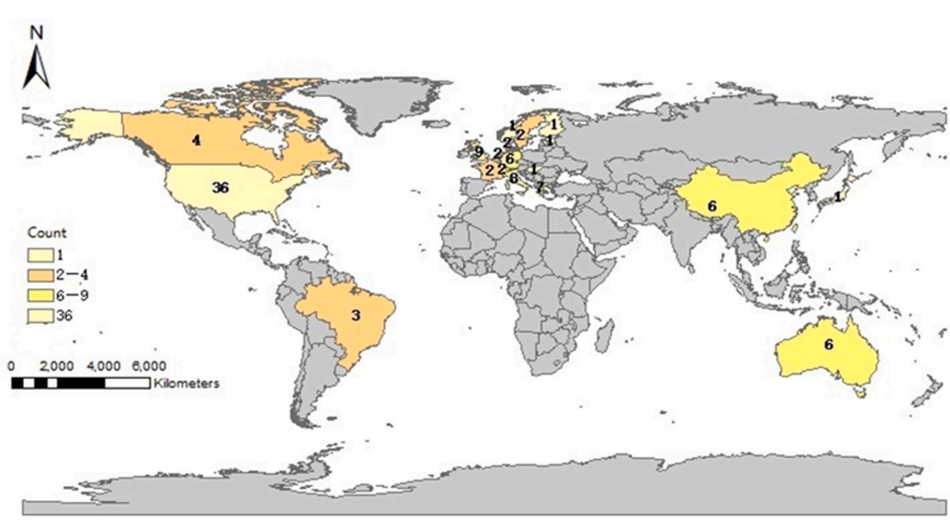


Fig. 2. Global cruise disease research productivity contribution.

Table 3
Top 4 organizations in terms of total link strength.

Organizations	Documents	Citations	Total link strength
HLTH PROTECT AGCY	3	121	20
CTR DIS CONTROL & PREVENT	14	554	19
ROBERT KOTH INST	3	102	18
UNVI THESSALY	6	54	18

There are only three organizational collaboration groups and the largest group is composed of five members, including the University of Thessaly in Greece, the British Health Protection Agency, the Robert Koch Institute in Germany, etc. Among them, the University of Thessaly in Greece is more central. The subsequent cooperation is carried out by 1–2 members, the map node composition is loose, and the intensity of cooperation between organizations in this field is relatively low.

3.5. Analysis of prolific authors

To identify prolific authors, the square root of the total number of authors (396) was calculated according to Price's (1976) law and got the value 19.90 [29]. Initially, the 20 most productive authors were considered. However, the number of articles published by the 20th author to the 32nd author is 2, and there are great similarities in the scientific research of cruise diseases, so the top 32 authors were selected [30]. The contributions of the 32 authors range from 2 to 7 articles, which isolated them from other researchers with a yield of 1 article in the WOS database [30]. The number of articles was reduced from 79 to 36 through author co-signatures.

Only connected nodes are displayed on the map. In Fig. 4c, the authors whose total link strength is more prominent are Harris J, Nichols G, and Hadjichristodoulou C. These three authors co-exist in a prolific author cooperation network (Fig. 4a). Fig. 4a and b are visual maps of the prolific author network, both made up of 6 members. Among them, Nichols, Gordon and Fromkin, Kenneth have the closest relationship with the other 5 authors. The author group centered on Fromkin, Kenneth (Fig. 4b) has a relatively stable structure, and the cooperation intensity is higher than that of the author group centered on Nichols, Gordon (Fig. 4a). In addition, there are multiple authors who lack contact. Overall, the intensity of collaboration among prolific authors is relatively low.

If the documents published in 2014–2019 are regarded as contemporary work, there are only 12 contemporary authors among the 32 prolific authors (Fig. 5). After screening, the initial identification of 36 documents were reduced to 6 documents (which are contemporary) [30], which accounted for only 9% of the total. The research scope of these articles is only four countries: the United States, Italy, Brazil, Sweden.

4. Research contents and hotspots

4.1. Classification of research contents

Currently, the literature on cruise diseases research covers 19 categories of WOS (Fig. 6), of which the top five are infectious diseases, accounting for 52.2%; public environmental occupational health, accounting for 43.5%; medicine general internal, accounting for 24.6%; immunology, accounting for 18.84%; microbiology, accounting for 17.4%.

4.2. Themes and hotspots of cruise diseases research

Since keywords are a precise summary of the literature, analyzing high-frequency keywords can directly reflect the subject content and hot issues in the academic field [31]. Bibliometric data shows that this research involves a total of 239 keywords. The time change of the keywords from 1996 (dark blue) to 2019 (dark red) is shown in colour (Fig. 7a). As shown in Fig. 8a, cruise disease research is mainly concentrated in 2010–2015. In each research sub-field, there are frequently occurring keys such as epidemiology, outbreak, transmission, passenger and so on.

The co-occurrence threshold of keywords is set to 3, and 22 keywords are introduced into the visual analysis. VOSviewer 1.6.1 automatically divides the extracted keywords into 5 clusters (Fig. 7b), which are represented by different colors. Circles of the same color indicate similar themes. As shown in Fig. 8b, the keywords with larger circles are

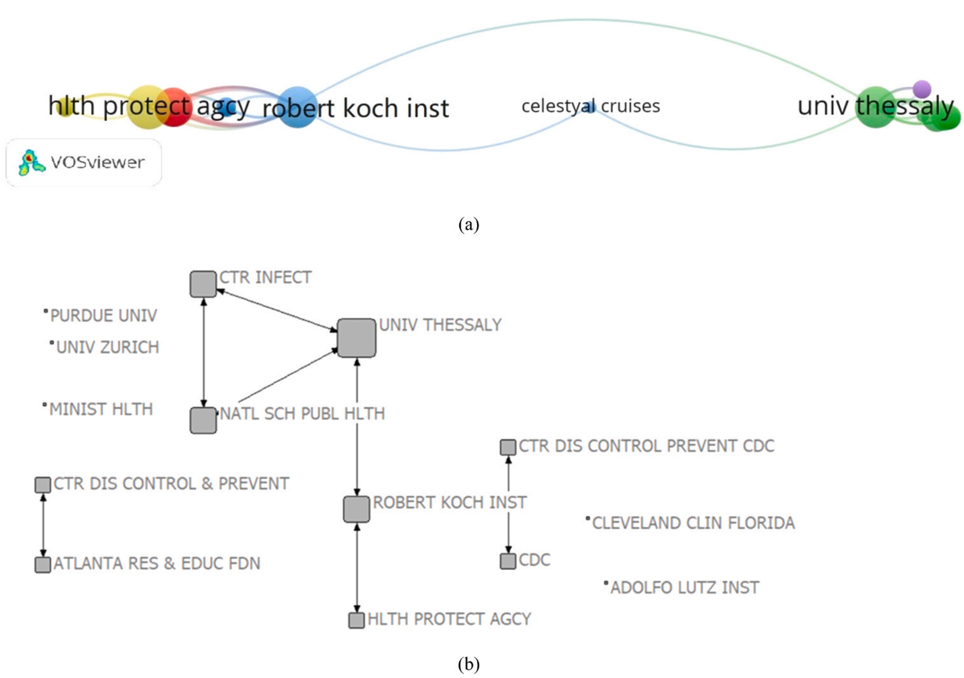


Fig. 3. Organizational cooperation network in cruise disease research. Note: (a) network visualization of 150 organizations based on total link strength; (b) network visualization with a record ≥ 2 in WOS.

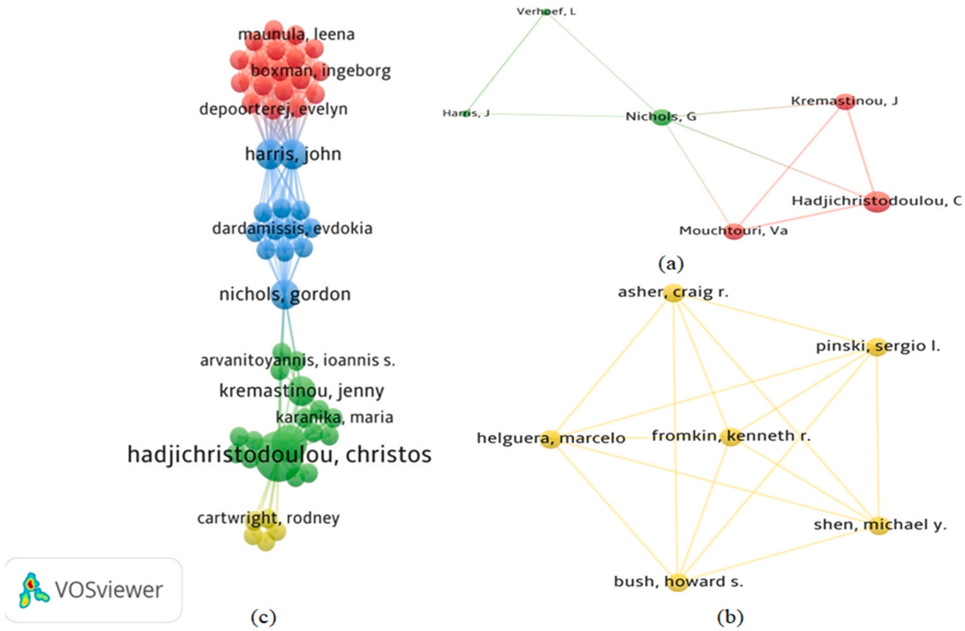


Fig. 4. Author cooperation network in cruise disease research. Note: (a) and (b) are cooperative groups of prolific authors; (c) network visualization was based on total link strength.

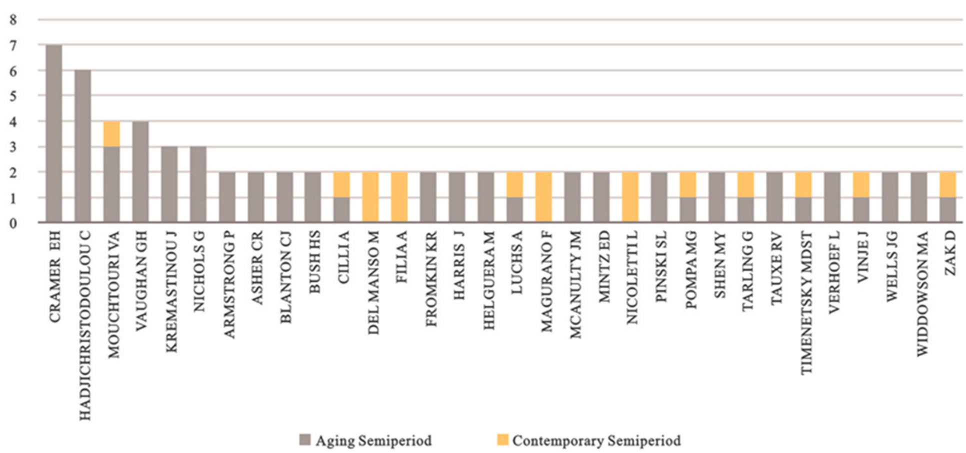


Fig. 5. Prolific contemporary authors in cruise diseases.

outbreak, gastroenteritis, norovirus, cruise ship, transmission, passenger behaviors. The close distance between these keywords shows similar research themes.

Based on the analysis of the keyword network, Table 4 summarizes the research themes of cruise disease. Norovirus, respiratory diseases, Legionnaires' disease and vaccine-preventable diseases account for a large proportion of these research themes (Fig. 8).

Norovirus is a common cause of outbreaks of acute gastroenteritis and diarrhea in cruise ships. It spreads among the crowd through food, person-to-person contacts, etc., even if sanitary treatment has been carried out on board ships, new strains of the virus strain can still be created and spread on land [32]. By quantifying the environment in which norovirus is transmitted, examining the factors that contribute to outbreaks, the relative impact of direct transmission, and passenger behavior, scholars have found that environmental transmission triggers a series of epidemics, but that direct transmission dominates [33–35]. Scholars have also found that vigorous promotion of good hand-washing habits can prevent or reduce outbreaks of disease; isolating sick passengers and cleanliness are beneficial, but they do not seem to be so effective in controlling the epidemic [35,36].

Respiratory diseases are common infections on cruise ships, including and influenza A (H1N1, H3N2), influenza B other diseases [37,38]. Reviewing the flu cases on cruise ships, it is found that influenza can spread widely during outbreaks of cruise ship activities and occur outside of the traditional flu season [39]. Individuals in crew cabins and restaurants faced the highest infection risk [38]. The risk of infection can be reduced to some extent by increasing the ventilation rate in some or all locations [38]. The use of high efficiency particulate air filters and ultraviolet germicidal irradiators in the ventilation system is the most effective measure [38]. In addition, implementing a comprehensive epidemic prevention and control plan, including timely antiviral treatment, may reduce the rate impact of influenza infection on cruise passengers [39–41].

The increasing incidence of legionellosis among cruise passengers is related to water supply systems [42], especially in closed and crowded environments. Legionella readily survives and multiplies in water pipes and spreads into the environment through air conditioning systems and water distribution points [43]. Chemical, physical and bacteriological analysis of water samples collected from key locations (crew compartments, kitchens, coffee bars, rooms with central air conditioning

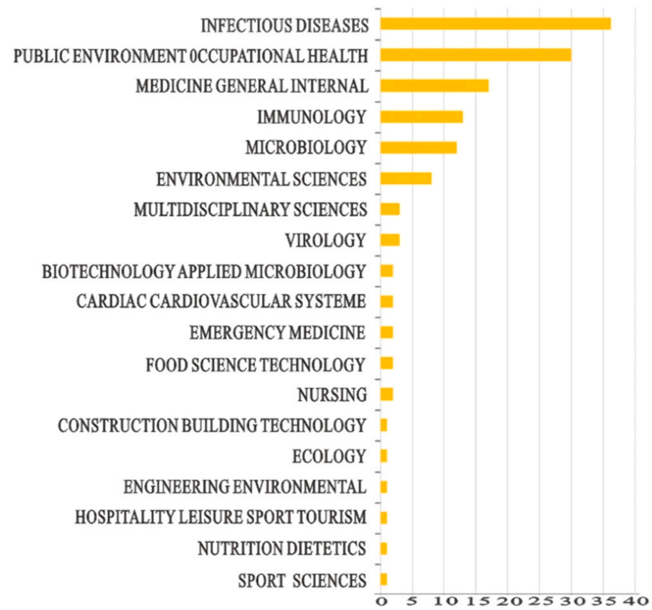


Fig. 6. Contribution to scientific productivity by WOS categories.

systems, and etc.) revealed that nearly half of the area was contaminated by Legionella, concentrated in showers and hand basins [44]. Therefore, some scholars have put forward a water safety plan to apply water treatment systems to ship water supply systems, including drinking water, recreational water facilities, decorative water facilities and fountains, which is expected to improve ship water management and thus reduce the incidence of diseases [45].

The international composition of the ship's population and the enclosed environment are conducive to the spread of vaccine-preventable diseases such as measles, rubella and chickenpox among passengers [46]. A review of these cases reveals that most varicella patients are crew members [47]. These crew members are usually from tropical areas where varicella immunity was acquired in childhood or early adulthood, or no varicella vaccination program [47]. Cruise lines should ensure that crew members are immune to these diseases [48], and should consider whether it is a cost-effective option to screen crew members for varicella, measles and other diseases and vaccinate them before placement [47,48].

In addition to the above four categories, passengers on board may also suffer from motion sickness, cardiovascular, hepatitis E and other diseases [49–51]. Research on the patterns and characteristics of injuries and illnesses on polar cruises is conducive to the formation of more standardized medical facilities and personnel training guidelines, thereby improving the quality of life on cruises [49].

In the current epidemic, the Diamond Princess cruise is a study case of the spread of COVID-19. The related research mainly focuses on the clinical characteristics of COVID-19, epidemiological investigations, and descriptive studies of the COVID-19 epidemic among passengers and crew [52–54]. The results show that COVID-19 can be transmitted by droplets, contacts, aerosols and "fecal-mouth" [2]. Estimating the number of novel coronaviruses breeding on cruise ships, it is found that the characteristics of cruise ships have clearly magnified the potential for disease transmission [55]. Isolation, rapid and comprehensive detection of infection play an important role in controlling the epidemic [13]. The Princess Cruises, which landed in Taiwan, has effectively reduced the infection and death rates among cruise passengers through the application of big data analysis technology [56].

Based on the above analysis, Table 5 summarizes the types and prevention and control measures of cruise diseases.

4.3. *Influencing factors of cruise disease prevention and control*

Fig. 9 summarizes the prevention and control management factors in the research on cruise diseases transmission methods and prevention and control measures. The factors include the port country's epidemic prevention capacity, the mode of disease transmission, the relevant regulations on international public health disposal, the design and construction of cruise ships, the medical and health conditions on cruise ships, and the characteristics of cruise tourism activities.

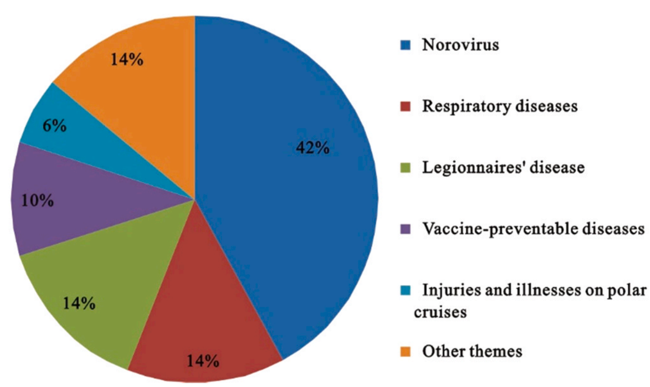
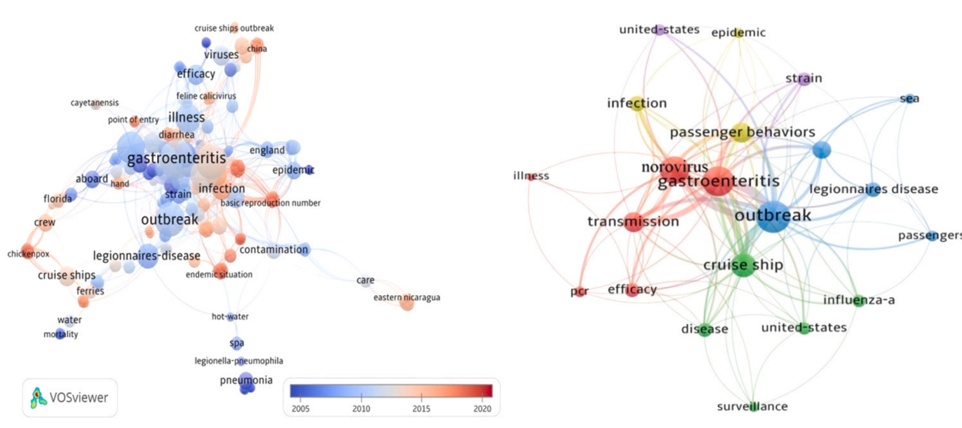


Fig. 8. Research hotpots of cruise disease.



(a) (b)

Fig. 7. Keywords visualization network in cruise disease research. Note: (a) overlay visualization was based on occurrences-weights and average publication year scores; (b) network visualization with frequency ≥ 3.

Table 4
Research themes on cruise diseases.

Primary themes	Secondary themes	Tertiary themes
Norovirus (gastroenteritis, diarrhea, stomach upset, etc.)	Epidemiological research	Incidence rate, time, location, characteristics of infected population, etc.
	Source-based investigations	Foodborne pollution, point source pollution, waterborne pollution
	Disease transmission research	Outbreak environment and means of transmission
		Impact of direct transmission
	Passenger behavior research	Early awareness of virus perception
		Passenger behavior and virus transmission during the outbreak
		The effectiveness of passengers' willingness to wash their hands
Respiratory diseases (influenza A (H1N1, H3N2), influenza B, etc.)	Epidemiological research	Incidence rate, time, location, characteristics of infected population, etc.
	Degree and method of transmission	Airborne transmission and indoor social networks
	Prevention & Response	Disease/health surveillance and vaccine effectiveness research
Legionnaires' disease	Epidemiological research	Incidence rate, time, location, characteristics of infected population, etc.
	Source of infection	Water supply system, central air conditioning system, pool, etc.
	Influences	Clinical and public health
	Prevention tool	Water safety management and planning
Vaccine-preventable diseases (measles, rubella and chickenpox, etc)	Epidemiological research	Incidence rate, time, location, characteristics of infected population, etc.
	Management and control	Investigation of contacts and vaccinators
Injuries and illnesses on polar cruises	Patterns & Characteristics	Incidence rate, time, location, characteristics of infected population, etc.
Other themes	Medical facility hygiene and health care information for travellers	
	Impact on health protection in onshore communities	
	Research on motion sickness, cardiovascular, hepatitis E and other diseases	

4.3.1. *Port country's epidemic prevention capacity*

The sudden mass epidemic on cruise ships is a challenge for every port state. As an important link between cruise ships and port destinations, ports play a crucial role in epidemic prevention and control. The Japanese government's response to the outbreak of the Princess Diamond outbreak reflected the limitations of its emergency resources and the inadequacy of the Yokohama Port Epidemic Prevention Emergency Response Plan, which was mainly characterized by inadequate detection capacity, a single detection method, and limited medical reception capacity, which led to an increased risk of cross-infection [57].

4.3.2. *The mode of disease transmission*

It can be seen from Table 4 that the main mode of disease transmission on cruise ships is respiratory infections caused by droplets or aerosols, and pathogens are excreted with excrement from patients or carriers, and contaminate hands, water, food and utensils through domestic contact. Infections can be summarized as droplets, contact, aerosols, and "fecal-oral" transmission.

4.3.3. *The relevant regulations on international public health disposal*

Different from river cruise ships and regular passenger ships, which are generally of national origin, more than 60% of the world's cruise ships fly Flags of Convenience for ease of navigation and management [58]. The Diamond Princess's emergency response to the COVID-19 outbreak highlighted the complexity of handling international public health incidents on cruise ships, and it is reflected in the division of responsibilities between the flag state and the port state, as well as the different nationalities of the ship's operators, crew and passengers [2]. It is also a test of relevant international public health laws, reflecting the serious deficiencies in the prevention, detection and response to health emergencies at the national level, and it does not meet the requirements of international regulations [18].

4.3.4. *The design and construction of cruise ships*

The main route of transmission of COVID-19 on cruise ships is considered to be person-to-person transmission, but other routes should not be overlooked, such as aerosol transmission via central air supply or drainage systems [59]. Inappropriate use of heating, ventilation, and air conditioning (HVAC) systems on cruise ships can lead to the spread of disease [5], and confined environment allows for higher rates of diseases transmission [60,61]. The design of sanitary piping systems and waste disposal discharges on cruise ships also increase the likelihood of disease transmission [62].

4.3.5. *The medical and health conditions on cruise ships*

Medical facilities and staff on cruise ships need to have a higher level of service due to the aging passengers and the isolation of the environment [63]. After the outbreak of the epidemic on the Diamond Princess, due to the lack of medical and health facilities, non-traditional quarantine measures such as classified isolation and batch transfer were not taken in time [2]. Instead, centralized quarantine measures were adopted, which did not meet the characteristics of the spread of the epidemic and increased the potential risk of infection for larger confined spaces.

4.3.6. *The characteristics of cruise tourism activities*

The special feature of the cruise ship is that it is an isolated system, with diverse people on board, strong mobility, and a high concentration of population in a limited space, which shortens social distance and provides very favorable conditions for the spread of the virus [11]. Cruise travel has aggravated the spread of diseases to a certain extent. The cruise ship sails in various locations, and the origin or destination is rich in tourism activities, which enables passengers to have a large area of contact with the local community.

5. Conclusion and recommendations

5.1. *Conclusion*

The COVID-19 pandemic has had a profound impact on international tourism and cruise industry. In this context, the analysis in this paper attempts to provide a critical perspective for the scientific research involved in cruise disease. The current research analyzed 437 articles in the cruise field and 69 articles in the cruise diseases field. The study results show a significant increase in articles published in the cruise field from 1996 to 2019, with "disease outbreaks" being one of the top ten keywords. In contrast, cruise disease research has a low number of publications, with an average annual publication volume of less than five articles. Scholars pay little attention to them, with fewer cooperative research groups.

The countries with high global productivity in cruise disease are, in turn, the United States, the United Kingdom, and Italy. This is linked to the market of the global cruise industry. Research results in this field are highly concentrated and relatively discrete globally, with a few countries/regions possessing the majority of published research results. There are few cooperative groups between prolific authors and organizations, and the overall intensity of collaboration was low. Since the

Table 5
Types of cruise diseases and prevention and control measures.

	Type	Disease	Mode of transmission	Prevention and control measures in the cruise environment	Study
Infectious diseases	Gastrointestinal transmission	Norovirus; Viral hepatitis E, and etc.	The pathogens are excreted from the body of the patient or carrier, and infected by eating into the body by contaminating hands, water, food and utensils through daily contact	Isolation of the source of infection; Hygienic management of food and water on cruise ships; Tourist hygiene habits (e.g. washing hands frequently, not drinking raw water); Medical facilities and first aid capabilities on the cruise ship	[35,36, 63]
	Respiratory transmission	Influenza A; Influenza B; Legionnaires' disease; measles, rubella, chickenpox; COVID-19	The pathogens invade from human respiratory tract infections such as the nasal cavity, throat, trachea and bronchus; The pathogens are excreted from the body of the patient or carrier, and infected by eating into the body by contaminating hands, water, food and utensils through daily contact	Isolation of the source of infection; Increasing the ventilation rate of the place; High efficiency particulate air filter and ultraviolet sterilizer are used in ventilation system; Application of water treatment system; Timely and comprehensive quarantine; Medical facilities and first aid capabilities on the cruise ship	[34,35, 38,63];
Non-communicable diseases	Cruise transportation triggers	Motion sickness	–	Advance training of doctors on board; Medical facilities on the cruise ship	[49]
	Others	E.g. cardiovascular	–	Medical facilities and first aid capabilities on the cruise ship	[63,70]

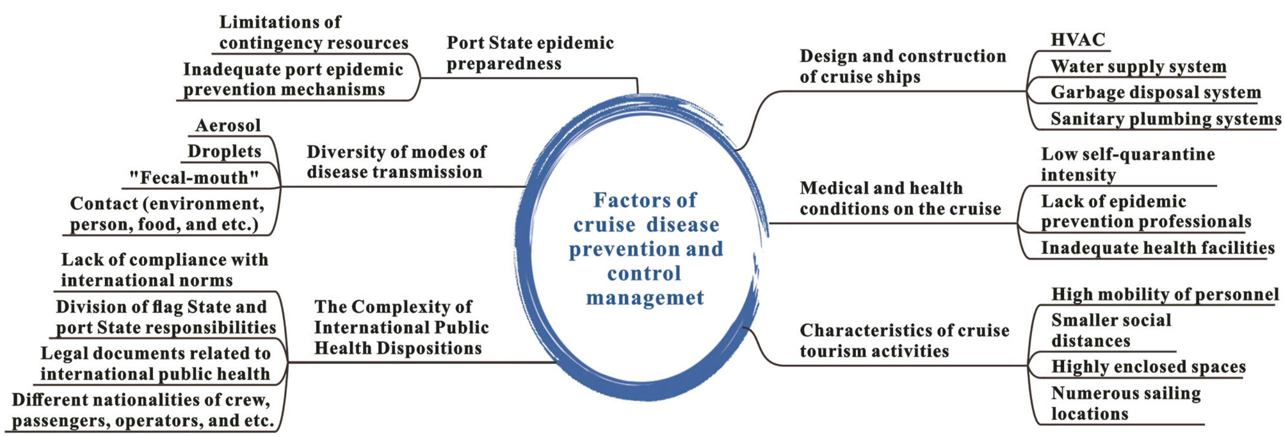


Fig. 9. Factors of cruise diseases prevention and control management.

outbreak of COVID-19 epidemic, scholars have gradually paid more attention to the field of cruise diseases, and the intensity of collaboration between authors and organizations is gradually increasing.

Cruise diseases research is mainly concerned with epidemiology, occupational health in the public environment, internal medicine, immunology and microbiology. The research area not only focuses on disease prevention and health protection, but also extends to other fields like ecology, architecture, sports, leisure tourism, etc.

From 1996–2019, the hot themes of cruise disease research are norovirus, respiratory diseases, Legionnaires' disease, and vaccine-preventable diseases, all of which involve epidemiology. The branch of research in norovirus on cruise ships is even richer. COVID-19 is currently a relatively active research topic. Passenger behavior is more striking in Fig. 7, but in the research hot spot, the focus is on the characteristics of the infected population rather than the passenger behavior during the disease outbreak. Injury and illness researches on polar cruises account for only 6% of the total, which may be related to the fact that there were fewer polar cruise itineraries in the past. There may be a link between the level of health-care facilities on cruise ships and the spread of disease. The transfer of people infected with diseases on cruise ships will affect the health protection of local communities. Furthermore, no other cruise ship disease has had such a huge impact on global health protection as COVID-19, which also requires the prevention of pandemics in international policies and regulations to be strengthened.

The diversity of disease transmission modes, the characteristics of cruise tourism activities and the complexity of dealing with international public health events increase the difficulty of managing disease prevention and control on cruise ships, placing higher demands on port state epidemic prevention capabilities, cruise ship design and construction and medical and health conditions.

To sum up, there are still some neglected but worthwhile research themes in cruise disease:

a) Researches on passenger behavior during cruise ship diseases outbreak.
b) Epidemiological researches of polar cruise.
c) Researches on the relationship between the level of medical facilities and staff training on cruise ships and disease transmission.

d) Researches on the relationship between cruise diseases and local community health protection.
e) Researches on the role of policies and regulations in cruise disease prevention.

In addition, from Table 1 and Fig. 7b, it can be seen that the hot keywords in the cruise research lack risk management. The research on cruise diseases is mainly focused on one disease, and lacks systematic research on disease risk management. On the basis of existing and available literature, in the discussion section, we put forward and summarize the influencing factors of cruise disease risk management and construct a risk management framework to provide reference for the sustainable development of cruise industry.

5.2. Recommendations

5.2.1. Timeline of the cruise disease risk management process

It is far from enough to rely solely on vaccine development to fight various infectious diseases [64]. There is an urgent need for a more effective "active prevention and control" approach to rapidly prevent and stop the spread of new infectious diseases and to keep the spread of such diseases to a minimum until they are eradicated [64].According to the "Research Report on Restart of Chinese Cruise Industry ", the risk of cruise disease can be summarized in the following three keys [17]: a) the risk of viruses boarding the ship; b) the risk of virus transmission on board the ship; c) the method to control the spread of the disease after contracting the virus. Given the uniqueness of international cruise ships and the characteristics of disease transmission, a systematic and comprehensive disease risk management framework for cruise ships should be established, with the timeline as the baseline, and a reasonable cruise ship disease risk management process can be formed (Fig. 10).

Before arriving at the port, the destination, cruise passengers and crew are subjected to an epidemiological investigation. Cruise lines should deny boarding to people with questionable survey results and change questionable destinations to intercept the source of infection and prevent the spread of the virus in a timely manner.

After arriving at the port, the port department should conduct a health screening on the personnel, and only healthy personnel can board the ship. The disinfection of baggage requires an independent dynamic operation line to avoid cross-infection.

During normal sailing, cruise passengers and crew need to conduct real-time health tests. Once a disease infection event occurs, the staff should immediately check the epidemic, determine the source of the infection, conduct zoning isolation, and report the situation to the superior or the next port. When returning to the port, the cruise line and port authorities should make use of the ship-port synergy to effectively organize the disembarkation of people in groups.

5.2.2. Risk management framework

The "Community Capacity" component of Health Emergencies and Disaster Risk Management (Health-EDRM), developed by the World Health Organization, emphasizes the importance of local participation in addressing health risks in emergencies [65]. Cruise ships, known as "marine mobile community", are more prone to mass outbreaks of disease than communities on land [66], so it is important to establish a "maritime mobile community prevention and control system" (Fig. 11).

Firstly, cruise lines can add a central disease command center on board, which is designed to respond quickly to large-scale outbreaks and act as a nerve center to mobilize resources and coordinate personnel. Secondly, we continue to deepen our cooperation with governmental and non-governmental organizations to promote the application of science and technology in cruise disease risk management and to develop health regulations for cruise ships that are above international standards. For example, through cooperation with EcolocxTech, Norwegian Cruise Line has enabled its 28 cruise ships to have a new disinfection technology- HOCl technology, which is safe and highly toxic. In cooperation with the world's leading medical experts and the US Centers for Disease Control and Prevention (CDC), strict health and safety cruise measures have been formulated for each cruise ship, with health regulations far exceeding national standards [67].

The influence of cruise design and construction on disease prevention and control management cannot be ignored. This has given rise to a new topic *how to design an "immune" ship*, the so-called prevention

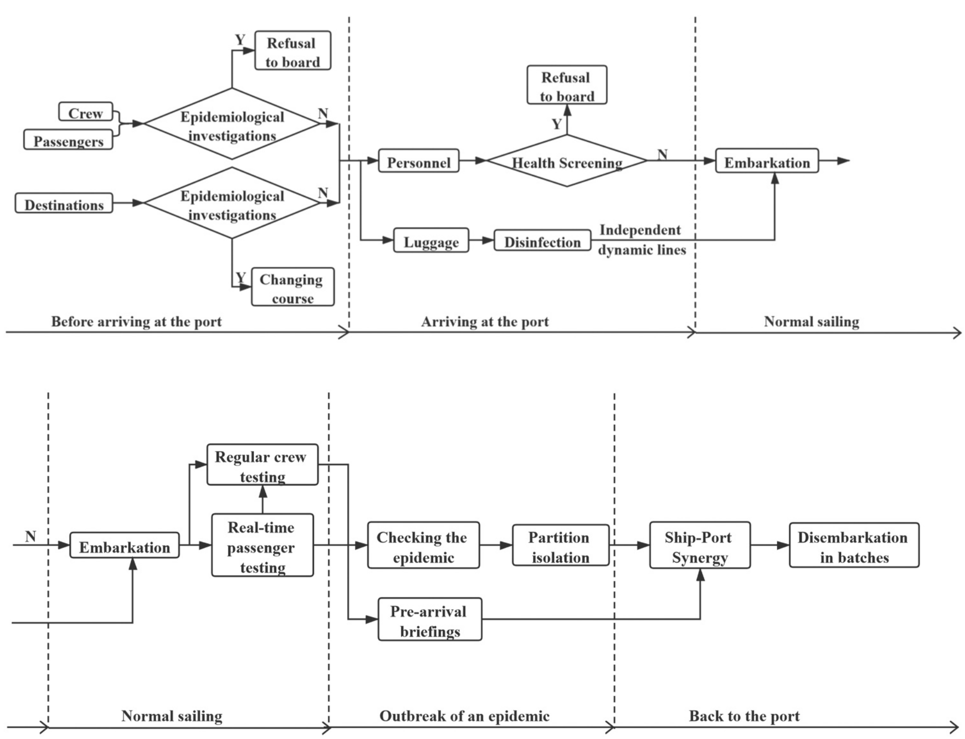


Fig. 10. The process of cruise ship disease risk management.

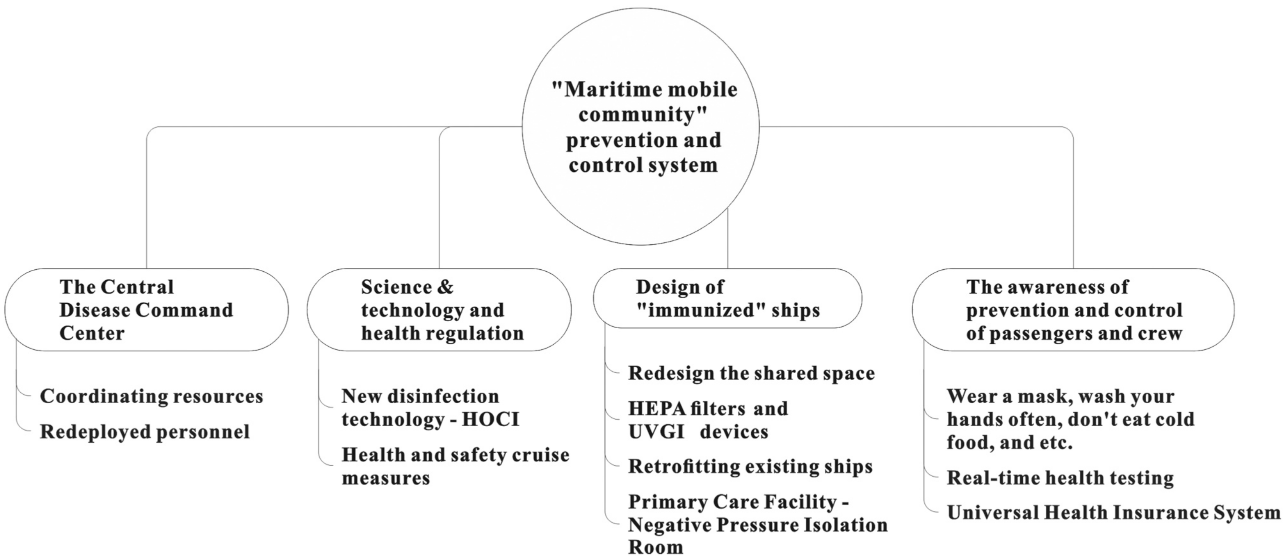


Fig. 11. Maritime mobile community prevention and control system.

through design (PtD). This paradigm is advocated by the National Institute of Occupational Safety and Health in the United States [68]. PtD technology can be applied in the process of vessel design, construction and modification [68]. The PtD method can be used to control the capacity of a cruise ship, thus allowing the implementation of a social distance criterion. Architects and engineers may consider redesigning shared spaces to accommodate fewer people and increase personal space. If the danger cannot be eliminated or replaced, engineering can be the preferred control method. For example, HVAC systems with both HEPA filters and ultraviolet germicidal (UVGI) devices should be the primary combined control measure, as well as increasing the airflow from the HVAC system to the dining rooms, where the risk of infection is higher, could also be an effective control measure [69]. Engineering controls such as these can be implemented at any stage of the ship construction, including retrofitting existing ships' water treatment systems, sanitary plumbing systems and waste disposal systems.

In view of the medical and health conditions of cruise ships, cruise lines need to devote themselves to the improvement of basic medical facilities. Cruise lines should pay more attention to medical services and links to cruise health websites [63]. In addition, the upgrading of medical facilities on cruise ships and the implementation of active telemedicine conferences are alternative methods of air evacuation that need to be studied [70]. In addition, every cruise ship should be equipped with medical isolation facilities. On 14 September 2020, a new Negative Pressure Isolation room was opened at the Tianjin Cruise Terminal in China, which is an important isolation medical facility for the prevention of serious outbreaks of infectious diseases by controlling the source of infection and cutting off the transmission route [71].

Raising public awareness of disease is necessary to control an ongoing epidemic [72]. This is also an important means to reduce the difficulty of cruise risk management due to the diversity of disease transmission methods. In addition to increasing the social distance of passengers, cruise disease command center should mobilize people to take self-reinforcing preventive measures, including washing hands frequently, wearing masks, avoiding cold and raw food, and repeated testing. In addition, Taiwan's national health insurance system played an important role in the epidemic [73]. Cruise lines and the governments of countries such as flag states, tourists and staff should implement a universal health insurance system.

It is important to establish a "maritime mobile community prevention and control system". Based on the research on cruise diseases by scholars from 1996 to 2019, combined with the influencing factors of cruise disease prevention and control, the risk management framework of cruise diseases is summarized as Fig. 12.

The big data analysis techniques, government initiatives, and collaborative governance model applied by Taiwan, China in response to the COVID-19 pandemic are used for reference [56,73]. Of course, it is particularly important for cruise disease risk management to reduce the complexity of dealing with international public health events. This requires the joint participation of multiple entities to form a long-term and effective cooperation mechanism, thus avoiding systemic failures in the understanding of the pandemic by the cruise industry management [74]. Major stakeholders in the cruise industry, including trade groups, industry leaders, infection control experts, and government and non-governmental organizations, can work together to develop a broader contingency plan to ensure effective outbreak response on board and shore assistance at ports [68]. For example, all parties actively cooperate with mask manufacturers to ensure the supply and distribution of masks [73].

For the port epidemic prevention department, it is necessary to fully study the main risks of various infectious diseases on international cruise ships, find out the key points of risk control, and establish a systematic and complete international cruise epidemic prevention and control system [2]. In practice, the functions of multi-departmental joint prevention and control should also be brought into play, and large-scale personnel transfer and rescue exercises should be designed to improve the port's crisis management capabilities. Port authorities should do a good job in "zero infection" of employees and disinfection of luggage/materials by implementing border control and isolation measures, carrying out all-round and multi-means detection measures for tourists, isolating infected tourists and transfer them to hospitals for treatment in time. At the same time, port state governments could establish "temporary cabin hospitals" in ports where cruise ships stop or nearby islands to deal with mass disease outbreaks and to avoid problem of insufficient resources [2].

It is widely accepted that both "transparency" and "authority" are necessary in the battle against COVID-19 [73]. Big data analysis allows not only the tracking of disease transmission routes and close contact surveys, but also epidemiological investigations of people and destinations [64]. Cruise lines should work to form cooperative mechanisms with governmental and non-governmental organizations in various countries on disease prevention and control, and to form a team of senior experts in data analysis, medical practice and research, public health, infectious diseases, biosecurity, and maritime operations, among others, to build a cruise health line data platform to monitor travelers' whereabouts and health in real time. A health code or electronic health card is

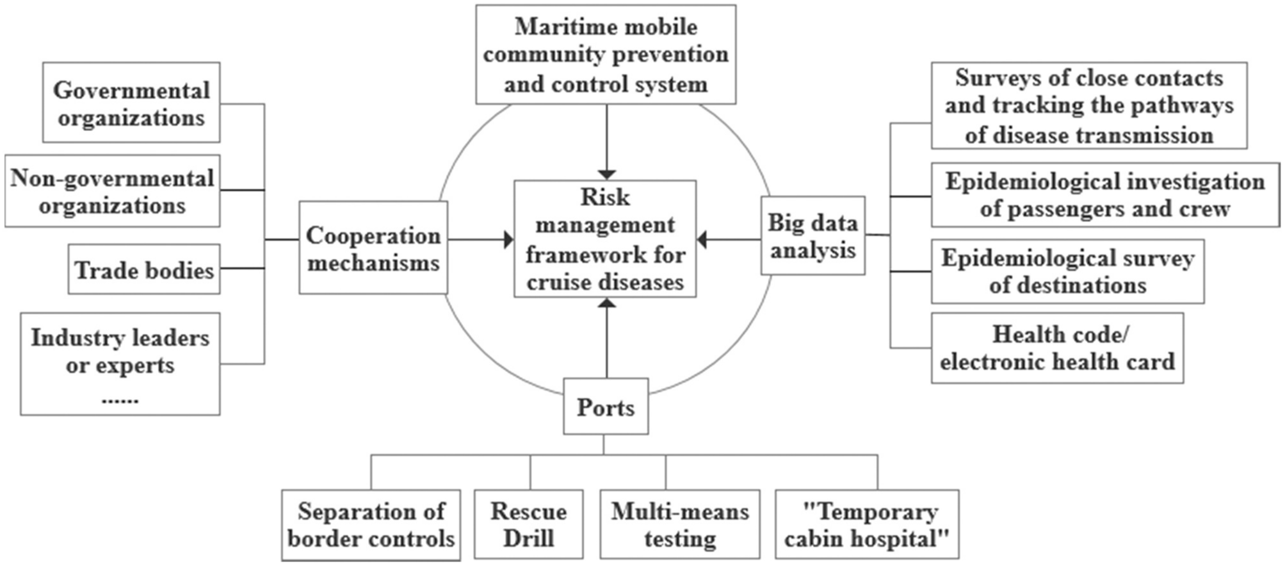


Fig. 12. Risk management framework for cruise diseases.

formed through a big data platform, making the system a tool to help track citizens' health status and whereabouts [73].

Conflict of Interest

The authors declare that they have no conflict of interest.

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Solution for the Problem of Sustainable Staff Scheduling in Semi-Automated Dock Container Terminals in Ports

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Abstract

Port operations in container terminals are as important as container transportation itself. A port has a complex system in which a wide variety of operations take place, and a wide variety of resources are required to interact with each other. The aim of a port operator is to complete the service required in the shortest time and in the most efficient way. The quayside of the port, the equipment used such as cranes and field vehicles, and the operations officer and personnel are factors that directly affect the service provided at a port. The port management aims to maximize efficiency by reaching the maximum number of movements with the least possible cost. Increasing the efficiency and quality of the working personnel is extremely important in achieving this aim. This study provides efficient, fair, and balanced scheduling of field personnel and shift supervisors working in port operations using a real-life case of the semi-automated docks at an international port. A goal-programing model is constructed to manage the workforce needed by the port for a one-week working period and to assign the shift supervisors to the shifts in a balanced way. The personnel's preferences and qualifications, which directly affect productivity, are also considered while planning. Results show an increase in productivity, quality of life, concentration, and employee job satisfaction. The results of the suggested mathematical model in the study show that the demands of the workers facing conflicting constraints were met with the least deviation from goals.

Keywords

freight systems, intermodal freight transport, optimization, planning and logistics, model/modeling, marine, ports and channels, optimization

In recent years, intercontinental commercial activities have increased as the world economy embraces greater globalization. This development, in the context of worldwide pandemics and conflicts, makes transportation and logistics activities more important than ever. The technological and economic advantages of sea freight have steadily increased its share of the transportation sector (*1*). Moreover, container transportation is seen as a key factor in the development of countries and the globalization of the international economy (*2*). All these bring out the importance of ports.

Francisco et al. (*3*) defined the port system over six entities in 1984: cargo, ships, docks and piers, storage areas, ground transportation, and handling equipment (*4*). Handling equipment has different functions and is examined in two main groups: field and quay equipment. An empty container handler (ECH), a form of field equipment, can only stack empty containers. Container reach stackers (CRSs) and rubber tired gantry cranes (RTGs) are field equipment that can stack both empty and full containers. This two pieces of equipment are responsible for transferring containers inside the stacker and between the terminal vehicle and the stacker. The field vehicle, called a yard terminal tractor (YTT), carries containers in the field. A ship-to-shore gantry crane/dock crane (STS) is a piece of dock equipment. It loads from

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the pier on to the ship and discharges from the ship to the pier. A mobile harbor crane (MHC) is a crane-shaped and freely movable piece of berth equipment. It works the same as an STS. But, since it is movable, its usage area is wider.

There are operators using each of the above-mentioned pieces of equipment at container terminals. The records of the movements made by the equipment are processed on hand terminals by the officers known as “pointers.” Pointers are divided into field and ship pointers. There is one shift supervisor for every shift at a port. A field shift supervisor, ship shift supervisor, and an equipment shift supervisor are also required for every shift.

Let us now summarize the tasks when there is a cargo ship to be worked on. An operator is required for each piece of equipment and a pointer is required for each crane (MHC or STS) working on the ship. In the field, at least one pointer should be assigned according to the intensity of the work. The number of pointers working in the field may vary according to the structure of the field, workload, and operational conditions. In addition, during the unloading and loading movements, there is one rudder for each crane and two shoes on the ship. A cox gives commands to the crane operator and guides them in those places that the operator cannot see. The shoemaker, on the other hand, is responsible for the disassembly and assembly of container shoe mechanisms. To speed up the operations, two people are assigned to the right and left heads of the container. In order not to disrupt the operations, an appropriate number of CRSs and RTGs should be used for each MHC or STS. YTTs should feed these vehicles. Generally, two CRSs or RTGs are required for one MHC or STS in semi-automated container terminals. For the efficiency of the CRSs and RTGs, five YTTs are considered sufficient. Thus, each STS can perform 25 movements per hour, while each MHC can perform 15 movements per hour, ensuring efficient capacity usage.

Assigning the field personnel to their duties in the most appropriate way in container terminals can increase efficiency, reduce costs, and increase profitability. For this reason, this study considers the problem of scheduling port personnel in the most appropriate way to achieve the highest efficiency with the lowest cost, and in line with the seven port performance indicators published by UNCTAD. The port performance indicators were initially evaluated by experts experienced in the sector and weighted using an analytical hierarchy process (AHP). The AHP method was used in the paper. There were some interactions between criteria. Because of the need to use the AHP technique, a hierarchical structure was established between the criteria. It is thought that there is no network structure among the criteria whose weights will be evaluated. AHP, which is a more general form of analytical network process (ANP), was thought to be more suitable for this evaluation (*5*). Assignments were scheduled according to the abilities of the personnel. In scheduling studies, sustainability is called “schedulability.” Any task system is determined to be schedulable and remains so if it behaves “better” than mandated by its system specifications (*6*). Sustainability is formally defined in the literature and the concept has been subjected to systematic analysis in the context of uniprocessor scheduling of periodic and sporadic task systems (*6*). We can, therefore, call our study a sustainable personnel scheduling study. This study can be adapted to other problems with minor constraints and boundary changes in the model. As we mentioned when defining the phrase “sustainable,” having a “schedulable” structure can again be considered a reflection of the sustainability of our model. The lack of any previous study on the problem of scheduling the personnel working in container terminals will make this study different from others.

Semi-Automation Container Terminals

Container ports have field and quay equipment to handle full and empty containers. There are several factors that affect the amount of equipment for an operation. These are the:

- size of the ship;
- operational distribution of the ship in the warehouse;
- workload of the port;
- number of pieces of equipment;
- physical structure of the field and so forth.

Operators who work on the equipment first go through the orientation by learning the process at a YTT. When operators first come to the field, their initial involvement in the operations is handling empty containers. After gaining two years’ experience in ECHs, they can switch to CRSs to handle full equipment. During the time they work on CRSs, they also receive RTG training and take the professional competency exam. If successful, they receive the Level 3 port RTG operator certificate allowing them to operate RTGs. While 450 h are sufficient for in-port training in many ports, there is a professional qualification certificate requirement for external applications. The competencies in this section were introduced as personnel assignment competencies and were included in the model. In addition, an assignment model has been developed that takes these capabilities into account.

It is seen that working with maximum efficiency and minimum downtime in container ports is both commercially important and key to running a competitive business. Transporting, storing, handling, and maintaining ship operations in the terminal are the most important steps in the processes in ports.

Staff Scheduling in Container Terminals

Providing the most efficient service in the shortest time at container terminals around the world is of great importance for customers. Although the performance of ports depends very much on the equipment, it is also affected by the performance of the personnel. This is because the assignment of the personnel working on each piece of equipment to the relevant job in the most efficient way is the most important factor determining the efficiency of the process. Management involves many decision-making mechanisms and thus requires a decision support process. Since each individual will be evaluated as a separate system, different decisions made by supervisors working in different shifts may adversely affect standardization. For this reason, the problem to be addressed within the scope of this study is the fair and standard assignment of the work to the field personnel during the port operation process. Waiting times of ships at anchor will thus be reduced, the evacuation and loading planning will be done quickly, the time during which the ship occupies the port will be shortened, and the personnel will be used with maximum efficiency.

Disruptions that may occur in operational processes at container terminals will affect all supply chain stakeholders. For example, the lower efficiency of the unloading/loading equipment will lead to the prolongation of the overall operational process. This will cause the prolongation of the ship's stay at the port, which in turn becomes a financial cost for the carrier, causing the customers to receive their cargo late and generating a series of other costs and delays in the whole supply process. With disruption minimized, on the other hand, ships approaching the port will be able to complete their operations more quickly and leave the port on time. The port operators will then be able to prepare more quickly for the next operation.

According to Fancello et al. (*7*), ports have a complex system in which a wide variety of operations take place, using various resources. Port operators aim to maximize efficiency by performing the maximum number of movements at the lowest possible cost. To achieve this, studies to increase the efficiency and quality of the personnel working in the process are very important (*8*).

In its report titled "Port Performance Indicators" UNCTAD (*9*) recommended port performance indicators which were shown as reference points for the industry in 1976. These indicators were analyzed under seven different criteria:

- dock efficiency;
- crane efficiency;
- ship efficiency;
- terminal site efficiency;
- labor productivity;
- equipment efficiency; and
- cost effectiveness.

These criteria are interconnected, especially the labor productivity of the personnel. For this reason, it is to be expected that productivity will increase with the correct personnel scheduling in the planning process.

In periods when personnel scheduling problems arose, while only the required number of workers were assigned, it became important to meet the demands of the personnel and to effect satisfactory scheduling over time. While the requests of the personnel were originally of lesser importance, their degree of importance has now increased considerably. On the other hand, there is no stereotypical personnel scheduling model that is generally used in the literature (*10*).

Operations planning (CFS/Container). Since the planning of the operation process for each ship is determined after the receipt of the ship's berthing plan, the equipment distribution per ship is made according to the number of unloadings and loadings, the position of the cargo in the ship's hold, and the distribution in the field. In addition, the average number of movements that each piece of equipment can make per hour is fixed and assignments to ships are made accordingly. For example, an STS operating in a semi-automated container terminal can make 25 movements per hour when operating at average efficiency, while an MHC operating in the same port can make 15 movements per hour. In a fully automated terminal, an STS of average efficiency can make 30 movements per hour, while an MHC located in the same port can make 22 movements per hour. For this reason, when scheduling personnel, the working capacity of the equipment is taken as the basis rather than the working performance of the operators. The aim is thus to achieve the highest efficiency at the lowest cost according to the number of movements to be made.

Literature Review

When the literature is examined, it is possible to find many studies on personnel scheduling. This is because personnel scheduling problems can be handled by using different models and different personnel types wherever there are personnel. There are examples of personnel scheduling in various sectors such as health care, management, and logistics. Work done on personnel scheduling is summarized below.

Bard et al. (*11*) presented a full-scale model of the tour scheduling problem posed by the United States Postal Service and examined various scenarios aimed at reducing the size of the workforce. The problem is formulated as a pure integer linear program and solved with CPLEX. Gordon and Erkut (*12*) worked on organizing the planning process to save time for the volunteer staff at the Annual Edmonton Folk Music Festival and to meet the preferences of the volunteers as much as possible. Topaloğlu and Özkarahan (*13*) proposed a mathematical model taking into account the preferences of the employees. In the proposed model, they aimed to determine the balanced assignment of employees to shifts, break times, and working days. Legato and Monaco (*14*) discussed the manpower planning that emerged in a container terminal in their study. The study showed that the specific manpower planning problem in a container terminal can be divided into short-term and long-term planning and can thus be modeled and solved efficiently with heuristic procedures and mathematical programming techniques.

Dell'Olmo and Lulli (*15*) modeled a terminal using a network of complex platforms, each of which has an engineering and operational capability. The problem with their study was a kind of generalized timing across platforms. The study produced a maximum deviation of 6.3%. The quality of the results obtained supports the applicability of the proposed model. Ernst et al. (*16*) conducted a review of staff scheduling and listing.

Azaiez and Al Sharif (*17*) created a model to address the scheduling of nurses. In this model, limitations were determined within the framework of the nurses' requests and suggestions, and within the working rules of the hospital. Topaloğlu (*18*) presented a goal-programming model using both loose and tight constraints over a one-month planning period. He applied the model thus created in the emergency department of a large local hospital. Chu (*19*) worked on workforce scheduling problems. He developed the model he created for the staff working at Hong Kong International Airport. Sammarra et al. (*20*) proposed a Tabu search heuristic for scheduling dock cranes. In their paper, they proved that this scheduling can be viewed as a vehicle routing problem, which can be separated into routing and scheduling problems.

Sungur (*21*) presented a model to meet the required amount of labor force in a beauty salon at minimum cost. Jenal et al. (*22*) studied nurse scheduling using goal programming. Fancello et al. (*7*) applied a prediction model and an optimization model in their study on a port operator. With the artificial neural network-based model, the uncertainty interval of the arrival times of the ships at the port has been reduced. So, in practice, it has only been possible to achieve an approximate increase in the accuracy of the demand forecast with the precision of the planning resources (sentence will be transposed). According to the results obtained from the study, the two properly reviewed integrated models can be used as a useful planning support tool.

Bağ et al. (*23*) focused on nurse scheduling in their study. They used the 0 to 1 goal-programming method to solve the problem. Hung-Tso et al. (*24*) worked on team scheduling. Li et al. (*25*) presented a hybrid approach of goal programming and a metaheuristic search for personnel planning in their study. Atmaca et al. (*26*) focused on nurse scheduling in a hospital. Louly (*27*) created a monthly work plan for engineers in their study.

Bektur and Hasgül (*28*) made a work plan for some staff serving in a restaurant. Agyei et al. (*29*) proposed a mathematical model for nurses working in a hospital in Ghana. Sulak and Bayhan (*30*) studied nurse scheduling in their study. Hidri and Labidi (*31*) developed a model for assigning physicians to shifts by dividing doctors into six teams in three designated departments in the intensive care unit of a hospital.

Labidi et al. (*32*) focused on the problem of scheduling a Bank's information technology personnel. The problem was formulated with the multi-objective programming model. Özder et al. (*10*) discussed the scheduling problem of cleaning personnel in the public sector. *They used ILOG CPLEX studio IDE Optimization program for finding the solution of the established mathematical problem.*

Yelek et al. (*33*) studied shift scheduling for students working part-time in a library. They used the ILOG CPLEX Optimization program to model the problem.

Koçtepe et al. (*34*) focused on the scheduling of personnel assigned in a basketball game. They set up a 0 to 1 integer model to solve the problem. Özder et al. (*35*) conducted a literature search on personnel scheduling.

Cürebal and Eren (*36*) developed a decision support mechanism proposal for the assignment of security personnel working in a hospital and the problem of shift scheduling. In their studies, they used the AHP TOPSIS method in the evaluation of the competency scores and the goal-programming method for the assignments.

Method

Goal programming (GP) and analytic hierarchy process (AHP) methods are used in this paper. Multi-criteria decision-making methods are very popular in scheduling studies (*35*). The necessary explanation about why these methods are used will be detailed in this section.

The first studies on personnel scheduling were generally on cabin operator scheduling. In general, the first such studies were in 1950 by Edie (*37*) and Dantzig (*38*). Dantzig organized the scheduling for vehicle cabin operators and used linear programming as a solution. In his study, he wanted to minimize the cost, provided that the amount of labor required is as much or more than it should be. Although a clear mathematical method is not used, attempts have been made to reduce costs by balancing the workforce. The GP method is also frequently used in scheduling studies (*35*).

In GP, each goal constraint is transformed into a goal, and it is ensured that the goals are achieved to minimize the deviations from these goals. GP was first introduced in 1955 by Charnes et al. (*39*). Later, Charnes and Cooper (*40*) did another study on GP in 1961. GP was developed with the work of Lee (*41*). This method is the most widely used method among multi-criteria decision-making methods.

The mathematical representation (*42*) of GP is as follows:

$$Minimize\ Z = \sum_{i=1}^{k} (d_i^+ + d_i^-)$$

$$\sum_{j=1}^{n} a_{ij}x_j - d_i^+ + d_i^- = b_i \qquad \forall\ i$$

$$d_i^+ \times d_i^- = 0 \qquad \forall\ i$$

$$x_j,\ d_i^+, d_i^- \geqslant 0 \mathrm{i} = 1...\mathrm{k}; \mathrm{j} = 1...\mathrm{n}$$

where
x_j = jth decision variable,
d_i^+ = positive bias variable of the ith goal,
d_i^- = negative bias variable of the ith goal,
Parameters a_{ij} and b_i are the decision-variable coefficient and the goal's desired value, respectively.

The AHP was first proposed by Myers and Alpert (*43*) and was developed as a model by Saaty (*44*) and made available to solve decision-making problems (*5*). AHP can be explained as a decision-making and estimation method which gives the percentage distributions of the decision points for the factors affecting the decision when the decision hierarchy can be defined.

AHP is based on one-on-one comparisons on a decision hierarchy, using a predefined comparison scale, both for the factors affecting the decision and the significance of the decision points for these factors. As a result, the differences in importance are transformed into a percentage distribution on the decision points (*45*).

Application

Although the shifts of the workers in the ports are determined on a monthly basis, the ship operation planning process is generally handled on a weekly basis. The reason for this is that although the berthing plan of the ships is determined weeks in advance, it can be easily affected by weather conditions, disruption of the previous port operation process, or technical disruptions meaning that the plans may vary. For this reason, the weekly expected ship plan is usually taken as a basis for the planning of the operational process.

The scheduling problem was modeled and solved based on a real-life case: an international port in Turkey with semi-automated container terminals, a port area of 1,000,000 m^2, eight docks, a container pier 920-m long with a capacity of 1,000,000 TEU/year. There are two MHCs, four STSs, four CRSs, and three ECHs in this terminal area. There are 102 operators, 50 pointers, four supervisors, two chiefs, three shift workers, and four shift specialists working in the port. During 2021, a minimum of 40 and a maximum of 53 ships docked at the port on a monthly basis, and the average monthly number of ships was 47.25.

In this context, while the operation was completed in 10 h 30 min and three posts using three STSs in a ship operation with 600 movements, an operation of 1,040 movements was completed in 14 h 54 min and four posts with four STSs. When only MHCs were used, an operation of 291 movements could be completed in 17 h 40 min and two posts.

When STS and MHC are used together, an operation of 705 movements was completed in 13 h 40 min and two posts. There were three supervisors and one field pointer fixed in each 8-h shift, while 12 personnel were working in total (with field equipment) per crane working at each post. In the light of the information mentioned in this section, the requirement to provide the number of personnel required to be appointed in relation to the rate of use of tools and equipment has been added to the model with constraints.

The application part of our paper can be examined in two parts. In the first part of the application, experience weights were calculated for each employee with the AHP method. The weight score of each individual as a result of this calculation is given in Table 1. Each score given in Table 1 is the result of the evaluation of each worker by the experts at the port. These scores have emerged as a result of the evaluation of experience. It includes the scores of each employee obtained from the data in the performance evaluation and management database in the port personnel management system and obtained as a result of a study evaluated by the human resources specialists in the port. Points were created for each person between 0 and 100.

The AHP method was created from the scores obtained by evaluating more than 30 criteria of each individual. Calculations and pairwise comparisons of criteria were obtained by consulting experts. In the second part of the application, the weights obtained by the AHP method in the first part were used in the GP method and an attempted was made to obtain a fair table.

Our mathematical model can be defined as follows:

Table 1. Experience Scores of Each Personnel (From 0 to 100).

P.N.	Score	P.N.	Score	P.N.	Score	P.N.	Score	P.N.	Score	P.N.	Score
1	68	31	90	61	71	91	94	121	89	151	70
2	32	32	90	62	47	92	49	122	88	152	59
3	71	33	89	63	65	93	62	123	94	153	94
4	47	34	91	64	55	94	63	124	49	154	49
5	65	35	79	65	53	95	66	125	62	155	88
6	55	36	77	66	58	96	73	126	63	156	98
7	53	37	76	67	67	97	88	127	66	157	75
8	58	38	48	68	82	98	77	128	87	158	73
9	67	39	59	69	71	99	71	129	86	159	83
10	82	40	89	70	69	100	47	130	73	160	94
11	71	41	98	71	94	101	65	131	69	161	49
12	69	42	53	72	49	102	55	132	96	162	62
13	72	43	23	73	62	103	53	133	99	163	63
14	70	44	22	74	63	104	58	134	65	164	66
15	59	45	95	75	66	105	67	135	95	165	77
16	94	46	48	76	75	106	82	136	76		
17	49	47	49	77	78	107	71	137	94		
18	62	48	69	78	82	108	69	138	49		
19	63	49	65	79	41	109	70	139	62		
20	66	50	92	80	89	110	59	140	63		
21	75	51	85	81	78	111	94	141	66		
22	57	52	85	82	79	112	49	142	55		
23	88	53	76	83	66	113	63	143	50		
24	61	54	77	84	65	114	66	144	46		
25	66	55	74	85	54	115	75	145	40		
26	63	56	56	86	39	116	78	146	37		
27	62	57	59	87	49	117	66	147	34		
28	59	58	63	88	55	118	77	148	29		
29	89	59	66	89	69	119	85	149	25		
30	92	60	63	90	58	120	85	150	89		

Note: P.N. = personnel number; Score = experience score of each personnel calculated by experts.

Parameters:

n: Personnel $n = 165$

m: Days $m = 30$

l: Shifts $l = 3$

i: Personnel index $i = 1,2, ..., n.$

j: Day index $j = 1,2, ..., m.$

k: Shift index $k = 1,2, ..., l.$

w_i: Experience weight received by each staff member $i = 1, 2, ..., n.$

Decision Variables:

$$\boldsymbol{X_{ijk}} = \begin{cases} 1, & \textit{If personnel i is assigned to day j on shift k} \\ 0, & \textit{otherwise} \end{cases}$$

$$\boldsymbol{h_{ij}} = \begin{cases} 1, & \textit{If the personnel i is on day}-\textit{off in day j} \\ 0, & \textit{otherwise} \end{cases}$$

Constraints:

1. Constraint: The daily personnel needs should be met:

Number of staff needed for the morning shift

$$\sum_{i=1}^{n} w_i \times X_{ij1} \geqslant 64 \qquad j = 1, 2, ..., m. \tag{1}$$

Number of staff needed for the evening shift

$$\sum_{i=1}^{n} w_i \times X_{ij2} \geqslant 64 \qquad j = 1, 2, ..., m. \tag{2}$$

Number of personnel needed for the night shift

$$\sum_{i=1}^{n} w_i \times X_{ij3} \geqslant 44 \qquad j = 1, 2, ..., m. \tag{3}$$

2. Constraint: Each staff member should be assigned to only one shift per day:

$$\sum_{k=1}^{l} X_{ijk} \leqslant 1 i = 1, 2, ..., n. \;\; j = 1, 2, ..., m. \tag{4}$$

3. Constraint: Each staff member do not work on the day off:

$$\sum_{k=1}^{l} X_{ijk} \leqslant (1-h_{ij}) \quad i=1,2,...,n. \; j=1,2,...,m. \quad (5)$$

4. Constraint: Each staff member should not work more than five consecutive days:

$$h_{ij} + h_{i(j+1)} + h_{i(j+2)} + h_{i(j+3)} + h_{i(j+4)} + h_{i(j+5)} \geqslant 1 \quad i=1,2,...,n. \quad j=1,2,...,m\text{-}5. \quad (6)$$

5. Constraint: Determination of the maximum number of shifts that each staff member should work during the planning period:

$$\sum_{j=1}^{m} X_{ij1} \leqslant 8 \quad i=1,2,...,n. \quad (7)$$

$$\sum_{j=1}^{m} X_{ij2} \leqslant 8 \quad i=1,2,...,n. \quad (8)$$

$$\sum_{j=1}^{m} X_{ij3} \leqslant 8 \quad i=1,2,...,n. \quad (9)$$

6. Constraint: Determination of the minimum number of shifts that each staff member should work during the planning period:

$$\sum_{j=1}^{m} X_{ij1} \geqslant 7 \quad i=1,2,...,n. \quad (10)$$

$$\sum_{j=1}^{m} X_{ij2} \geqslant 7 \quad i=1,2,...,n. \quad (11)$$

$$\sum_{j=1}^{m} X_{ij3} \geqslant 5 \quad i=1,2,...,n. \quad (12)$$

7. Constraint: It is about not to be assigned to the morning and evening shifts of the next day:

$$X_{ij3} + X_{i(j+1)1} + X_{i(j+1)2} \leqslant 1 \quad i=1,2,...,n. \; j=1,2,...,m. \quad (13)$$

8. Constraint is not to be assigned to the morning shift of the next day:

$$X_{ij2} + X_{i(j+1)1} \leqslant 1 \quad i=1,2,...,n. \; j=1,2,...,m. \quad (14)$$

Goal Constraints:

Goal 1: Constraint written to minimize the assignment of the personnel as days off, working days, days off when assigning them to shifts:

$$h_{ij} + X_{i(j+1)1} + X_{i(j+1)2} + X_{i(j+1)3} + h_{i(j+2)} + a_{ij}^{-} - a_{ij}^{+} = 2 \quad i=1,2,...,n \quad j=1,2,...,m\text{-}2. \quad (15)$$

Goal 2: The goal constraint written to minimize the assignment of personnel as working days, days off, working days when assigning them to shifts:

$$X_{ij1} + X_{ij2} + X_{ij3} + h_{i(j+1)} + X_{i(j+2)1} + X_{i(j+2)2} + X_{i(j+2)3} + b_{ij}^{-} - b_{ij}^{+} = 2 \quad i=1,2,...,n \quad j=1,2,...,m\text{-}2. \quad (16)$$

Goal 3: Constraint written to ensure that the total number of shifts to which each staff member is assigned during the planning period is as equal as possible:

$$\sum_{j=1}^{m} (X_{ij1} + X_{ij2} + X_{ij3}) + c_{ij}^{-} - c_{ij}^{+} \leqslant 22 \quad i=1,2,...,m. \quad (17)$$

$$\sum_{j=1}^{m} (X_{ij1} + X_{ij2} + X_{ij3}) + d_{ij}^{-} - d_{ij}^{+} \geqslant 23 \quad i=1,2,...,m. \quad (18)$$

Goal 4: Among the personnel assigned to the daily morning shift during the planning period, the constraint aiming to assign the operators with a lot of experience and those with less experience to the same shift as much as possible:

$$\sum_{i=1}^{m} (w_i \times X_{ij1}) + e_j^{-} = 8 \quad j=1,2,...,m. \quad (19)$$

Goal 5: Among the personnel assigned to the daily evening shift during the planning period, the constraint aiming to assign the operators with a lot of experience and those with less experience to the same shift as much as possible:

$$\sum_{i=1}^{m} (w_i \times X_{ij2}) + f_j^{-} = 8 \quad j=1,2,...,m. \quad (20)$$

Objective Function:

$$\mathit{Minimize}\ Z = \sum_{i=1}^{n}\sum_{j=1}^{m}\left(a_{ij}^{-} - a_{ij}^{+}\right) + \left(b_{ij}^{-} - b_{ij}^{+}\right) + (c_{ij}^{-} - c_{ij}^{+}) + \left(d_{ij}^{-} - d_{ij}^{+}\right) + \sum_{j=1}^{m} e_j^{-} + f_j^{-} \quad (21)$$

Shift-based personnel assignment is shown in Table 2. Solving the model is achieved with the following computer features: processor “Intel (R) Core (TM) 1165G7 @ 2.80 GHz 1.69 GHz,” 16 GB of memory, and Windows 11 operating system. The proposed model is written in the ILOG CPLEX Optimization Studio 20.1 version program and the model was solved in 7.44 s. IBM ILOG CPLEX Optimization Studio is a prescriptive analytics solution that enables rapid development and deployment of decision optimization models using mathematical and constraint programming. This program combines high-performance CPLEX and CP Optimizer solution tools with a complete development environment that supports Optimization Programming Language (*46*). Table 2 shows the total number of assignments of each staff member to each shift over a one-month period. (For example, the 90th staff member

Table 2. Total Workloads of Each Person in a Month Based on Shifts.

P.N.	S1	S2	S3	T	P.N.	S1	S2	S3	T	P.N.	S1	S2	S3	T	P.N.	S1	S2	S3	T
1	7	8	8	23	43	7	7	8	22	85	7	8	8	23	127	7	7	8	22
2	8	8	7	23	44	8	7	7	22	86	8	8	7	23	128	8	7	7	22
3	7	7	8	22	45	7	8	8	23	87	7	7	8	22	129	7	8	8	23
4	8	7	7	22	46	8	8	7	23	88	8	7	7	22	130	8	8	7	23
5	7	8	8	23	47	7	7	8	22	89	7	8	8	23	131	7	7	8	22
6	8	8	7	23	48	8	7	7	22	90	8	8	7	23	132	7	8	8	23
7	7	7	8	22	49	7	8	8	23	91	7	7	8	22	133	8	8	7	23
8	8	7	7	22	50	8	8	7	23	92	7	8	8	23	134	7	7	8	22
9	7	8	8	23	51	7	7	8	22	93	8	8	7	23	135	8	7	7	22
10	8	8	7	23	52	8	7	7	22	94	7	7	8	22	136	7	8	8	23
11	7	7	8	22	53	7	8	8	23	95	8	7	7	22	137	8	8	7	23
12	8	7	7	22	54	8	8	7	23	96	7	8	8	23	138	7	7	8	22
13	7	8	8	23	55	7	7	8	22	97	8	8	7	23	139	8	7	7	22
14	8	8	7	23	56	8	7	7	22	98	7	7	8	22	140	7	8	8	23
15	7	7	8	22	57	7	8	8	23	99	8	7	7	22	141	8	8	7	23
16	8	7	7	22	58	8	8	7	23	100	7	8	8	23	142	7	7	8	22
17	7	8	8	23	59	7	7	8	22	101	8	8	7	23	143	7	8	8	23
18	8	8	7	23	60	8	7	7	22	102	7	7	8	22	144	8	8	7	23
19	7	7	8	22	61	7	8	8	23	103	7	8	8	23	145	7	7	8	22
20	8	7	7	22	62	8	8	7	23	104	8	8	7	23	146	8	7	7	22
21	7	8	8	23	63	7	7	8	22	105	7	7	8	22	147	7	8	8	23
22	8	8	7	23	64	8	7	7	22	106	8	7	7	22	148	8	8	7	23
23	7	7	8	22	65	7	8	8	23	107	7	8	8	23	149	7	7	8	22
24	8	7	7	22	66	8	8	7	23	108	8	8	7	23	150	8	7	7	22
25	7	8	8	23	67	7	7	8	22	109	7	7	8	22	151	7	8	8	23
26	8	8	7	23	68	8	7	7	22	110	8	7	7	22	152	8	8	7	23
27	7	7	8	22	69	7	8	8	23	111	7	8	8	23	153	7	7	8	22
28	8	7	7	22	70	8	8	7	23	112	8	8	7	23	154	7	7	8	22
29	7	8	8	23	71	7	7	8	22	113	7	7	8	22	155	8	7	7	22
30	8	8	7	23	72	8	7	7	22	114	7	7	8	22	156	7	7	8	22
31	7	7	8	22	73	7	8	8	23	115	8	7	7	22	157	8	7	7	22
32	8	7	7	22	74	8	8	7	23	116	7	7	8	22	158	7	7	8	22
33	7	8	8	23	75	7	7	8	22	117	8	7	7	22	159	8	7	7	22
34	8	8	7	23	76	8	7	7	22	118	7	7	8	22	160	7	8	8	23
35	7	7	8	22	77	7	8	8	23	119	8	7	7	22	161	7	8	8	23
36	8	7	7	22	78	8	8	7	23	120	7	8	8	23	162	7	7	8	22
37	7	8	8	23	79	7	7	8	22	121	7	8	8	23	163	8	7	7	22
38	8	8	7	23	80	8	7	7	22	122	8	8	7	23	164	7	8	8	23
39	7	7	8	22	81	7	8	8	23	123	7	7	8	22	165	7	8	8	23
40	8	7	7	22	82	8	8	7	23	124	8	7	7	22					
41	7	8	8	23	83	7	7	8	22	125	7	8	8	23					
42	8	8	7	23	84	8	7	7	22	126	8	8	7	23					

Note: S1 = Shift 1; S2 = Shift 2; S3 = Shift 3; P.N. = personnel number; T = total workload in a month.

has been assigned to the morning shift eight times, the noon shift eight times and the night shift seven times in a month.)

Looking at the results, it can be seen that each employee has an equal number of days off. In the obtained scheduling study, the personnel are in balance in the total number of days assigned. Given the large number of employees and the number of spaces that need to be present, the size of the problem makes it very difficult to perform scheduling manually. Moreover, the manual execution of this process poses a risk to the fairness of the distribution of work. When scheduling was done manually, it was determined that some of the employees (P5, P7, P19, P22, P44, P47, P56, P64, P69, P72, P83, P97, P103, P111, P139, P146, and P158) worked extra days and could not take their leave. This situation causes problems among employees. With these mathematical models used, both the time spent for the preparation of the charts were shortened, helping to obtain quality charts. In the mathematical model developed in the study, the requests of the employees were fulfilled as much as possible.

Given the large number of operators and the equipment necessary for the port operations, the sheer size of the problem makes manual scheduling very difficult. Moreover, the manual execution of the processes poses a risk to the fairness of the work distribution. With the proposed GP model, the preparation time of the personnel charts is shortened, and a fair and balanced scheduling of the personnel is achieved.

Conclusion and Discussion

This study examines a personnel scheduling problem at an international container port with real-life data based on the port's semi-automated container terminal operations over the last two years. The problem was modeled using GP which included balancing the monthly working hours of the employees, assigning the night shifts fairly, and most importantly assigning the experienced operators with the inexperienced ones to the same shift for the purpose of continuous training. The experience match was done using an AHP. ILOG CPLEX studio was used to code the model, and the best solution was reached with the CPLEX solver in the IDE program.

Previously, work schedules were made manually for each division, which caused the preparation of each monthly work plan to take too much time. Moreover, the shifts allocated to each operator were not always equally and fairly distributed. Since the numbers of operators, days, and shifts are used in the mathematical models created, the solution space of the model and the number of combinations that it compares are very high. Operating a working model of this sort by hand is very complicated and difficult. In addition, a quality work schedule cannot be obtained. With mathematical models, the preparation process of the charts is shortened, and quality charts obtained. Contradictory constraints were used in some of the mathematical models developed in the study, and the requests of the foremen were fulfilled as much as possible. Conflicting constraints and demands from the workers were met with the GP method with the least deviation.

The previous schedules caused an unfair distribution of work as they were not systematic and were done manually by the shift supervisors. This situation negatively affected the motivation of the employees. Moreover, employees attached importance to the requesty for an equal number of night shift assignments. With this study, fairness was ensured in the distribution of shifts.

Overall, this study can guide researchers in solving staffing scheduling problems, especially under conditions associated with pandemics. The successful real-life study that has produced this solution will also be of interest in many related applications. It will also be a resource for future work. For example, future work might examine how activities and scheduling can be done in close circles or environments with highly skilled employees who are not allowed to work together.

The assignment of employees to specific jobs has been a concern in the service industry for many years. In recent years, given the increasing service lines in the service sector and the importance given to customer satisfaction and the expectation of balanced work, more weight has been given to the assignment of personnel. The models created in this study could be used more widely, in sectors other than port operations. This study has focused on the number of duty points, the number of personnel, personnel demands, and so on. However, wider planning could be achieved by increasing the types of point included. Depending on the size of the model used, metaheuristic methods could be a preferred option.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Emir Hüseyin Özder; data collection: Mehmet Gümüş; analysis and interpretation of results: Emir Hüseyin Özder; draft manuscript preparation: Emir Hüseyin Özder and Mehmet Gümüş. All authors reviewed the results and approved the final version of the manuscript.

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The role of ship inspections in maritime accidents: An analysis of risk using the bow-tie approach

Panagiotis Sotiralis, Konstantinos Louzis and Nikolaos P Ventikos

Abstract

Ships are subject to inspections from different maritime stakeholders, such as port states, classification societies, shipowners, managers and operators. Each one implements their own inspection content depending on their role in the construction and operation phase of the vessel life cycle. Because few studies have investigated the influence of ship inspections on accidents, it is uncertain to which extent the current inspection regimes are contributing to reducing accidents. In addition, maritime risk analysis has, so far, not considered thoroughly the role of the inspection process in accident development. As a result, an improved understanding of the influence inspection methods would facilitate the implementation of effective measures for reducing accident probabilities or consequences. The approach used in this article involves identifying the underlying causes and the resulting consequences of accidents that may be associated with inspection issues and combining this knowledge in bow-tie representations. The developed bow-tie diagrams provide useful insights into the role of insufficient inspection practices in the development of maritime accidents and the severity of the resulting consequences. Furthermore, the developed diagrams may be used for investigating the risk from inspection issues by producing generic accident scenarios with every possible combination of the different parameters that describe all the possible pathways, from causes to consequences. Although this is a qualitative approach, it provides valuable insights into safety concerns that result from inspection practices and may also be used as a basis for further quantitative risk analysis.

Keywords

Risk-based inspection, maritime accidents, risk analysis, bow-tie analysis, ship inspections, maritime accident investigation

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Introduction

Ship inspections are routinely carried out by different maritime stakeholders, such as shipping companies, flag or port states, classification societies and vetting or insurance companies. Each one implements different practices depending on their role in the construction and operation phase of the vessel life cycle. However, different inspection regimes share common objectives, such as ensuring the structural and operational integrity of the ship and ultimately preventing maritime accidents. Knapp and Franses[1] have provided an overview of the different kind of inspections that are carried out on ships and have classified them according to the requirements they satisfy into statutory and class, insurance and commercial (Figure 1). Only a handful of studies in the international literature have explored the impact of the various inspection regimes and inspections usually are not considered as contributing factors to maritime accidents. As a result, the question for the magnitude of influence of the inspections concerning the decrease in these accidents remains.[2] As Bijwaard and Knapp[3] have highlighted, the fact that ships are over-inspected does not in itself ensure safe operation, if it is not accompanied by close cooperation and data sharing between the various maritime stakeholders. In addition, even though inspections are usually carried out by qualified personnel who follow standardized procedures, the quality of the result

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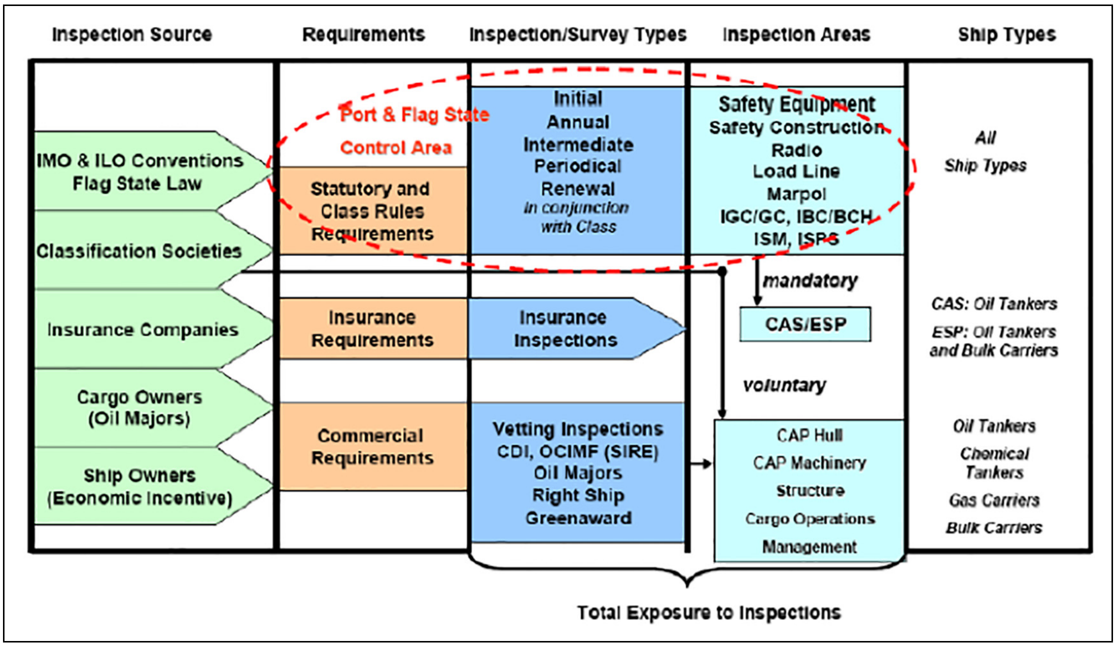

Figure 1. Ship inspections and surveys.[1]

varies due to the presence of factors such as stress and fatigue, which relate to the conditions in the working environment, and factors such as the skill and competency of the inspectors. The maritime industry has experienced catastrophic accidents that have been attributed to inspection-related issues, such as the Erika and the MSC Napoli, and therefore, the importance of effective inspections for maintaining ship safety during operation and maintenance should not be overlooked.

Risk-based methodologies are gaining traction in the maritime industry, as a tool for reducing accidents by systematically identifying the potential hazards and evaluating the resulting risk. These tools are used by various stakeholders who approach the problem from different perspectives, such as the International Maritime Organization (IMO) with the introduction of the formal safety assessment (FSA) as a tool for developing regulations and shipowners/operators who use risk assessment as a tool for controlling risks that may limit ship operability.

However, the maritime industry may benefit the most from risk-based inspection, only if the understanding of the role of inspections in the development of maritime accidents is increased. The main objective of this article is to determine the role of omissions during the inspection process in the development of different accident categories. This is achieved by investigating the causes and resulting consequences of maritime accidents that are related to issues in hull and machinery inspections and structuring bow-tie diagrams that describe the different pathways along the entire accident chain of events. The bow-tie representations are subsequently used for producing generic scenarios that are useful for identifying combinations of risk-contributing factors that may not have occurred in the past. The work presented in this article has been carried out in the context of the European Union EC-funded SAFEPEC research project (http://safepec.eu), which aims to develop risk-based tools for ship inspections that will increase their effectiveness and reliability, while also minimizing the related cost, by focusing inspection efforts on sensitive, high-risk areas on-board, and provide early warning for possible safety issues. The work presented in this article is the preliminary part that provided input for a broader analysis that involved implementing Bayesian Networks (BNs) for quantifying the effect of the inspection process on the occurrence of different accident categories and on the magnitude of their consequences.

The rest of the article is structured as follows. The following section contains an overview of the literature on accident modelling techniques that have been used for risk analysis in various industries and their key characteristics. This section focuses on bow-tie diagrams and their advantages in the scope of the analysis presented in this article. The next section provides a brief description of the theoretical background on bow-tie diagrams and outlines the methodology that is applied in this article. The next section presents the developed bow-tie diagrams for different ship types and accident categories that are directly or indirectly attributed to omissions during the inspection process. This section also presents a validation example for the bow-tie diagrams using data from a real-world accident and an example of a generic scenario that may be produced from the developed bow-tie diagrams. Finally, the article concludes with important results and observations derived from the analysis.

Background

Rapid technological developments and the occurrence of major accidents in safety critical industries, with adverse consequences on human health, the environment and material damage, such as the Piper Alpha accident, have highlighted the need for effective risk management. According to the review work on risk by Aven,[4] the ability to anticipate unwanted events and address risk are key elements for operational decision support in functional systems. Since 1980, the concept of safety barriers has played a major role in safety management. Safety barriers are defined as 'physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents'.[5]

Effective risk management is directly linked to understanding the chain of events that lead to an accident and the events that lead to the adverse consequences, as well as how the failure of safety barriers facilitates the development of an accident. Accident models may be classified into the following three categories: sequential, epidemiological and systemic. The sequential and epidemiological models have contributed to the understanding of accident chains and the identification of causation.[6] Sequential accident models that also incorporate graphical representations of safety barriers include safety barrier diagrams,[7] event trees[8] and bow-tie diagrams.[9] Bow-tie diagrams are a comprehensive visualization of the relationship between the accident causes and the resulting consequences and describe how the accident develops as preventive and mitigative controls (i.e. safety barriers) fail. Systemic models are comprehensive, yet mostly qualitative analysis tools, for sociotechnical systems with complex dependence structures. Examples of systemic accident models are AcciMap and/or ImproMap, STAMP models, MTO-analyses and the FRAM method. The AcciMap accident modelling technique is based on Rasmussen's[10] risk management framework and involves analysing causal chains of events by structuring generalized cause–consequence charts, which have been used widely as a basis for predictive risk analysis.[11] The choice of set to include in a cause–consequence chart is defined by the choice of the critical event, which reflects the release of a well-defined hazard source, such as 'loss of containment of hazardous substance', or 'loss of control of accumulated energy'. The critical event connects the causal tree (i.e. the logic relation among potential causes) with a consequent event tree (i.e. the possible functional and temporal relation among events) explicitly reflecting the switching of the flow resulting from human decisions or by automatic safety systems.[12]

This article uses the bow-tie technique for modelling accidents related to inspection issues, mainly because of its visual strength in showing the connection between causes and consequences, and the fact that they may be used either for qualitative or quantitative analysis. The bow-tie technique has a proven track record in the offshore,[13] process, petrochemical,[14] civil aviation[15] and security risk industries and is continuously adapted to suit different needs. In the maritime industry, bow-ties have been used in FSAs that have been submitted to the IMO for different ship types.[16–21] Mokhtari et al.[22] have incorporated bow-ties into the risk assessment phase of a risk management framework for sea ports and offshore terminals that may be used for detailed investigation of the identified risk factors. Khakzad et al.[23,24] have incorporated bow-tie diagrams in the context of dynamic risk analysis by mapping them into BNs for updating probabilities based on new evidence. Safety barriers are also commonly incorporated into bow-tie diagrams and are termed preventive if they limit cause frequency or protective if they are used to mitigate the consequences of the accident. Badreddine and Amor[25] have classified safety barriers into active or passive depending on their functionality. Active barriers require a source of energy to function (i.e. automatic or manual action) and include safety valves and alarms. Passive barriers do not require a source of energy and include firewalls and the watertight subdivision of a ship.

The main advantage of bow-tie diagrams is that they provide an explicit, linear visual representation of the risk,[26] including the cause and effect scenarios and the relationships between various system components. Also, they allow the identification of inadequately controlled threats and/or consequences and the exploration of mitigative measures. Their flexibility is compounded by the ability to include a variety of parameters such as environmental effects, human behaviour and mechanics, on a single representation. As a result, bow-tie diagrams may be a very useful tool to depict and maintain an up-to-date, real-time, working risk management system.

Methodology

The strength of bow-tie diagrams stems from their ability to utilize the combination of Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) towards the delivery of a complete risk assessment picture. Bow-tie diagrams are a graphical representation of a series of events leading to the top event (accident) and a series of events that result from the accident, which effectively describes a complete accident scenario, from causes to consequences (Figure 2). The events leading to the top event form a fault tree, where causes may be classified either as basic or intermediate. The relationship between events are represented by logical 'AND' and 'OR' gates. The AND gate means that for an event to occur, all its related causes must occur as well, whereas the OR gate means that if any of the related causes occurs, then the event occurs.[27] The events that result from the accident form an event tree, where, according to Badreddine and Amor,[25] consequences may be classified into secondary events (i.e. primary consequences), dangerous events and major events (i.e. final consequences).

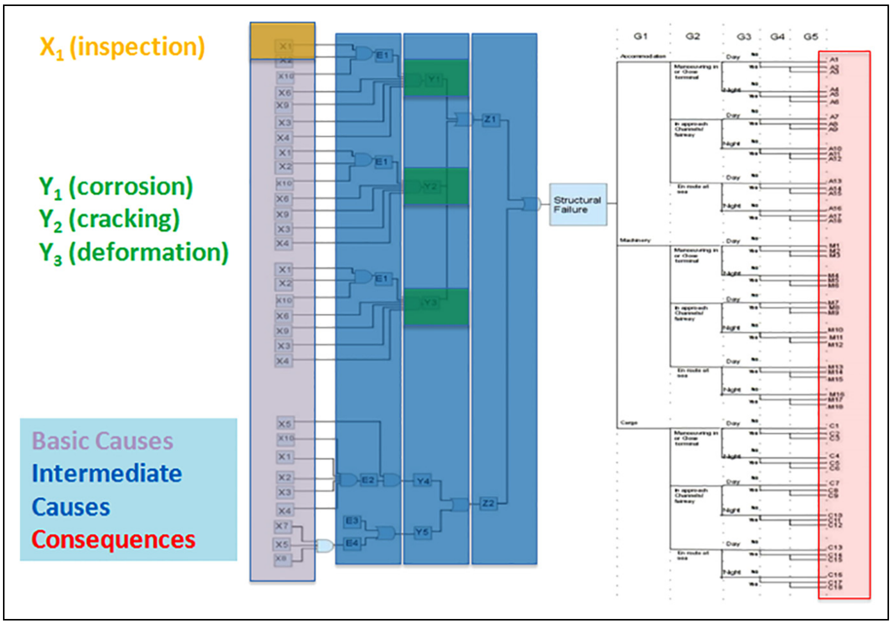

Figure 2. Generalized bow-tie diagram.

The analysis in this article was based on a thorough analysis of information in accident reports that were published by the following national authorities: Marine Accident Investigation Branch (MAIB), Maritime New Zealand (MNZ), Marine Safety Investigation Unit (MSIU), National Transportation Safety Board (NTSB), Federal Bureau of Maritime Casualty Investigation (BSU), Transportation Safety Board of Canada (TSBC), Swedish Accident Investigation Authority (SHK), The Danish Maritime Accident Investigation Board (DMAIB) and Hellenic Bureau for Marine Casualties Investigation (HBMCI).

From over 600 accident reports that covered a time frame of 25 years (from 1991 to 2015), 100 cases that were either directly or indirectly related to inspection issues were selected for analysis. The main objectives were to identify the underlying causes and associate them, if possible, with inspection practices, as well as to identify the resulting consequences to human health, the environment (e.g. oil outflow) and to property (i.e. the fate of the ship itself). The analysis considered the following ship types, as they were in the scope of the SAFEPEC project: general cargo ships, container ships, passenger ships and cruise ships. In addition, the analysis considered the following accident categories: failure of equipment (e.g. life-saving appliances and cranes), structural failure, fire and explosion. These were selected because, as derived from the analysis of the accident reports, they may be safely correlated to omissions during the inspection process. It should be noted that although the work presented in this article involved the development of a bow-tie diagram for every different ship type and accident category, the following section provides some indicative examples due to limitations of space.

The bow-tie diagrams in this article were developed with a high-level approach, following the rationale of the FSAs submitted to the IMO and using significant input from experts in the maritime industry. They attempt to incorporate all the different causes that lead to the accidents, as well as all the different consequence paths that follow, in an accurate and efficient manner. The role of inspections and maintenance (i.e. omissions during the inspection process as initiator events) is clearly defined in the fault tree part of the diagrams and is also considered for the resulting consequences. The various causes in the fault trees are classified into the following levels, according to their order of occurrence: basic (X), intermediate (E), intermediate (Z) and intermediate (Y). Levels Z and Y are particularly important for the construction of the fault trees because they are the immediate conditions that are identified for the accident and therefore define how basic causes will be traced. On the other hand, omissions during the inspection and maintenance processes are usually determined to be basic causes because they create the conditions for reaching the top event, given that the preventive safety barriers are not sufficiently effective.

The construction of the bow-tie diagrams for each accident category and ship type was followed by a qualitative analysis of the identified causes and consequences. The approach followed for the analysis of the causes was to implement a qualitative minimal cut set analysis. A cut set is defined by Limnios[28] as ‘a subset of events, whose simultaneous existence involves the occurrence of the top event, and which is independent of the occurrence or non-occurrence of the other events of the Fault Tree’. Minimal cut sets are derived by applying logical operations on the combinations of events that lead to the accident, based on the principle

Table 1. Consequence levels and the corresponding severity index (SI) rating that were used in the analysis.

Severity index (SI)	Extent of damage area	Damage to vessel	Health and safety consequences (crew, passengers)
1	Minor repairable		Possible injuries
2	Extended	Possible damage	Injuries
3	Serious	Damage	Injuries
4	Very serious	Serious	Injuries and fatalities
Worst case	Loss of vessel	Loss of cargo	Loss of all crew

of reduction. This analysis was used to provide a preliminary evaluation of the importance of efficient inspections in the accident causal chain. The analysis of the consequences was based on rating their severity using the logarithmic severity index (SI) proposed by the IMO in the FSA guidelines.[29] The SI is divided into four levels of increasing severity and is appropriately scaled for the field of maritime safety (Table 1).

Finally, the in-depth analysis of the accident reports led also to the identification of main and intermediate causes that are attributed to the human element (e.g. inexperienced personnel, untrained personnel and inappropriate actions). These causes have been incorporated into the structure of the developed bow-ties for the various accident types under investigation. The derived threads of the bow-ties that include this specific type of causes may be further exploited in the context of the ISM (International Safety Management) inspection/audit regime for the enhancement of the safe operation of the vessels.

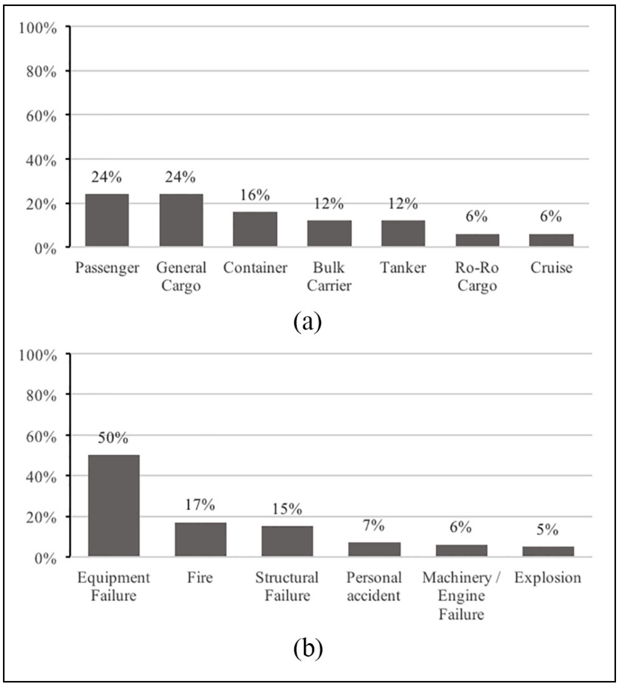

Figure 3. Percentage distributions in inspection-related accidents: (a) ship types and (b) accident categories.

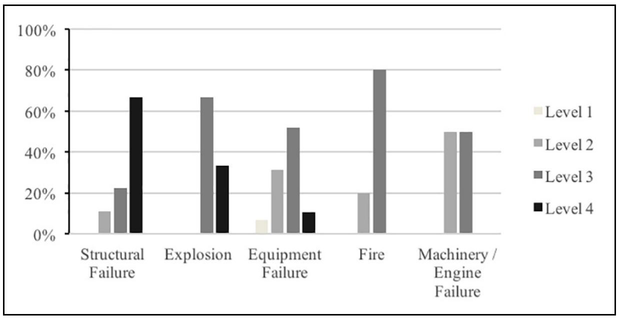

Figure 4. Severity index (IMO) distribution per accident category in inspection-related accidents.

Results

This section depicts the developed bow-tie diagrams for indicative examples of different ship types and accident categories that are related to omissions during the inspection process. The section illustrates an example from the validation of the bow-tie diagrams using accident data from a case that was not used during the development process. Furthermore, an indicative example of a generic scenario that may be elicited from the developed bow-tie diagrams is presented.

As it is already pointed out, the initial statistical sample was consisted of 600 accident reports, 100 reports for general cargo ships, 110 reports for tankers, 100 for bulk carriers, 90 reports for container ships and Passenger ships, 50 reports for RoRo (roll-on/roll-off) vessels and 40 reports for cruise ships, covering a time frame of 25 years, from 1991 to 2015. From the initial sample, 100 cases had a direct or indirect link with inspection omissions. The most common types of ships that have been involved in accidents due to inspection issues are passenger and general cargo ships followed by containers, bulk carriers and tankers in descending order (Figure 3(a)). As shown in Figure 3(b), the most common accident category is failure of equipment (50%), followed by fire (17%) and structural failure (15%).

Figure 4 shows that structural failures have the highest proportion of Level 4 severity rating because they usually result in multiple fatalities and total loss of the vessel. The second largest proportion of Level 4

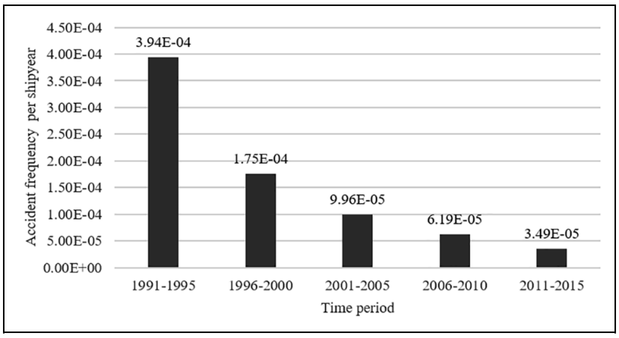

Figure 5. Accident frequency of general cargo ships for the period 1991–2015 (i.e. 25 years).

consequences is found in explosion accidents. About 80% of fire accidents have a high consequence severity rating (SI = 3), mainly due to the often difficult firefighting process. Equipment failures range from minor to severe consequences, with over 50% of the accidents leading to Level 3 severity rating. Finally, machinery and engine failures are equally divided between Level 2 and Level 3 ratings.

Finally, the statistical analysis that was performed shed light on the improvement over time in the reliability of inspections due to the emergence of stricter or refined inspection procedures/guidelines. Figure 5 depicts the frequency of maritime accidents of general cargo ships related to inspection omissions for a time frame of 25 years. Based on this figure, the improvement in the effectiveness of the inspections due to stricter or refined inspection policies/regimes is evident. More specifically, the adoption of ISM code in 1994 and the ERIKA packages 1 and 2 in 2002 led to the significant decrease in the accident frequency in the forthcoming years after their effective implementation.[30]

Bow-tie for structural failure accidents

The initiating factors (X level of causes) for structural failure accidents include poor inspection and maintenance procedures, as well as other factors such as the human element, deficiencies in manuals and incorrect installation. The intermediate causes (I and E levels) focus on procedural omissions and violations and are transitional events that contribute to the development of the accident. The next level of intermediate causes (Y level) represents how different structural elements of the ship may fail and are the immediate causes that lead to the top event of the fault tree. Similar fault trees were constructed for the different ship types that were considered in this analysis. Figure 6 shows the developed bow-tie diagram for general cargo ships, where poor inspection is considered a basic cause and corrosion, cracking and deformation are considered intermediate causes.

The qualitative cut set analysis that was performed for the fault tree part of this structural failure bow-tie diagram (Table 2) showed that there are three different events (first-order cut sets) and four different combinations of events (second-order cut sets) that are sufficient for a structural failure accident to occur in general cargo ships. Causal events related to inspection and maintenance issues appear in the second-order cut set {X3, X4} = {Poor maintenance, Poor inspection} and in the first-order cut set {I1} = {Insufficient attention to repairs}. Therefore, it is observed that poor inspection may not necessarily lead to a structural failure accident in general cargo ships but has the capacity to do so when combined with poor maintenance. However, since maintenance work is often carried out based on the findings from inspections, the importance of this process being efficient is apparent.

Table 2. Results from the qualitative cut set analysis and related risk factors for the structural failure accident (general cargo ships).

Cut set	Order of cut set	Related risk factors
{X1, X2}	Second	Design/endurance test
{X3, X4}	Second	Inspection/maintenance
{X5, X6}, {X7, X8}	Second	Operational/human error
I1	First	Inspection/maintenance
E2	First	Weather conditions
E3	First	Operational/human error

A detailed account of the events in every level of the fault tree part of this bow-tie diagram is given in Table 3.

The event trees that were constructed for the structural failure accidents include the following factors (Table 4): the location of the failure on the ship; the leg of its journey during the accident (e.g. en route or port approach); the time of day when the accident occurred; whether a secondary accident was triggered after the initial accident, and whether there was any additional structural damage; and whether the structural failure result in water ingress.

Bow-tie for Fire/explosion accidents

Fire and explosion accidents follow similar chains of events when they develop, and therefore, they are approached as a single bow-tie diagram. As for the other accident categories that were examined, inspection and maintenance issues are found to contribute as a basic cause (X level). Events in Level E focus on actions that are performed incorrectly and act as an intermediate link between Levels X and Y. Intermediate events in Level Y represent a higher level of human error, while immediate causes (Level Z) represent the highest level of human error (operational error) that causes situations such as leakage or excessive temperatures.

The qualitative cut set analysis that was performed for the fault tree part of this fire/explosion bow-tie diagram (Table 5) showed that there are 12 different

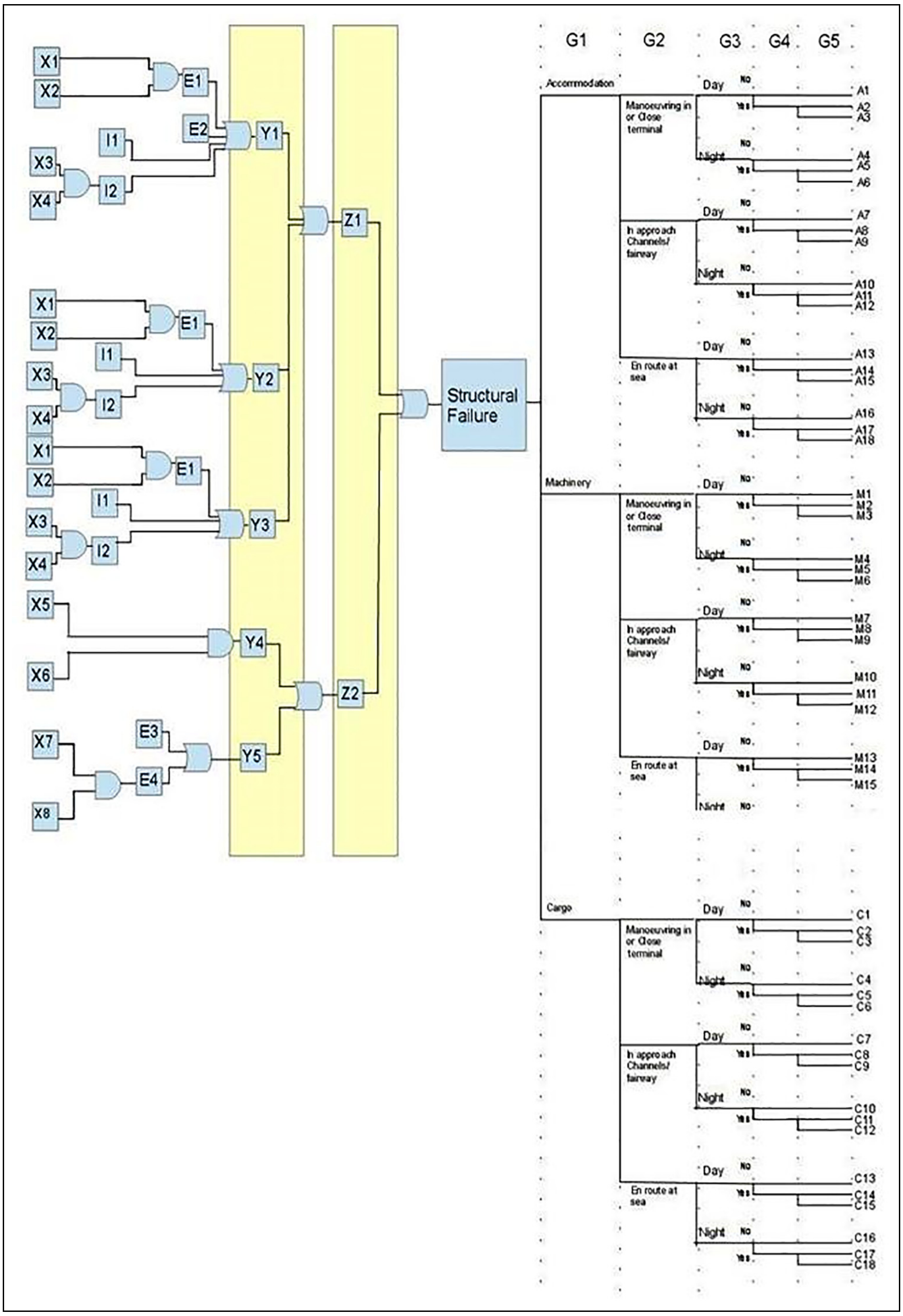

Figure 6. The integration of the inspection and the different causes (e.g. corrosion, cracking) into the bow-tie structure.

events (first-order cut sets) and two different combinations of events (second-order cut sets) that are sufficient for a fire/explosion accident to occur in passenger ships. Causal events related to inspection and maintenance issues appear in the following first-order cut sets: {X1} = {Poor repairs}, {X2} = {Poor maintenance}, {X3} = {Poor Inspection}. Therefore, in the case of fire/explosion accidents for passenger ships, inspection-related issues are a sufficient and capable condition that could potentially lead to the occurrence of the accident. This is an indication that although operational/human error events are more likely to result in a fire/explosion accident, which agrees with the consensus on the dominance of human error in the development of accidents,[31] inefficient inspections are indeed a major risk-contributing factor.

Figure 7 shows the developed bow-tie diagram for fire/explosion accidents of passenger ships. A detailed account of the events in every level of the fault tree part of this bow-tie diagram is given in Table 6.

The event tree diagrams for fire/explosion accidents use the following event gates (see Figure 7 for notation

Table 3. Events in the fault tree part of the bow-tie diagram for structural failure accidents of general cargo ships, according to their assigned level.

Event level	Event symbol	Event description	Event level	Event symbol	Event description
Level X	X1	Poor design calculations	Level E	E1	Inferior quality of structure
	X2	Poor endurance tests		E2	Weather conditions
	X3	Poor maintenance		E3	Violation of regulations
	X4	Poor inspection		E4	Process not followed
	X5	Inexperienced personnel	Level Y	Y1	Corrosion
	X6	Untrained personnel		Y2	Cracking
	X7	Crew did not pay attention		Y3	Deformation
	X8	Deficiencies of manuals		Y4	Insufficient quality of personnel
Level I	I1	Insufficient attention to repairs		Y5	Inappropriate actions
	I2	Inattentions	Level Z	Z1	Poor condition of structure
				Z2	Operational error

Table 4. Consequence event gates in the bow-tie diagrams for the structural failure accidents.

Event gate symbol	Event gate	Description	Values
G1	Location	Where was the failure located?	Accommodation, cargo hold, engine room and other machinery spaces
G2	Operational state	Which phase of its journey was the ship in?	En route, approaching harbour and in terminal
G3	Time of day	When did the accident occur?	Day, night
G4	Consequent accident	Was there a secondary accident?	Possible accidents could be, for example, fire/explosion, structural failures
G5	Loss of water tightness	Did the structural failure result in water ingress?	Yes, no

Table 5. Results from the qualitative cut set analysis and related risk factors for the fire/explosion accident (passenger ships).

Cut set	Order of cut set	Related risk factors
{X1}, {X2}, {X3}	First	Inspection/maintenance
{X4}	First	Design
{X5}, {X6}	First	Operational/human error
{X7}, {X8}, {Y5}, {Y6}, {Y3}	First	Mechanical failure
{E1}	First	Operational/human error
{X9, X10}, {X11, X12}	Second	Operational/human error

Table 6. Events in the fault tree part of the bow-tie diagram for fire/explosion accidents of passenger ships, according to their assigned level.

Event level	Event symbol	Event description	Event level	Event symbol	Event description
Level X	X1	Poor repairs	Level Y	Y1	Corrosion
	X2	Poor maintenance		Y2	Cracking
	X3	Poor inspection		Y3	Overheating machine
	X4	Poor design		Y4	Hot surfaces
	X5	Poor supervision from the crew		Y5	Incorrect tightening
	X6	Incautious practice of metalworking		Y6	Use of unauthorized spare part
	X7	Electrical malfunction		Y7	Insufficient quality of personnel
	X8	Mechanical malfunction		Y8	Inappropriate actions
	X9	Inexperienced personnel	Level Z	Z1	Leakage
	X10	Untrained personnel		Z2	Inappropriate temperature
	X11	Crew did not pay attention		Z3	Crankcase explosion
	X12	Deficiencies of manuals		Z4	Sparks
Level E	E1	Violation of regulations		Z5	Operational error
	E2	Process not followed			

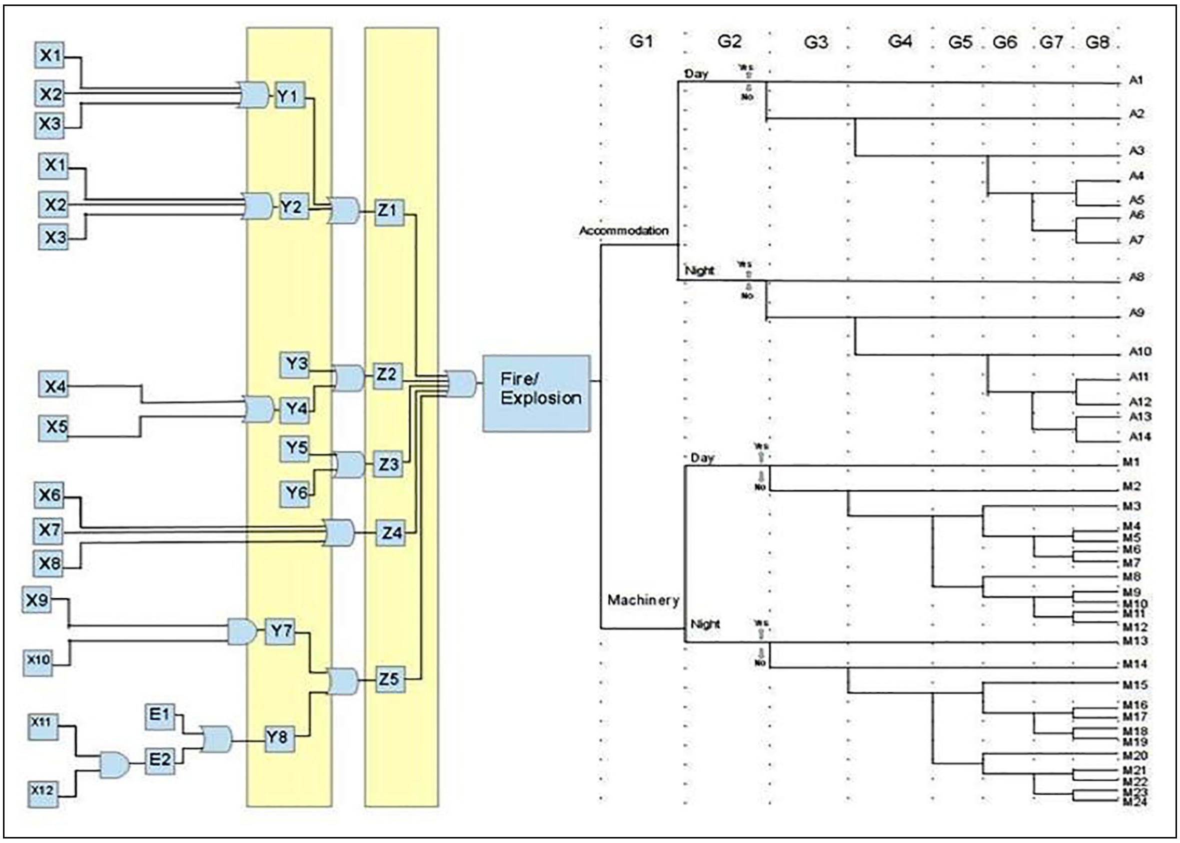

Figure 7. Bow-tie diagram for fire/explosion accidents of passenger ships.

Table 7. Consequence event gates in the bow-tie diagrams for fire/explosion accidents of passenger ships.

Event gate symbol	Event gate	Description	Values
G1	Location	Where was the failure located?	Accommodation, cargo hold, engine room and other machinery spaces
G2	Time of day	When did the accident occur?	Day, night
G3	Automatic firefighting	Was the automatic firefighting system activated?	Yes, no
G4	Manual firefighting	Was the manual firefighting procedure properly followed?	Yes, no
G5	Fire spread to accommodation	Did the fire spread to the accommodation?	Yes, no
G6	Assistance from other vessel or land/rescue of passengers	Was assistance from other vessel or land provided to the ship?/Were the passengers rescued?	Yes, no
G7	Fire extinguishing, vessel towing	Was the fire extinguished and the vessel towed?	Yes, No.
G8	Ship evacuation/rescue of crew	Was the ship evacuated?/Was the crew rescued?	Yes, no

and Table 7 for a detailed explanation): location (G1), time of day (G2), automatic firefighting (G3), manual firefighting (G4), fire spread to accommodation (G5), firefighting assistance from other vessel or land (G6), fire extinguishing, vessel towing (G7) and ship evacuation/rescue of crew (G8). The consequences in the event tree are rated using the IMO SI in a uniform manner for all accident categories (see Table 1). The worst case that is considered involves the total loss of the vessel, the cargo and the crew.

Bow-tie for equipment failure accidents

The basic causes (Level X) for equipment failure accidents include, among others, the following factors: human error, poor inspection and maintenance processes, design flaws and installation errors. Events in Level E focus mainly on actions that are incorrectly performed and processes that are violated, while Level Y describes the failure type for the equipment. Immediate causes (Level Z) include causes such as

Table 8. Identified causes and consequences of the Swanland accident.

Causes	Details	Consequences	Details
X3	Poor maintenance of vessel	G1	Midship section (cargo)
X4	Poor inspection of vessel	G2	En route
E3	Violation of Maritime Solid Bulk Cargo Code	G3	Night
Y1	Corrosion/no repairs	G4	Foundering
Y5	Inappropriate actions (e.g. failure in mustering the crew, the preparation of the life rafts for launching was incorrectly ordered by the second officer)	C18	The vessel sank/ loss of six crew
Z1	Poor condition of structure		
Z2	Operational errors		

insufficient personnel, deficiencies of any kind of manual and/or regulatory violations.

The developed event trees for the equipment failure accidents use the same event gates and the same levels of consequence as those in the structural failure accidents.

Calibration and validation of bow-tie diagrams

The initial structure of the bow-tie diagrams was based on an elaborated analysis of the collected accident reports (100 accidents), as well on feedback from expert group judgement from the maritime industry. Additional maritime accident cases were also used to further calibrate the structure of the developed bow-tie diagrams, by identifying their causes and consequences from available accident descriptions. Subsequently, the developed bow-tie diagrams were evaluated and modified accordingly where it was deemed necessary. Indicatively, the calibration process for structural failures of general cargo ships involved using 10 additional accident case studies. Modification of the bow-tie diagram that involved the addition of either a cause or a consequence that had not been considered during the initial development resulted from two of these cases, while the rest fully validated the final structure.

An example of one of the accidents that were used for calibration concerns the sinking of the general cargo ship 'Swanland'. The details of this case are briefly presented below, based on the corresponding investigation report that was conducted by the MAIB[32] in the United Kingdom. On 27 November 2011, the Swanland experienced a structural failure when heading directly into rough seas and gale force winds, while on passage from Llanddulas, Wales to Cowes. The vessel sank about 17 min later. Two members of the crew managed to swim clear and were rescued by boarding on a life raft. The body of the chief officer was recovered from the sea during an extensive air and sea search, but the remaining crew was not found. There was no significant pollution. The longitudinal strength of the ship had probably weakened significantly over the previous 2.5 years due to extensive corrosion. The vessel had undergone some maintenance and repair work but it lacked focus and oversight. In fact, since 2009, no structural repair work had been conducted. Other contributing factors included the following: non-compliance with the International Maritime Solid Bulk Cargo Code, insufficient loading information, a lack of effective safety management, poor quality of survey and audit, lack of oversight of the Classification Society by the flag state and the financial pressures of operating this type of vessel in the current economic downturn. The investigation also identified several safety issues concerning the immersion suits and life jackets available on-board the vessel.

Based on this narration, the causes and consequences for this accident were identified and assigned to the corresponding events in the bow-tie diagram for structural failure of general cargo ships (see Table 8). Subsequently, this accident scenario was marked on the corresponding bow-tie diagram (see Figure 8) for visualizing the results.

Example of generic scenario

The developed bow-tie diagrams may be used for producing multiple generic accident scenarios, with any of the possible combinations of causes (contributing factors), safety barriers and consequences (different outcomes) for the selected ship types and accident categories. The generic scenarios contain the entire accident event chain, from causes to consequences, and contain inspection-related aspects, critical parameters and safeguards. These theoretical accident scenarios may be used for systematic analysis, per ship type, of all the possible combinations of risk factors that contribute to the occurrence of each accident type and all the possible resulting consequences. Complemented by a suitable barrier analysis, the generic scenarios may be used for preventing the simultaneous occurrence of risk factors that have not occurred in the past. An example of such a generic scenario that involves a fire accident in a passenger ship is shown in Figure 9 (the accident pathway is marked in red), while Table 9 shows a detailed explanation of the marked causes and consequences. The description for this hypothetical accident could read as follows:

> Poor maintenance work or omissions during the inspection process led to leakage in the piping system due to excessive corrosion. As a result, a fire broke out and then it expanded into the accommodation space of the passenger ship during the night. Failures in the automatic firefighting system and a failure to manually extinguish the fire led to injuries and fatalities for the crew and damage to the vessel.

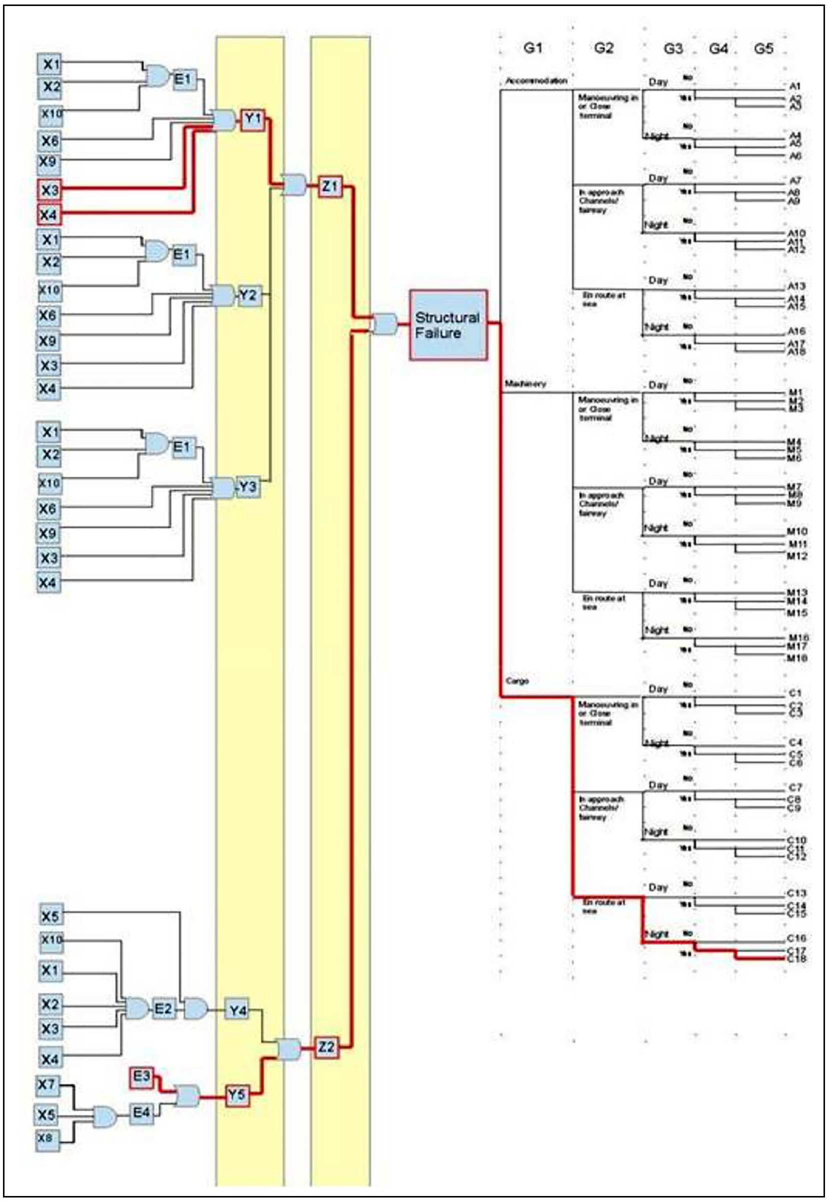

Figure 8. Representation of the sinking of the Swanland on the developed bow-tie diagram for structural failure of general cargo ships.

Table 9. Identified causes and consequences of the accident sequence represented by the generic scenario example.

Causes	Details	Consequences	Details
X2	Poor maintenance	G1	Accommodation space
X3	Poor inspection	G2	Night
Y1	Corrosion	G3	Automatic firefighting
Z1	Leakage		

Conclusion

Since only a handful of studies have investigated the influence of inspections, it is unclear how much the current ship inspection framework is contributing to the reduction in the number of maritime accidents. This problem is compounded by an unclear understanding of the role of omissions in the inspection process in the development of maritime accidents. Establishing a link between inspection issues and the risk of maritime accidents requires examining how ineffective inspections contribute to the occurrence of accidents and what are the resulting consequences.

In the context of the EC-funded research project SAFEPEC, this article presents results from the in-depth analysis of 100 investigation reports from accidents that are either directly or indirectly related to

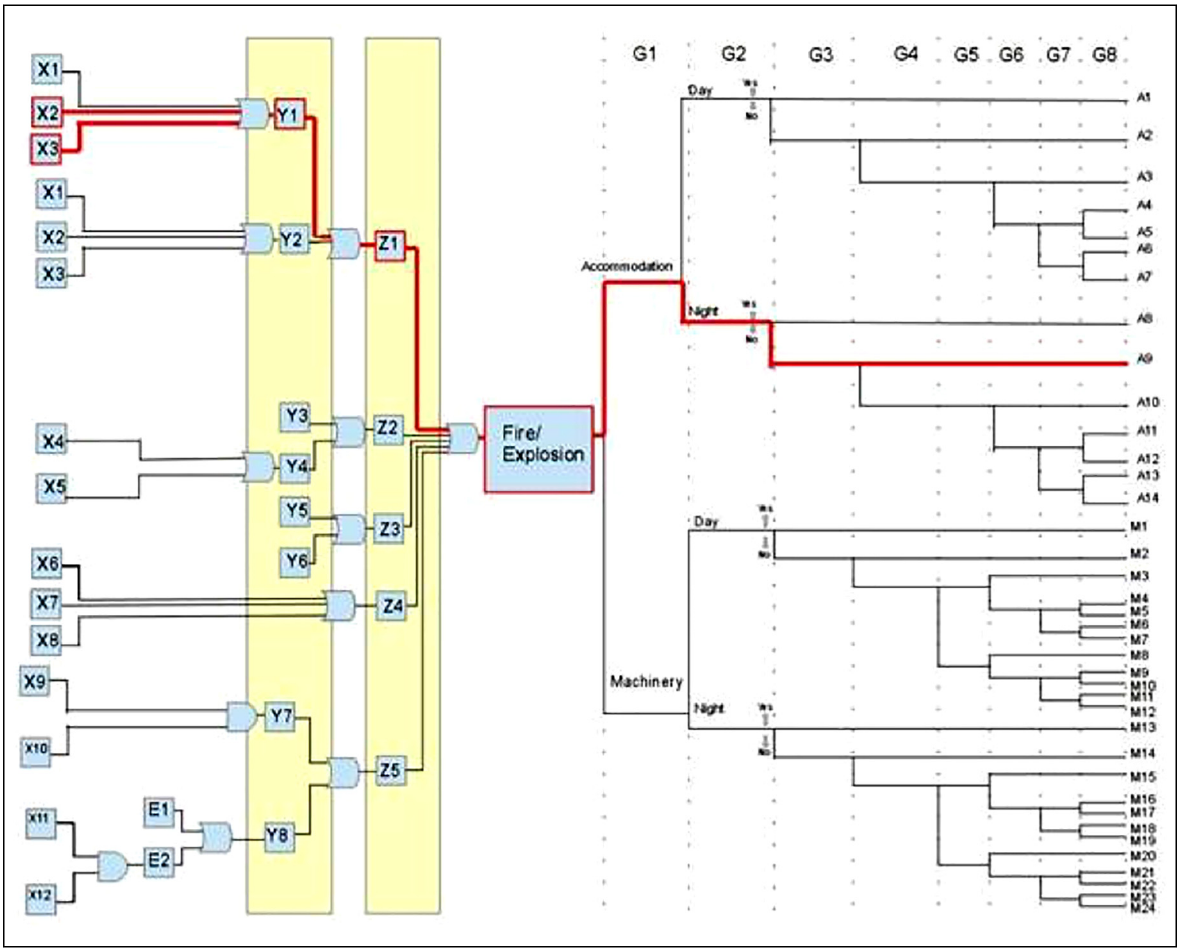

Figure 9. Representation of the generic accident scenario 'Fire' for a passenger ship.

omissions during the inspection process. The contributing factors that led to the occurrence of these accidents and the magnitude of their consequences were determined by elaborating on the collected data, as well as by acquiring feedback from expert groups in the maritime industry. The identified parameters were modelled in bow-tie diagrams, which were developed for ship types and accident categories that were in the scope of the SAFEPEC project. Subsequently, the bow-tie diagrams were calibrated using information from additional accident cases that also relate to inspection issues. These accident models are the basis for formulating generic accident scenarios for different ship types and accident categories that describe the entire chain of events, from causes to consequences, and combine every possible combination of the different parameters. The generic scenarios may be used for further exploring the risk from inspection issues in a systematic and comprehensive manner by considering combinations of risk factors that have not occurred in the past.

The main conclusion from the analysis is that omissions during the inspection process are a significant factor that contributes to the occurrence of maritime accidents such as structural failures and explosions that have severe consequences for human health, the environment and property (i.e. the cargo and the ship). In the accident sample, over 60% of structural failures (that comprise 50% of all accidents in the sample) and over 30% of explosions led to total consequences with Level 4 severity, on the IMO SI. The importance of this issue is highlighted by the fact that 24% of the accident cases involved passenger ships, which is a safety critical ship type due to the large number of passengers onboard, while 24% involved general cargo ships, which is a very common ship type with a large global fleet. The results of the qualitative cut set analysis for the fault trees have showed that even though the accepted dominance of operational errors is apparent in the developed bow-tie diagrams, inefficient inspections are a significant contributing factor to the occurrence of various types of accidents with potentially severe consequences. While omissions in maritime inspections are not an immediate cause, they play a significant role because failures and faults, such as corrosion, cracks and signs of fatigue, that remain undetected may escalate to accidents with consequences that may lead up to the total loss of the ship itself.

The importance of ship inspections in the development of maritime accidents indicates that more resources need to be focused on increasing their effectiveness, which will ultimately contribute to increasing maritime safety during the operation and maintenance phase of the life cycle of ships. This goal may be accomplished by establishing a more effective risk-based approach for ship inspection and maintenance. Risk-based inspection will provide tools for identifying critical mechanical and structural elements with high probability of failure. Following the example of sectors such as the offshore oil and gas and the petrochemical industries, where risk-based inspection is a proven concept, the maritime industry will benefit from its application by reducing total risk in a cost-effective manner.

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ARTICLES FOR FACULTY MEMBERS

AUTOMATED CONTAINER TERMINAL AND MARITIME CONSTRUCTION RISK

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Towards AI driven environmental sustainability: an application of automated logistics in container port terminals

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ABSTRACT

Artificial intelligence and data analytics capabilities have enabled the introduction of automation, such as robotics and Automated Guided Vehicles (AGVs), across different sectors of the production spectrum which successively has profound implications for operational efficiency and productivity. However, the environmental sustainability implications of such innovations have not been yet extensively addressed in the extant literature. This study evaluates the use of AGVs in container terminals by investigating the environmental sustainability gains that arise from the adoption of artificial intelligence and automation for shoreside operations at freight ports. Through a comprehensive literature review, we reveal this research gap across the use of artificial intelligence and decision support systems, as well as optimisation models. A real-world container terminal is used, as a case study in a simulation environment, on Europe's fastest-growing container port (Piraeus), to quantify the environmental benefits related to routing scenarios via different types of AGVs. Our study contributes to the cross-section of operations management and artificial intelligence literature by articulating design principles to inform effective digital technology interventions at non-automated port terminals, both at operational and management levels.

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1. Introduction

Ongoing growth in international trade has fuelled the development of port container hubs as critical nodes in global supply networks. Indicatively, global container port throughput increased by 4.7% during 2017–2018, amounting to over 793.26 million 20-foot equivalent units (TEUs), thus reflecting the expansion of manufacturing operations (UNCTAD 2019, 14). In addition, the capacity of large container ships has increased above 10,000 TEUs (UNCTAD 2019, 69), thus creating challenges in port terminals regarding performance efficiency and service levels (Zhong et al. 2020). From an environmental sustainability viewpoint, international shipping is responsible for 2.2% of global CO_2 emissions and of the United Nations – International Maritime Organization (IMO) has set a strategic goal to halve greenhouse gas (GHG) emissions by 2050 (GEF-UNDP-IMO GloMEEP Project and IAPH 2018). Towards this path, academics and practitioners have proposed policies for promoting net-zero GHG emissions in the port sector via technology interventions at the shoreside (GREENPORT 2019). To that end, automation in ports and terminals on the landside[1] is regarded as a viable option that can promote sustainability (Fenton et al. 2018). An example of such interventions is the use of Automated Guided Vehicles (AGVs) as an enabling technology of intelligent logistics. In this context, our motivation is to examine the role of AGVs as a key technological application in next-generation container terminals and investigate how Artificial Intelligence (AI) can improve AGVs' performance and container port management.

Fully automated container hubs are expected to incur reduced operating expenses by 25–55% and increased productivity throughput by 13–35% (Chu et al. 2018). Notwithstanding the proclaimed benefits of automation, only 3% of container terminals around the globe are either semi- or fully- automated (Mongelluzzo 2019), thus indicating a need for further research as to adoption obstacles and associated cost–benefit outcomes. Similar to other domains, the main reasons for the low penetration of automation in ports refers to the duality of capital-intensive investments as well as the resistance from labour unions. The latter expresses the so-called 'fear of automation' (Spencer 2018). In the operations management literature, technology-enabled container handling in port terminals is generally well studied (Gharehgozli,

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Roy, and de Koster 2016); however, two main gaps can be identified. First, the studies on modelling port operations mainly consider conceptual port layouts and myopically focus on performance improvements in specific operations by considering uninterrupted material and process flows. For example, Liu et al. (2004) used simulation modelling to determine the optimal number of AGVs to deploy in common yard layouts and investigated the respective container terminals' operational performance. Second, the challenge of orchestrating real-time collaboration between the different systems, actors, and entities (e.g. port authorities, cargo owners, quayside cranes, yard cranes, vehicles, etc.) is discounted due to the added complexity of the modelling process. Specifically, the literature discussing the use of AGVs in container port terminals focuses on routing and scheduling aspects with the vast majority of modelling efforts investigating performance improvements such as the number of AGVs, the travel distance by vehicles, and/or efficiency and effectiveness of the applied analytic approaches (e.g. computational time and optimality gap).

Furthermore, extant studies on the use of AGVs in real-world container port terminals are limited while the research objectives focus on the operational performance of the vehicle(s) and overlook any environmental sustainability implications. Indicatively, Gelareh et al. (2013) studied the Dublin Ferry port Terminal to optimise the time required by AGVs to process all tasks before the departure of a cargo vessel. Furthermore, there is a sparsity of studies investigating the use of AGVs powered by non-conventional diesel engines in container port terminals. Notably, Schmidt et al. (2015) assessed the use of electric AGVs at Hamburg's Altenwerder terminal, but the analysis mainly considered economic sustainability aspects. Therefore, research on the environmental sustainability impact of different types of AGVs in real-world container port terminals, in tandem with vehicle routing, is sparse.

In addition, the majority of modelling approaches that seek to address the routing of AGVs in container port terminals focuses on exact solution methods. The drawback of an exact solution method is the computational time requirements to calculate the optimal solution owing to the size or complexity of the constraints (Desrochers, Desrosiers, and Solomon 1992). Hence, exact solution methods are unable to tackle dynamic changes and be implemented in real-world problems that require immediate actions/responses. In this regard, AI could support sensor-driven robotic operations in complex environments that entail real-time information gathering and processing for operational efficiency (Selke et al. 1991), such as at automated container port terminals. Heuristic and metaheuristic search, a core area of AI, has flourished during the last years (Pillac et al. 2013), indicating the importance of AI in practical settings (Spanaki et al. 2021). Several heuristic and metaheuristic algorithms have been developed to tackle practical problems by seeking to incorporate strategies to avoid local optima and diversify their search process, hence obtaining high-quality solutions in short computational times. The interest in AI and automation has been rekindled due to the range of organisational operations that could be transformed based on data gathering, sharing and analytics (Spanaki et al. 2018; Sahu, Young, and Rai 2020). This research focuses on the routing of AGVs at container terminals and the associated environmental implications by adopting AI principles. An interface is required to transition from a simple machine code for operations optimisation to high-level application generators combining an AGV's sensory data (Hinde 1989). To this effect, we claim that AGVs need to have some degree of intelligence to support such an interface to account for any possible error observations experienced at a shop floor level.

More specifically, this research contributes to the ever-growing literature of container port terminals' digitisation by investigating the environmental sustainability implications of intelligent logistics operations enabled by AGVs. In particular, a case study is considered via simulation, while at the same time design principles are proposed regarding the introduction of AGVs in extant ports, specifically focusing on the related gaseous emissions' impact and energy consumption. The research objectives that this study seeks to address are: (a) *What are the structural modelling characteristics of routing algorithms of AGVs within the context of container port terminals?* and more specifically (b) *How could such logistics operations be designed and managed in order to contribute to environmental sustainability?*

In this context, this study contributes to the cross-section of the operations management and artificial intelligence fields by studying the relationship between digital technologies and container port design within the prospect of automated operations to inform relevant interventions. Our work promotes the adoption of intelligent logistics in container port operations, following the greater need in the manufacturing domain (Dolgui 2005; Chien et al. 2020). To address the first research objective, we perform a comprehensive literature review related to the routing of AGVs in container port terminals. Regarding the second research objective, we develop a simulation study that captures the prospect of intelligent container handling operations at a real-world container terminal (Piraeus port). Our results support the articulation of design principles in intelligent port logistics, ensuring operational performance and sustainability. We anticipate our work to be beneficial to stakeholders (including policymakers and local governments) to consider adopting automation at ports.

The remainder of this study is structured as follows. Section 2 reviews the relevant literature. A simulation model investigating the environmental impact of alternative AGV types and scenarios is developed in Section 3, while Section 4 presents and discusses the results. In Section 5, four design principles for intelligent port logistics are articulated to support the transition towards sustainable container terminals and harness competitive advantages, thus highlighting the academic and practical contributions of this study. The paper concludes in Section 6 with a discussion about limitations and future research directions.

2. Literature review

During the last three decades, there have been several studies about the use of AGVs in the workplace (Qiu et al. 2002; Fazlollahtabar and Saidi-Mehrabad 2015). Qiu et al. (2002) provided a comprehensive review on AGV routing and scheduling issues in industrial applications. The authors grouped the algorithms into three categories: (i) algorithms for generic path topology; (ii) path layout optimisation; and (iii) specific path topologies. In addition, Fazlollahtabar and Saidi-Mehrabad (2015) performed a literature review on the routing and scheduling of AGVs in business operations, distribution, transhipment, and cargo transportation in the industrial and construction sectors. The study focused on different methodologies that are used to optimise AGVs, indicating the following classification of main approaches to study AGVs: (i) exact and heuristic methods; (ii) metaheuristic techniques; (iii) simulation; and (iv) AI methods. In this research, we focus on the routing of AGVs in container port terminals with regard to shoreside operations and the role of AGVs as an enabling tool of efficiency improvements and effective port management. Our aim is to inform about existing routing algorithms and relevant modelling aspects.

2.1. AGVs' routing in container terminals

To perform a comprehensive literature review and identify all relevant published scientific articles regarding the examined topic, we conduct Boolean-type searches using appropriate keywords in the Elsevier's Scopus database to synthesise existing evidence (Aivazidou et al. 2016). Although there is a range of electronic search engines to retrieve academic contributions, Scopus was selected due to its wide acceptance for systematically mapping and reviewing the extant body of literature (Fahimnia et al. 2019; Pournader et al. 2020) and the excessive coverage (> 90%) of scientific articles in the 'Business, Economics & Management', 'Physics & Mathematics' and 'Engineering & Computer Science' domains (Martín-Martín et al. 2018). The query involved the terms: 'Automated Guided Vehicle', 'container terminal', and 'rout*' which were matched against the article's title, abstract and keywords. No specific time horizon was imposed and the results were filtered to include only peer-reviewed articles to ensure access to '*best-quality evidence*' (Tranfield, Denyer, and Smart 2003) written in the English language. The results were screened for eligibility, subject to the objectives of this research.

Based on the above criteria, 12 publications on the routing of AGVs were selected. Since the number of articles was low, we also included studies retrieved from other sources like the Thomson Reuters's Web of Science database, whilst considering conference papers as well. In alignment to Pournader, Kach, and Talluri (2020), our personal experience through investigating the Web of Science database led to the understanding that Scopus provides the plethora of most relevant articles published in the research topic of focus. In particular, for the purposes of this study, we observe that the search outcomes in Scopus completely cover and extend the search results in the Web of Science. The growing publications' trend during the recent years demonstrates the vivid research interest on AGVs' routing at freight ports.

2.1.1. Integrating routing and scheduling decisions

Dkhil, Yassine, and Chabchoub (2013) developed a bi-objective model to formulate the scheduling problem of activities in a single 'Quayside Cranes-AGVs-Yard Cranes' system under the objectives: (i) to minimise the container handling and transport time; and (ii) to minimise the AGV fleet size. The main idea was to address the task scheduling problem and decrease the operating cost at an automated container terminal. The study emphasised the formulation of the mathematical models for three alternative traffic layouts at the terminal, seeking to examine different terminal architectures and the impact of these on the scheduling decisions. Regarding the routing problem, the focus was on a tactical level; in particular, the authors' aim was to calculate the sufficient number of AGVs for the optimal schedule rather than the detailed routes of AGVs. Hence, operational routing decisions and the related gaseous emissions and/or energy considerations were overlooked.

In a similar stream of literature, Corman et al. (2016) studied the combinatorial scheduling and routing problem of AGVs in an automated container terminal. The authors proposed a mathematical formulation, based on the alternative graph model, to solve the combinatorial problem in a near-optimal way. Specifically, a hybrid model was deployed to address both discrete (i.e. assign containers to AGVs and then determine the order of containers' movement) and continuous dynamics (i.e. free-range trajectories of AGVs) of the examined setting. Metaheuristic algorithms, such as the Variable Neighbourhood Search and the Tabu Search, were applied to decide the assignment of containers to AGVs, while a truncated branch and bound algorithm was used to solve the scheduling problem. Numerical experimentations were conducted to evaluate the performance of the proposed approach, indicating its applicability in real world problems.

Another recent study from Zaghdoud et al. (2016) examined the problem of containers' assignment to AGVs, incorporating three sub-problems (routing, dispatching, and scheduling) by developing a hybrid approach. The optimisation of the operations as a single problem is a complex task; hence, the basic research idea was to decompose the problem into sub-problems. The authors proposed a hybrid solution that composes an exact algorithm for the routing problem, a genetic algorithm about the dispatching problem, and a heuristic algorithm for the scheduling problem. Numerical analysis indicated that the proposed algorithm is effective and computes high-quality solutions regarding the objective while the computational time is not significantly affected. However, the authors did not consider energy consumption along with the related emissions.

In regard to improve crane operations in port terminals, Yang et al. (2018) investigated the problem of integrated scheduling of quay cranes, AGVs and automated rail-mounted gantry cranes, for simultaneous container loading and unloading operations. The authors developed a two-level programming model to minimise completion time, considering also traffic congestion. The proposed solution combined a heuristic and a genetic algorithm. The idea behind the utilised approach was to develop an algorithm that firstly is effective in global search with the ability to obtain accurate solutions and secondly is flexible and applicable to different problems. The authors' contribution lies in the integrated programming of AGVs, quays and yard cranes to optimise vehicles' route planning at automated terminals while implementing traffic congestion prevention rules. This is also beneficial for terminal managers at an operational level.

Lu and Wang (2019) studied the scheduling of 'twin' yard cranes that interact with AGVs to minimise their waiting time and consequently the loading and unloading times of containers. The problem is NP-hard; hence, the authors developed a metaheuristic algorithm based on graph theory to tackle it. In particular, the proposed solution applied the Particle Swarm Optimisation method. The scheduling strategy directly affects the waiting time of AGVs and plays an important role in the terminal's operational performance. The authors evaluated the proposed algorithm and demonstrated the resulting benefits through numerical experimentation.

As regards container loading, Shouwen et al. (2020) considered the problem of container loading and unloading operations at an automated terminal. The authors studied a combinatorial optimisation problem regarding the integrated scheduling of quay cranes, AGVs, stacking cranes, and conflict-free AGV routing. Their proposed solution was based on a two-level programming model. First, they solved the integrated scheduling problem of the three classes of equipment and then, they determined the route that minimises the travel distance of the AGV fleet by designing two bi-level genetic algorithms to tackle the combinatorial problem. They also verified the effectiveness of that approach experimentally.

Hu, Dong, and Xu (2020) examined the dispatching and routing problem of AGVs at an automated container terminal, where the objective was to minimise the total travel distance of AGVs and reduce the operations time. The authors proposed a three-stage decomposition approach to tackle the problem, while time windows for the AGVs were considered. The three stages were: (i) task assignment based on quick response; (ii) route planning based on the minimum distance; and (iii) route re-planning based on both conflict type and processing time. Hence, the proposed solution combined elements of pre-planning and real-time planning algorithms.

Zhen et al. (2020) provided a decision framework to address the problem of scheduling and routing AGVs in a time-varying traffic environment. The authors sought to optimise the scheduling and routing of an AGV fleet considering the waiting time caused by traffic congestion. The main study objective was to find the optimal routing plan under the criterion of minimising the total penalty cost attributed to traffic congestion. Specifically, an integer linear programming model was employed to tackle the examined setting. The latter is realistic since several AGVs are used at automated container terminals. Computational experiments were conducted to validate the proposed decision support framework's efficiency and demonstrate high quality solutions within a (relatively) short computation time. This is also beneficial for both terminal managers at an operational level and port managers to design and schedule dynamic routing plans for AGVs under different traffic conditions.

Finally, Xu et al. (2020) studied the scheduling and routing problem of AGVs in an automated container terminal considering fully loaded mode. The authors examined the case in which an AGV can carry two containers at the same time, seeking to improve efficiency from a transportation perspective. The main idea was to allow a two-way loading between the dock and the container yard, while a quayside buffer exists to ensure coupling between quayside work and AGV routing. The problem was addressed based on a simulated annealing algorithm. The authors compared their proposed solution with two popular algorithms to verify the effectiveness of their approach. However, energy consumption considerations and the related emissions were not contemplated.

2.1.2. Routing decisions

Zeng and Hsu (2008) employed a mathematical model regarding the routing of multiple AGVs in a mesh topology, extending the idea of conflict-free routing of AGVs (Qiu and Hsu 2001). Qiu and Hsu (2001) formulated a mathematical model to achieve a conflict-free routing of AGVs, indicating the critical conditions and the key parameters for that. Zeng and Hsu (2008) explored alternative directions and velocities of vehicles to avoid collisions and minimise work completion time. The authors considered discrete time division and presented a mesh routing algorithm that guarantees freedom of conflicts by allowing the selection of suitable vehicles' velocities along different directions. Numerical experiments verified that the proposed routing algorithm achieves high performance; however, carbon emissions and/or energy consumption of the AGVs were not considered.

Jeon, Kim, and Kopfer (2011) developed an algorithm for AGVs' routing at port terminals based on machine learning. More specifically, the authors employed the Q-learning technique to achieve the shortest travel time instead of the shortest distance route (which is common in routing problems) for each delivery order. This was feasible since the authors considered the congestion at the container port terminal. The focus on travel time is logical, since one of the most critical aspects for efficient port operations management is to minimise the total time that a vessel is docked to the terminal. Furthermore, a simulation study was performed indicating that travel time for an AGV could be reduced up to 17.3% when the proposed learning-based route is applied.

Li et al. (2011) formulated a routing algorithm and investigated its performance through simulation under the objective to minimise AGVs' travel distance and cargo transport times. The results showed that the use of multiple intersections in a network can lead to shorter waiting times for vehicles at major intersections, while the total travel distance was significantly longer than that using central junctions. Moreover, the use of alternative routes provides more space for the movement of vehicles which leads to increased travel distances for the vehicles. A routing algorithm for AGVs in a conceptual terminal for the optimal management of containers between the quayside cranes and the stacking area, by allowing the AGVs to use the entire area and not only predefined and/or fixed paths, was developed by Duinkerken and Lodewijks (2015). The proposed method focused on minimising the routing cost (determined by four factors, namely: vehicle speed, travel time, avoidance of fixed obstacles, avoidance of other vehicles) to improve vehicles' average waiting time, average trajectory length, and number of moves per hour.

At the same time, Li et al. (2016) presented a traffic control for AGVs to exclude inter-vehicle collisions and system deadlocks. The traffic control approach allows each AGV to select its routes for any finite sequence of transportation tasks whilst avoiding collisions and deadlocks with the occurrence of vehicle breakdowns. Hence, the authors were able to design routing algorithms that guarantee the avoidance of collisions and deadlocks with full freedom of routing. A simulation-based case study at an automated container terminal was developed to demonstrate the applicability of the proposed approach, while the results were compared with cases in which the freedom of routing was not applied.

2.2. Research gap

The comprehensive literature review initially reveals that the AGVs' routing problem at a container terminal can be considered either in isolation or part of a more complex setup, involving coordination with other types of equipment. An interesting finding is that the environmental impact of AGVs, measured either through carbon emissions and/or energy consumption, has not been addressed when the routing problem is examined. The importance of considering energy consumption and related emissions factors is a critical aspect towards the net zero emissions target. Iris and Lam (2019) conducted a systematic review about the energy efficiency in ports, focusing on the business strategies and operations, technology adoption, renewable energy sources, alternative fuels, and energy management systems, to improve terminals' environmental performance. There are interesting studies related to the environmental sustainability of AGVs at container terminals, but routing decisions either on a tactical or operational level are not considered. The study by Schmidt et al. (2015) provides an indicative case in that regard, where the use of battery-electric AGVs was assessed based on their economic feasibility regarding capital cost and return on investment. This demonstrated that terminal operators could achieve more than 10%

of cost savings compared to utilising a fleet of diesel-powered AGVs. While there are several other studies that look at the environmental sustainability of battery-operated vehicles, it is beyond the scope of this work to review studies that do not address the AGV routing problem specifically.

The main methodologies that have been used in the literature for assessing intelligent logistics in a 'port-equipment-containers-AGVs' system relate to: (i) AI techniques; (ii) decision support systems; and (iii) operations research-based algorithms. Thereafter, the environmental impact, across the emissions-energy nexus, of intelligent autonomous vehicles in container port terminals has not been adequately studied. Extant scientific articles focus exclusively on the mathematical modelling and solving techniques of routing algorithms for AGVs in conceptual container port settings, without considering the related environmental footprints. As port authorities and institutions begin to recognise the issue of carbon emissions and energy consumption in ports, the relevant management bodies are likely to promote research on the introduction of AGVs and intelligent operations in container operations management.

In addition to that and considering the interaction between automation and port operations is a relatively new field in the literature, we also opted to seek how topics related to 'AGVs', 'Port Operations' and 'Automation' are clustered together. Using the literature search criteria that were outlined before, we extracted the unstructured part of the publications' metadata (paper abstract, author provided keywords, librarian indexed keywords) and created a topic model using the co-occurrence relationship of the words in the articles' abstract and the semantic distance between the keywords. For each paper, we tokenised the abstract by removing the stop-words and creating word frequency matrixes. For each theme, the ratio of raw frequency counts over total counts was used to estimate the percent of variance accounting for the themes (Figure 1). The dominant topic considers the application of AGVs in ports and the interaction with port operations. As can also be seen in the coloured clustering, the major component concerns the use of AGVs in container terminals and its interaction with algorithmic implementations in either scheduling or routing aspects. The periphery of the main theme also considers the interaction between AGVs with terminal efficiency and port operations.

3. Case study description

Design principles to deploy AGVs in non-automated container port terminals would be useful to guide digital-driven infrastructure investments. For our case study, we used the port of Piraeus (United Nations Code for Trade and Transport Locations – UN/LOCODE: GRPIR). This provided several advantages grounded on its strategic role as a major port terminal in the Mediterranean with multiple functions, such as bulk cargo, containers, passengers, cruise ships, etc.

3.1. Case background

Piraeus port has seen significant growth during the last few years, making it the world's fastest-growing port (Safety4Sea 2018). Maritime traffic at the Piraeus port has increased in the previous years due to: (i) the expansion of the container terminals; (ii) the continuous development of the cruise market; and (iii) the increasing touristic and passengers traffic owing to the unique landscape of the country and the multiple connections of Piraeus to Greek islands. The strategic role of the port of Piraeus for the international trade has been accredited by the acquisition of 51% of the Port's shareholding by the Chinese company COSCO Shipping Ports in 2016 (Huo, Zhang, and Chen 2018). According to AXSmarine's Alphaliner ranking[2], COSCO has the third-largest container fleet in the world with a combined owned and chartered capacity of about 2.94 million TEUs. The company has acknowledged the importance of Piraeus considering its strategic geographical location: '*. . . as the most advantageous geographical location being the first EU port after crossing Suez Canal, bridging all available transport modes (sea, rail, road, air)*'.[3]

The current management of containers in the port of Piraeus is performed via conventional forklift vehicles, resulting in constrained capacity, low efficiency and costly procedures. Hence, Piraeus port represents an appropriate case study to explore the impact of adopting and implementing AGVs in order to quantify the environmental impacts of using them to container port management operations. In addition, air pollution poses a major environmental issue in the Attica region (Mirasgedis et al. 2008), and the port of Piraeus contributes with elevated emissions due to the increasing passenger and container traffic. However, the pollutants' emissions from port activity, as well as the consequent health effects, have been calculated only from the viewpoint of maritime traffic (Chatzinikolaou, Oikonomou, and Ventikos 2015). In terms of its layout, the port's development started in 1973 with the trapezoid in shape Pier I. In 1978, construction of the second trapezoidal Pier II began at the same location, while Pier III was constructed as an extension. The annual capacity of Pier I is 1,000,000 TEUs. Figure 2 shows the locations of Pier I, Pier II and Pier III.

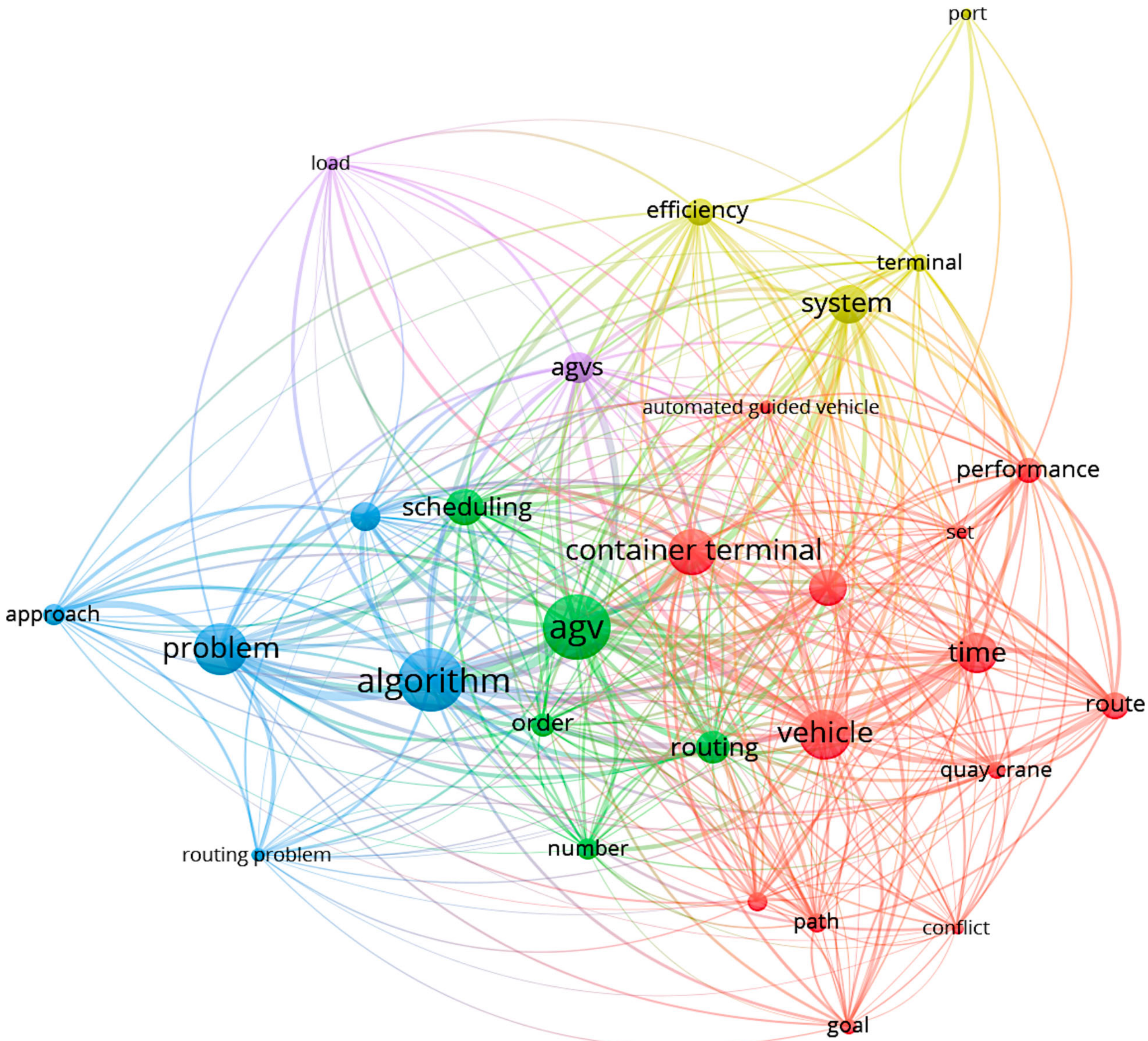

Figure 1. Network map illustrating the relations between key terms in the field of automation in container port terminals.

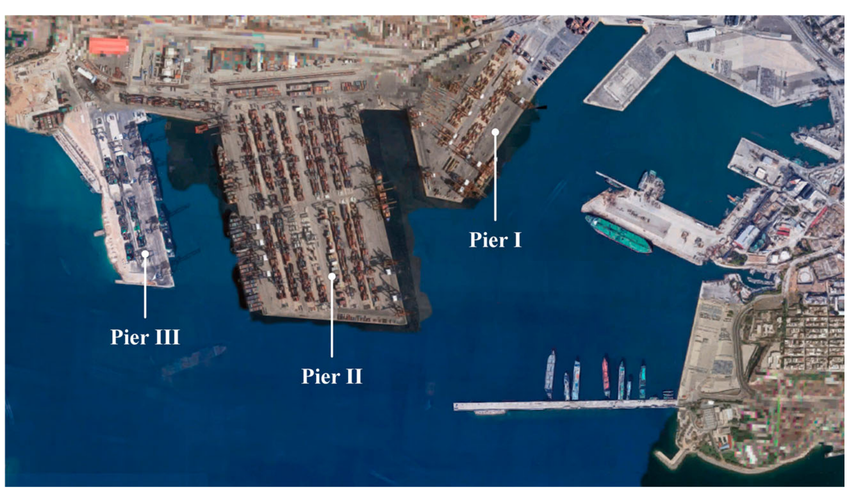

Figure 2. Topology at the container port terminal of Piraeus [*Source*: processed landscape view captured from Google Earth].

In this study, we focus on the import aspect of port operations, as our objective is to explore the benefits of automation and AI techniques on shoreside operations. Regarding the container unloading equipment from cargo vessels, Pier I in total utilises seven ship-to-shore (STS) cranes; four over Super Post Panamax; and (ii) three Panamax twin-lifts. In terms of container storage spaces and yard equipment, in Pier I exist: (i) four rail-mounted gantry cranes (RMG 1st Series) servicing a total area of 26,000 m^2 and 1,302 ground locations; and (ii) four rail-mounted gantry cranes (RMG 2nd Series) servicing a total area of 18,700 m^2 with 924 ground locations.

3.2. Case parameters

The case study considers that an AGV is installed at Pier I and is used to transport containers from the quayside cranes, which unload a vessel, to the yard cranes, which stack the containers to the storage area. The terminal operator's current policy requires that containers are first unloaded from the cargo ship with the quayside cranes, then transported by the AGV to a predefined yard space, and finally unloaded from the AGV and stored in the appropriate space by the yard cranes. Regarding the container sizes, we consider the two most frequently used types of containers in the shipping industry depending on their capacity, i.e. 20-ft and 40-ft. Therefore, these two types of containers are to be unloaded, transported, and stored.

We assume that the containers are initially loaded at respective ship compartments, namely: (i) Ship Compartment 1 – 40-ft containers; (ii) Ship Compartment 2 – 20-ft containers; (iii) Ship Compartment 3 – 20-ft containers; and (iv) Ship Compartment 4 – 40-ft containers. Each Ship Compartment is therefore served by a particular quayside crane: (i) STS SPP No 1 – Ship Compartment 1; (ii) STS SPP No 2 – Ship Compartment 2; (iii) STS SPP No 3 – Ship Compartment 3; and (iv) STS SPP No 4 – Ship Compartment 4. Furthermore, there are two stacking areas based on the container type, namely: (i) Yard Place 40-ft; and (ii) Yard Place 20-ft. Specifically, RMG No 1 is used for handling 40-ft containers in the Yard Place 40-ft, while RMG No 2 is used for handling 20-ft containers in the Yard Place 20-ft. As the focus of this research is to demonstrate the impact of alternative vehicle routing on the gaseous emissions and energy consumption at the shoreside of port terminals, we assume that stacking of mixed containers (e.g. a 40-ft container placed on top of two 20-ft containers and vice versa) at the same yard is not allowed.

Three types of an AGV are investigated, depending on the engine type and fuel, with corresponding environmental emissions and energy consumption factors; these are: (i) 'LPG' – liquefied gas-powered vehicle; (ii) 'ELE' – electric-powered vehicle; and (iii) 'DSL' – diesel-powered vehicle. Regarding the environmental impacts, this research employs the emissions and energy factors provided by Fuc et al. (2016) which had been estimated based on a Life Cycle Impact Assessment applied to forklift trucks with different engine types. The utilised environmental impact and energy consumption indicators are presented in Table A1 in Appendix.

3.3. Routing algorithms

To explore the role of AGVs' routing on the gaseous emissions and energy consumption in our study, we develop the following two algorithms: (i) '*Loop Routing*'; and (ii) '*Shortest Distance Loop Routing*'. The first algorithm is used as the reference standard case of automated logistics whereas the second introduces an element of intelligence in automated logistics where routing decisions involve a greater amount of data analysis to inform about the most distance-efficient routing process. These algorithms are to service one quayside crane at a time and unload the cargo vessel. The simulation results are leveraged to articulate design principles for intelligent container handling operations in ports.

3.3.1. Routing algorithm #1 – 'Loop Routing'

The '*Loop Routing*' allows only the clockwise navigation (monodirectional navigation) of the AGV. In brief, the AGV starts from the central depot and successively visits: (i) STS SPP No 4; (ii) STS SPP No 1; (iii) STS SPP No 3; and (iv) STS SPP No 2. The purpose of this sequence is to unload the containers from the cargo vessel in a rather naive manner, i.e. firstly the 40-ft and then the 20-ft containers for the uniform unloading of the vessel. There is an intersection where the AGV needs to make a routing decision as the two different types of containers have to be unloaded to different stacking spaces. The containers are unloaded with quayside cranes and transported by the AGV to RMG No 1 (stacking 40-ft containers at Yard Place 40-ft) and RMG No 2 (stacking 20-ft containers at Yard Place 20-ft). In case that all containers are unloaded, the AGV returns to the central depot for refuelling/recharging. The algorithm is diagrammatically described in Figure 3, while Figure 4 presents the flowchart of it.

3.3.2. Routing algorithm #2 – 'Shortest Distance Loop Routing'

The '*Shortest Distance Loop Routing*' allows the intelligent routing of the AGV based on the shortest distance required to transport a container from each quayside

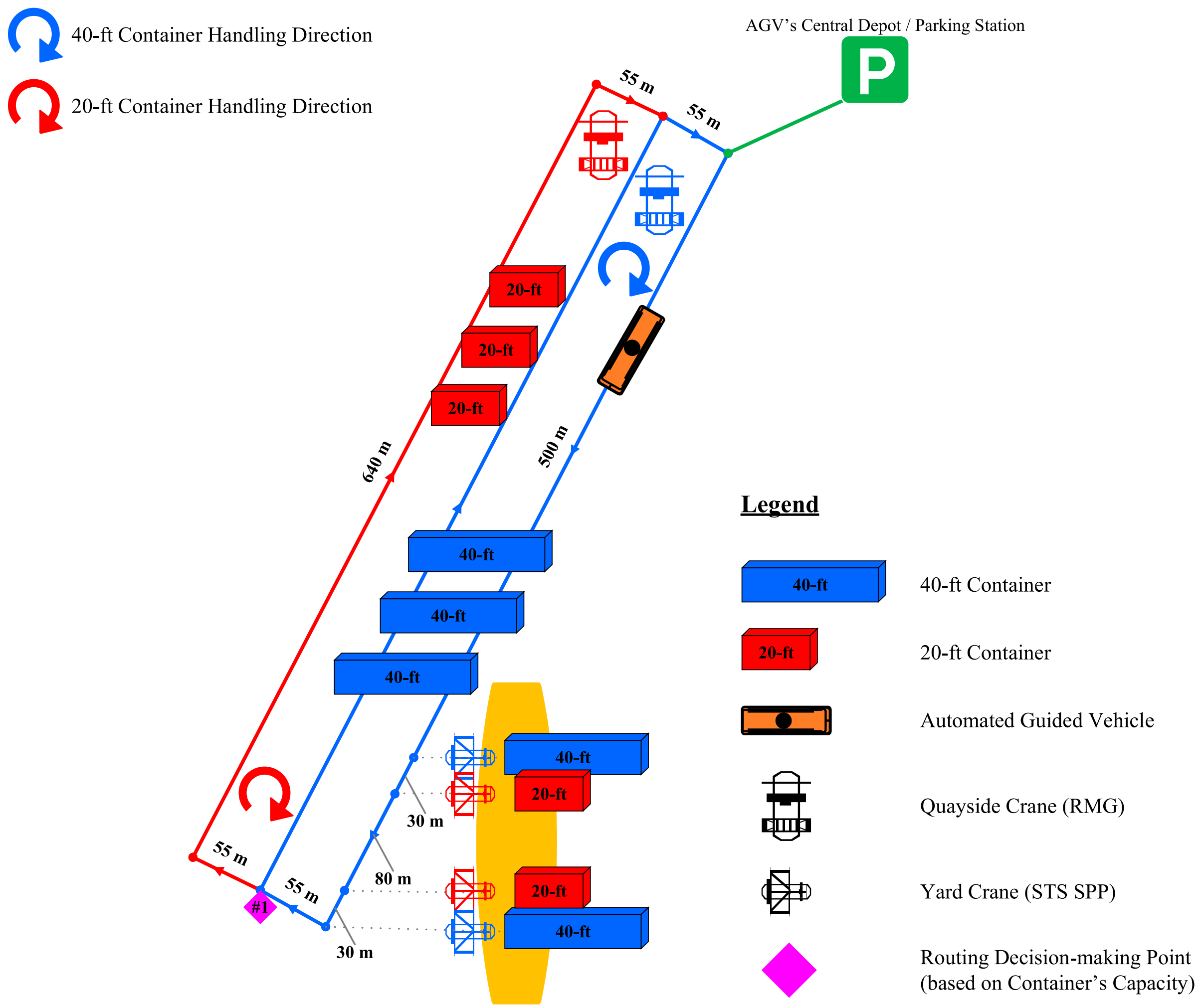

Figure 3. Visual representation of the '*Loop Routing*' algorithm.

crane to the suitable yard crane. The algorithm allows the bidirectional navigation of the vehicle, depending on the necessary route to ensure minimum travel distance. In brief, the AGV starts from the central depot and successively visits: (i) STS SPP No 4; (ii) STS SPP No 1; (iii) STS SPP No 3; and (iv) STS SPP No 2. The containers are unloaded with quayside cranes and transported by the AGV to RMG No 1 (stacking 40-ft containers at Yard Place 40-ft) and RMG No 2 (stacking 20-ft containers at Yard Place 20-ft). After each quayside crane unloads a container, the AGV assesses the total required distance of all alternative routes to deliver the container to the suitable yard crane. In total, six decision-making points are recognised where the AGV needs to make a routing decision, based on the different types of the container and the required travel distance. In case that all containers are unloaded, the AGV returns to the central depot for refuelling/recharging. The algorithm is illustrated in Figure 5, while its flowchart is shown in Figure 6.

Since this research's main objective is to provide evidence regarding the adoption of intelligent logistics for environmentally sustainable container freight management at ports, a further mathematical investigation of the examined algorithms is beyond the scope of this paper. Table 1 presents the experimental design in this research.

3.4. Model setup

The implementation of container terminal management policies is analysed via simulation that could improve system performance by enabling more efficient port equipment use. Simulation models can be categorised into: (i) continuous process; (ii) discrete-event; and (iii) combined simulation (El-Haik and Al-Aomar, 2006). Discrete-event simulation is the most common type of simulation. In general, it considers the discrete variables and cases where the state of a system changes at discrete points over time. In this study, discrete-event

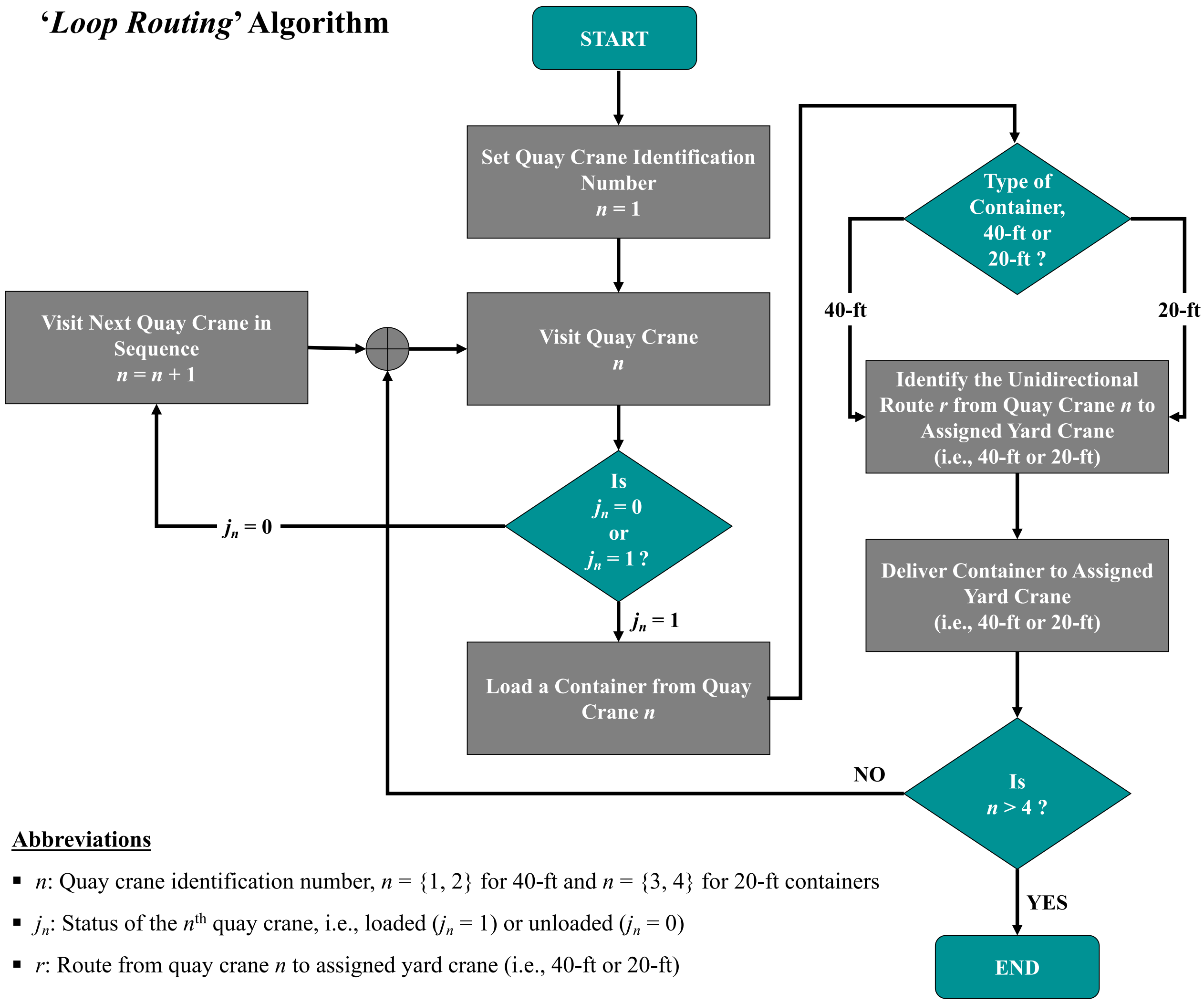

Figure 4. Flowchart of the '*Loop Routing*' algorithm.

simulation models were developed to study the impact of introducing AGVs in Pier I, container port of Piraeus, in terms of emitted gaseous pollutants and energy consumption.

The simulation models were developed in the WITNESS Horizon (Version 22.5) software environment of the Lanner Group. The basic modelling assumptions are presented in Table 2.

We ran the simulation models for a total number of 40 containers with an allocation of 20 containers per type and 10 containers per Ship Compartment.

3.5. Model validation & verification

Model validation ensures the accurate representation of the underlying real-world system; so, that the model is structured and behaves realistically (Al-Aomar, Williams, and Ulgen 2015). To validate the appropriateness of the proposed routing algorithms, the following procedural remedies were followed:

- *Inspection of visual elements* – The validation of the models was performed by monitoring their behaviour during the execution time to ensure that the handling of the two container types of containers and the AGV's routing were as expected, in alignment also with the topology of Pier I and the simulation assumptions.
- *Control of model input data* – The shop floor design of the port terminal and other data were retrieved from available official sources[4], while the operating parameters of the AGV and other equipment in the model (such as the emissions and energy consumption impact indicators) were retrieved from the scientific literature (Fuc et al. 2016).

Model verification assesses whether a model conforms to the desired conceptual design, logic, and conditions imposed at the beginning of a model's development stage (Al-Aomar, Williams, and Ulgen 2015). The following techniques were applied to verify the developed simulation analysis:

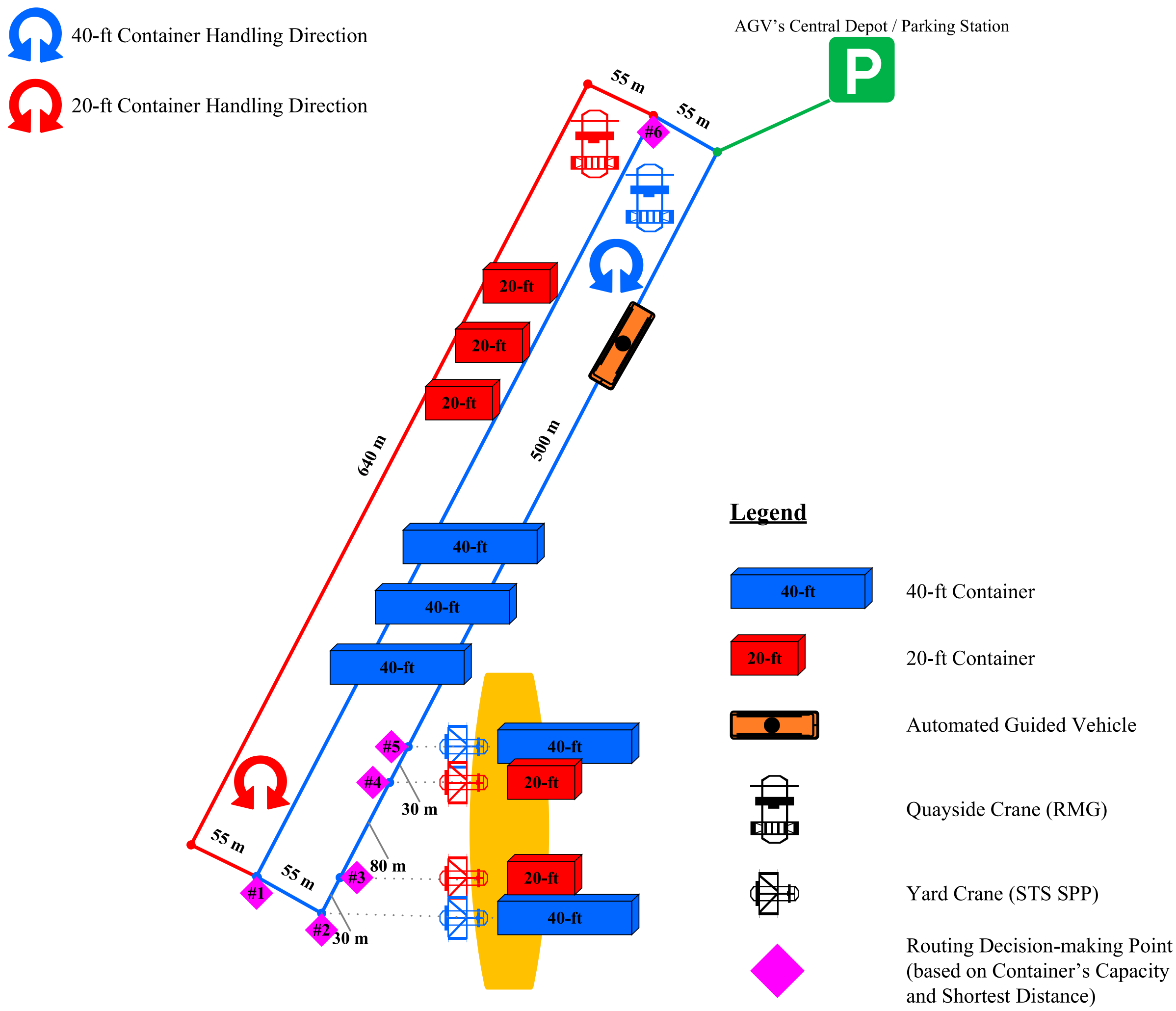

Figure 5. Visual representation of the '*Shortest Distance Loop Routing*' algorithm.

- *Detailed examination of model inputs* – Each input parameter was studied individually, while multiple simulations were used to ensure that the initial values of the parameters were used correctly during the simulation process. At the end of each simulation, the input parameters were studied to determine that their values did not change involuntarily during the simulation.
- *A thorough study of simulation results* – The simulation results were studied for different input parameter values (e.g. vehicle type, vehicle status, emissions, and energy consumption factors), and we observed the reasonableness of the outputs. In addition, we simulated both routing scenarios for the AGV in terms of a varying number of containers, and we observed the expected linear relation between the number of containers to be handled and the AGV's travel distance (Figure 7).
- *Leveraging the simulation package's visual features* – We leveraged the 'animation' features of the used software and visually observed whether the containers were delivered by the AGV to the intended crane and whether these were then stored at the intended stacking areas. Moreover, the algorithms' implementation was visually checked to verify that the shortest of the available alternative routes (specifically in Routing Algorithm #2) is actually selected.

4. Simulation results

This section summarises the simulation results seeking to quantify the environmentally sustainable gains when intelligent operations are adopted at container port terminals. We then discuss the results, focusing on the direct and indirect impact regarding gaseous emissions and energy consumption that can arise by the potential usage of AGVs and automation in container port terminals.

4.1. Travel distance

The simulation results demonstrate that the implementation of algorithms and intelligence in AGV routing

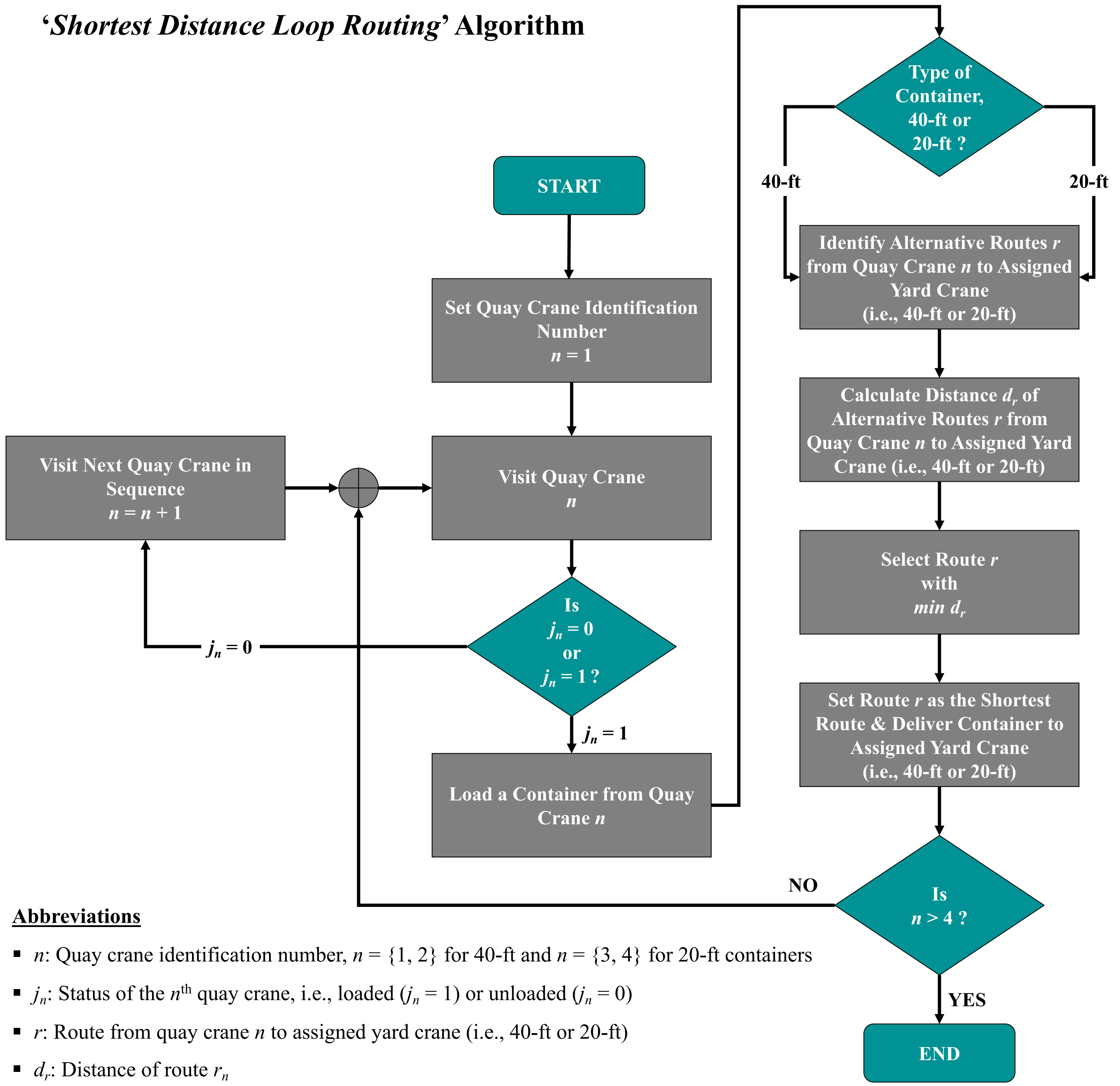

Figure 6. Flowchart of the '*Shortest Distance Loop Routing*' algorithm.

decisions has a direct impact on the total travel distance that is required in cargo handling operations. Specifically, the total travel distance by the AGV, per vehicle status (i.e. unloaded or loaded) and routing algorithm, is shown in Figure 8.

It is observed that the adoption of intelligent logistics (Routing Algorithm #2) is denoted by an increase in the number of decision-making points during the autonomous navigation of the robot vehicle. This leads the AGV to cover a shorter total distance by 5.6 km (for a total of 40 containers), compared to the reference case of Routing Algorithm #1; i.e. an improvement of about 10% is achieved. Notably, an improvement of around 18% is attained in case the AGV is loaded. Considering the higher emissions factors and energy consumption in the loaded status, the implementation of innovative technologies and AI principles is necessary for reducing the total travel distance that an AGV fleet has to cover in container port terminals regarding the loading, transportation and unloading operations. It should be noted that in the second scenario, due to the layout of the shop floor and the possibility of bidirectional routing, the loading and unloading operations do not yield any difference in the required travel distance. In the case where a monodirectional layout is imposed, the saving is considerable (as it can be seen in the first bar group in Figure 8).

In Routing Algorithm #1, there is a single routing decision-making point (Figure 3); in decision point #1

Table 1. Design of experiments.

AGV Type	Vehicle Status	Routing Algorithm	Container Type/Capacity
LPG	Unloaded	*'Loop Routing' & 'Shortest Distance Loop Routing'*	20-ft and 40-ft
	Loaded	*'Loop Routing' & 'Shortest Distance Loop Routing'*	
ELE	Unloaded	*'Loop Routing' & 'Shortest Distance Loop Routing'*	20-ft and 40-ft
	Loaded	*'Loop Routing' & 'Shortest Distance Loop Routing'*	
DSL	Unloaded	*'Loop Routing' & 'Shortest Distance Loop Routing'*	20-ft and 40-ft
	Loaded	*'Loop Routing' & 'Shortest Distance Loop Routing'*	

Symbol: 'LPG' – liquefied gas-powered vehicle; 'ELE' – electric-powered vehicle; 'DSL' – diesel-powered vehicle.

Table 2. Model assumptions.

#	Assumption
A1	A single AGV is considered in the shop floor environment.
A2	The speed of the AGV is constant but differs for the cases of unloaded and loaded vehicle.
A3	The possibility of disruptions (e.g. mechanical failures, equipment malfunctions) is omitted.
A4	Quayside cranes (type STS SPP) and yard cranes (type RMG) have specific functional parameters for loading and unloading containers.
A5	The capacity of the AGV is one container, regardless of each container's size.
A6	The weight of each container is considered one metric ton (1 t), regardless of its size.
A7	The unloading of containers by the RMGs is always performed from a specific location at the top of each route leading to the appropriate yard space.
A8	The stacking of mixed type containers is not permitted.

it is sufficient to consider only the capacity of the container where the delivery of a 20-ft container requires that an additional distance of 110 m is travelled, based on the topology of the operations layout. On the contrary, in Routing Algorithm #2 there are six decision-making points (Figure 5); for the decision points #2-#5, the algorithm needs to consider the total distance from the quayside cranes to the appropriate yard crane. For the decision points #1 and #6, the capacity of the container is the single decision variable. The distance savings in the case of the intelligent logistics could be up to 20% for the delivery of a 40-ft container and up to 15% for the delivery of a 20-ft container.

Overall, intelligent logistics need to consider the scheduling of operations in a 'port-equipment-containers-AGVs' system. A solution regarding the routing of AGVs should ensure, in real-time, that the idle time of quayside and yard cranes is minimised while these cranes shall not be occupied when the AGV is ready to receive/deliver a container. This requisite should be fulfilled provided that the ultimate objective of landside operations at port terminals is to support freight vessels and minimise the total time that a vessel is docked to the terminal since containerships are not built for remaining idle in ports. Therefore, both the container transport vehicle's velocity and the makespan of the cranes, need to be continuously monitored (e.g. via sensors) to inform in real-time the intelligent decision-making over the required operations.

4.2. Environmental impact

A strong correlation exists between travel distance and carbon emissions and energy consumption (Zissis et al. 2018). Hence, a potential reduction in travel distance results in environmental benefits. Tables 3 and 4 summarise the simulation outcome regarding the environmental impact associated to the examined algorithms, based on the investigated case study.

Concerning the environmental aspects, the preferable type of AGVs (regarding the engine) is the electric-powered vehicles (ELE) which is intuitive as such vehicles produce almost zero emissions. An interesting observation about the ELE vehicles is the small increase of the emissions when the respective container transport vehicles are loaded, compared to the unloaded status, while the respective increase is substantial for diesel-powered vehicles (DSL) and liquefied gas-powered (LPG) vehicles. In particular, for Routing Algorithm #1, when an ELE vehicle is used the increased total emissions (in mPt) are around 22% if it is loaded. In contrast, the corresponding increase is 82% for a DSL vehicle and 254% in the case that an LPG vehicle is used. This is more evident for Routing Algorithm #2, in which there is no difference at the emissions between the cases of unloaded and loaded ELE. Still, there is an increase of 50% and 192% between the unloaded and loaded status cases when DSL and LPG vehicles are used, respectively.

In addition, Table 5 summarises the simulation results per investigated algorithm and indicates the improvements in the emissions-energy nexus, in terms of the weighted ecological index mPt, emanating from the adoption of intelligent autonomous vehicles in port logistics, per type and status of AGV. We observe that there is a significant improvement of around 18% for loaded vehicles when intelligent logistics (i.e. Routing Algorithm #2) are implemented. This is also in line with the literature

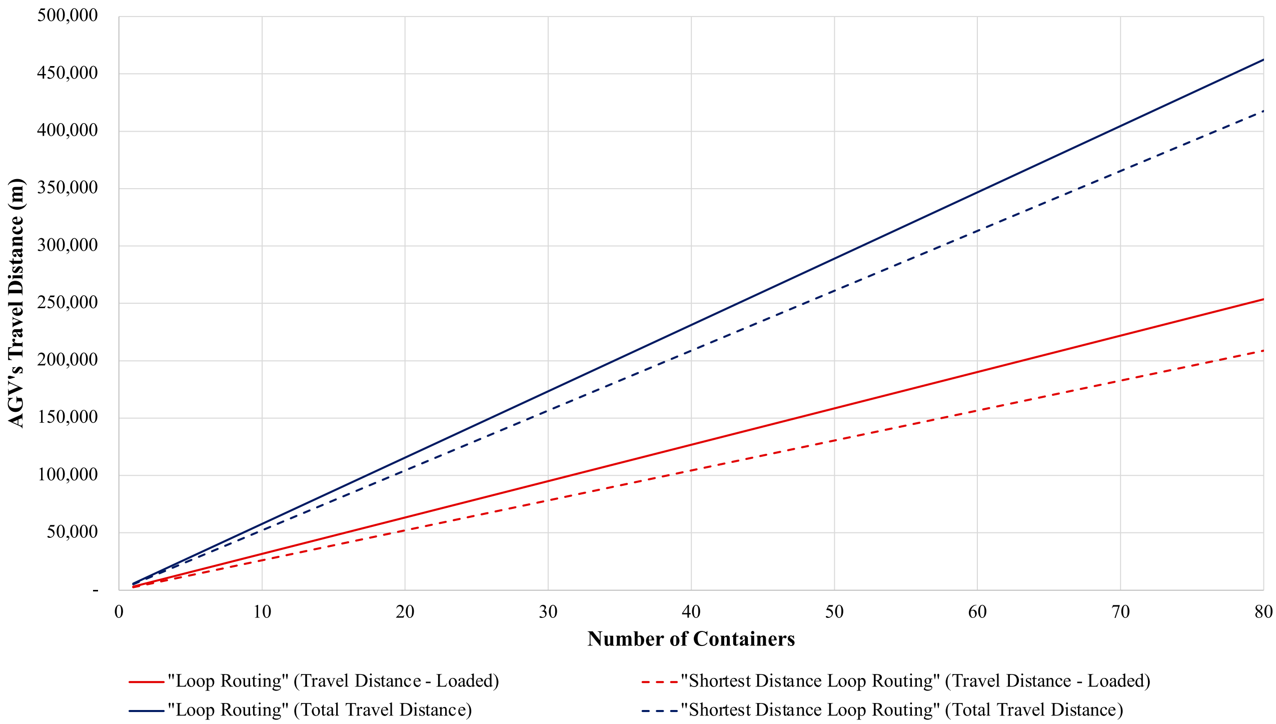

Figure 7. Model verification results.

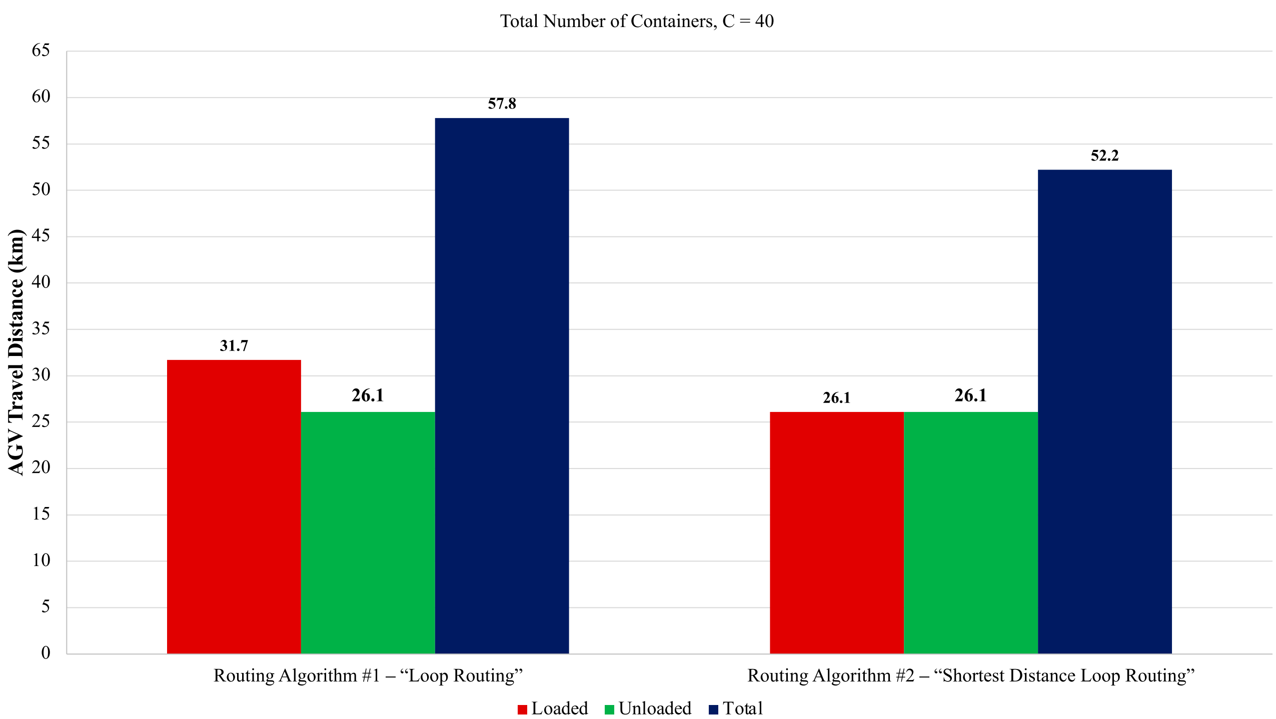

Figure 8. AGV travel distance (in km), per vehicle status (i.e. unloaded or loaded) and routing algorithm.

and how a potential reduction of travel distance affects the relative emissions and energy consumption (Zissis et al. 2018).

Our results reveal that intelligent logistics for landside operations at container ports can contribute, to a degree, to the directives of the European Union that necessitate the Member States to compose and implement programmes to limit their annual emissions. According to the European Environment Agency, poor quality environments contribute to 13% of deaths (EEA 2020). Therefore, tackling environmental pollution at individual sectors, like container port terminals, will help collectively

Table 3. Environmental impact of AGV for Routing Algorithm #1 – '*Loop Routing*' (Total number of containers, C = 40).

AGV Type	Vehicle Status	Total mPt Emissions (mPt)	Total Global Warming Impact (kg CO2-eq)	Total Respiratory Inorganics (kg PM2.5-eq)	Total Electricity (kWh)	Total Primary Energy – Non-renewable Energy (MJ primary)	Total Secondary Energy – Non-renewable Energy (MJ secondary)
LPG	Unloaded	52,461.000	54,810	75.69	0	873,567	41.76
	Loaded (1 t)	185,762.000	175,618	221.90	0	2,794,038	126.80
ELE	Unloaded	3,132.000	10,962	7.83	8,352	130,239	20.88
	Loaded (1 t)	3,804.000	13,631	12.68	10,461	163,255	25.36
DSL	Unloaded	21,924.000	45,414	57.42	0	680,427	28.71
	Loaded (1 t)	39,942.000	77,665	95.10	0	1,153,563	47.55

Symbol: 'LPG' – liquefied gas-powered vehicle; 'ELE' – electric-powered vehicle; 'DSL' – diesel-powered vehicle.

Table 4. Environmental impact of AGV for Routing Algorithm #2 – '*Shortest Distance Loop Routing*' (Total number of containers, C = 40).

AGV Type	Vehicle Status	Total mPt Emissions (mPt)	Total Global Warming Impact (kg CO2-eq)	Total Respiratory Inorganics (kg PM2.5-eq)	Total Electricity (kWh)	Total Primary Energy – Non-renewable Energy (MJ primary)	Total Secondary Energy – Non-renewable Energy (MJ secondary)
LPG	Unloaded	52,461	54,810	75.69	0	873,567	41.76
	Loaded (1 t)	152,946	144,594	182.70	0	2,300,454	104.40
ELE	Unloaded	3,132	10,962	7.83	8,352	130,239	20.88
	Loaded (1 t)	3,132.	11,223	10.44	8,613	134,415	20.88
DSL	Unloaded	21,924	45,414	57.42	0	680,427	28.71
	Loaded (1 t)	32,886	63,945	78.30	0	949,779	39.15

Symbol: 'LPG' – liquefied gas-powered vehicle; 'ELE' – electric-powered vehicle; 'DSL' – diesel-powered vehicle.

Table 5. Environmental impact improvement of intelligent logistics in terms of the weighted ecological index mPt, by AGV type and status (Total number of containers, C = 40).

		Weighted Ecological Index mPt		
AGV Type	Vehicle Status	Routing Algorithm #1 – '*Loop Routing*'	Routing Algorithm #2 – '*Minimum Distance Loop Routing*'	Improvement (mPt)
LPG	Unloaded	52,461	52,461	-
	Loaded (1 t)	185,762	152,946	32,816
ELE	Unloaded	3,132	3,132	-
	Loaded (1 t)	3,804	3,132	672
DSL	Unloaded	21,924	21,924	-
	Loaded (1 t)	39,942	32,886	7,056

Symbol: 'LPG' – liquefied gas-powered vehicle; 'ELE' – electric-powered vehicle; 'DSL' – diesel-powered vehicle.

to save millions of lives whilst bringing several direct and indirect benefits to issues including climate change, improved quality of life and well-being (especially in urban areas), children's development, and equity across the globe.

5. Implications

The discussion of the findings highlights the contribution of this study in terms of theoretical as well as practical implications (managerial and policymaking). Following the simulation results, a compilation of the different insights can be summarised in a design framework that encompasses four distinct elements: (i) application insights; (ii) analytics insights; (iii) sensor data acquisition; and (iv) utilisation of AI algorithms for feedback loop monitoring through data. When considering the introduction of intelligent logistics in non-automated container port terminals, the design framework summarised in Table 6 can inform technology adoption at theoretical and practical levels.

5.1. Theoretical implications

In the context of containers' handling on the shoreside of port terminals, AI-driven approaches have a demonstratable impact on the operational and environmental sustainability performance of the respective activities, particularly in terms of travel distance, gaseous emissions, and energy consumption. This result adds to an ever-growing stream of literature discussing the productivity gains from investments in production automation (e.g. Acemoglu and Restrepo 2019). Our results are on par with studies in the production research literature that

Table 6. Design principles on intelligent logistics in container port terminals.

Intelligent Logistics Design Principle		Intelligent Application	Evidence
#1	Strategic decision-making over the use of intelligent vehicles for container handling operations needs to be informed by: (i) real-world operational requirements (e.g. vehicle capacity, refuelling/charging time, port layout); (ii) operational and investment cost vs. environmental trade-offs; and (iii) proper collaboration with other equipment (e.g. cranes).	Intelligent Vehicles	• Literature taxonomy demonstrates that most studies only consider conceptual cases of port layouts while the respective mathematical modelling and analytics overlook real-world operational parameters. • Simulation modelling demonstrates the impact of the different types of vehicles on the environmental sustainability of logistics operations.
#2	Routing algorithms in container handling operations need to focus on reducing the travel distance of the vehicle(s), primarily on the routes in which transportation vehicles are loaded, to improve gaseous emissions and energy consumption.	Data Analytics	• Under the environmental sustainability lens, simulation modelling results demonstrate that operations research principles and data intelligence should be leveraged to improve performance during operations in which the utilised equipment is loaded.
#3	Centralised (e.g. control-towers) and/or decentralised (e.g. on-board) sensory applications are required for monitoring both intelligent equipment status and shop floor conditions, in real-time, to ensure operations efficiency and safety.	Sensors	• Simulation modelling results reveal that synchronisation of port equipment is required to avoid idle times and ensure high level of operations efficiency. For example, the uninterrupted trajectory of the intelligent vehicle indicates that real-time monitoring of shop floor conditions and equipment's technical characteristics is particularly required under variable conditions, e.g. heavy rain or snow may result in terrain slipperiness that could affect vehicle's functionality.
#4	AI algorithms that dictate the scheduling and planning of intelligent operations need to leverage multi-sources' data to result in informed decision-making, whilst ensuring data accessibility and security.	AI Algorithms	• Simulation models and physical-level demonstrations, illustrated through testbed developments, can help recognise operational parameters which need to be monitored so that at the cyber-level the AI algorithms can dynamically self-diagnose and optimise decisions and operations. • Simulation modelling reveals that the introduction of more intelligent logistics increases the number of decision-making points.

discuss the applicability of AGVs in various areas such as warehouse automation with human pickers (Masae, Glock, and Grosse 2020). Nonetheless, when considering digital technologies, such as AGVs in shoreside container port operations, productivity gains are not guaranteed if not optimised accordingly. Such risks are important to be considered since the introduction of AI and automation does not automatically warrant a positive outcome and carriers risks which are not easy to overcome (Baryannis et al. 2019). The design principles outlined here can inform further studies in automation technology acceptance in manufacturing settings where the minimisation of environmental impacts from typical container handling and terminal management operations is important.

Furthermore, this study concerns the optimisation of an AGV's movement in an environment where operations are constrained by layout configurations and orchestration with other equipment is necessary, thus escaping the typical grid-based routing that is common in production settings. In this regard, selecting appropriate routing algorithms and methods to optimise distances is highly dependent on the quality of sensor data that can be collected by utilising more extensive sensor arrays. Considering the optimisation process results and the parameters of our model, an extension to more granular sensor data can be used for even further adjustments. Therefore, this study also adds in that perspective, namely the design dimension of sensor requirements in the selection of routing schedules. Such automation approaches are also considered important in other mainstream settings of production research (e.g. Chien et al. 2020) where new hardware platforms are streamlined with human intervention thus enabling coordination through data and sensor augmentation (Sahu, Young, and Rai 2020).

5.2. Managerial and policy implications

The study has a set of practical implications for port operators and policymakers alike. Transitioning to sustainable port container systems requires investments in automation technologies, among others. Notwithstanding the evident financial benefits in terms of productivity and increase throughput considered in a return of investment appraisal, the environmental impact is also an essential parameter that this study highlights. Nonetheless, effective implementation of port automation and/or automation interventions in non-automated ports requires careful planning in both dimensions and particularly in the environmental impact of internal-combustion powered AGVs. This is particularly important considering the high barrier to entry for electrification in freight transport vehicles. Therefore, the need for measuring environmental performance needs to be established since the introduction of AGVs in non-automated port settings can have an increase in emissions from the improvement of operational efficiency at terminals and overshadow the tangible benefits from increased operation (e.g. meeting demand in less time, less docking time of vessels, fewer cases of damaged cargo, fuel consumption efficiency, fewer accidents). Therefore, this derived design principles, as presented in Table 6, may inform the implementation decisions of port planners and operators, on how to introduce intelligent logistics and autonomous operations.

Nevertheless, the regulatory landscape needs to also adapt to this new type of technology since the safety procedures for human operators need to adjust to the reliability standards and the data requirements that need to be accompanied in industrial-grade applications of AI (e.g. explanation of the decision-making parameters, human supervision, etc.). Policymakers need to understand the parameters involved in that aspect and incorporate clauses in the regulatory framework of port operations.

In addition to the above, the study also brings a major managerial takeaway in regard to assessing the return on investment of implementing automation in the shoreside part of port operations. A known case of AI adoption barriers is capital expenditure where in some industries such as manufacturing, the capital expenditure is difficult to be justified from productivity gains alone (Pillai et al. 2021). Therefore, incorporating spillover effects from other areas may help incorporate a holistic view about automation, with sustainability been highlighted in this study as a major point. Hence, managers should also consider the long-term environmental sustainability effects when assessing the return on investment of adopting AI and automation in a production setting such as a port.

6. Conclusions, limitations, and future research

In the Industry 4.0 and the Internet of Things era, the digitalisation of logistics operations, especially concerning the use of intelligent vehicles for container freight management, can offer a range of economic, environmental and social benefits, including (i) enhanced productivity; (ii) labour cost savings; (iii) reduced gaseous emissions and energy consumption; and (iv) increased levels of safety (Bechtsis et al. 2017). However, to fully leverage the potential and operability of new technological systems in shop floor settings, appropriate analysis approaches and tools are required to assess their efficiency (e.g. mathematical modelling, simulation, emulation) and enable operational efficiency for sustainability (Zissis, Ioannou, and Burnetas 2020). This research specifically focused on automated and intelligent container handling through AGVs in port terminals by embracing a novel perspective on environmental impact.

This research argues that AI approaches, which are recommended for intelligent operations in a range of industrial sectors involving complex processes and risk (Giannakis and Papadopoulos 2016; Baryannis et al. 2019; Sivarajah et al. 2020), are useful for the effective and efficient management that promotes sustainable development. However, the adoption of automated operations in several fields requires data analytics capabilities (e.g. data curation, data processing, etc.), for capturing insightful information and improving operations (Karafili, Spanaki, and Lupu 2018). In this context, we anticipate our work to be beneficial to a wider group of stakeholders such as terminal operators, port authorities, shipping companies and shippers, inland transport providers, and freight forwarders/logistics service providers, particularly considering the global environmental challenges across the emissions-energy nexus.

There are also a number of limitations regarding the outcomes this work that should be considered in future research. The most important one is that our study is based on secondary data in a single port layout. Hence, it is not feasible to compare how different port layouts will affect the results and examine how the size and level of maturity regarding the adoption of AI technology affect the operational performance of the landside operations at ports. Therefore, the incorporation of primary data can better inform the design of the developed simulation study. The latter does not examine the scheduling of the terminals' equipment but considers the routing of an AGV along with the relevant environmental ramifications. Finally, the study follows the assumption that the unloading policy of the terminal operator requires stacking cranes to be allocated per container type. This may not apply to other ports and terminal layouts and therefore, the model assumptions need to be tested in that regard. Despite the abovementioned limitations, we still believe that our study indicates the benefits that can arise from the implementation of intelligent logistics at container port terminals.

In terms of future research, the possibility of multi-level analysis of AGVs in Pier I, from conceptualisation to mathematical modelling, to simulation, to emulation, and to the investigation of testbeds and pilot applications, demonstrates great scientific interest (Tsolakis, Bechtsis, and Srai 2019). Such a modelling and analysis toolkit would facilitate the multi-level analysis of the routing and efficiency of AGVs and could lay the groundwork for the development of 'digital twins' in container port terminals. The continuous flow of data received through sensors can assist in orchestrating synergistic actions in an automated port, thus resulting in improved operational performance which is also sustainable at the same time. In addition, we have not considered the case of transhipment which becomes more and more dominant in container port operations. Finally, an avenue that seems promising, is the development and evaluation of sophisticated routing algorithms for port-oriented landside operations that will allow optimising the benefits from automation and AI techniques.

Disclosure statement

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

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Notes

1. Throughout the manuscript the terms shoreside and landside are used interchangeably to denote the port operations taking place in the land, including loading and unloading of cargo containers among other operations that require the vessel to be docked.
2. AXSMarine Alphaliner Top 100. https://alphaliner.axsmarine.com/PublicTop100/index.php.
3. COSCO Shipping iForex Forum Greece. www.coscoshipping.gr.
4. Piraeus Port Authority. http://www.olp.gr/en/

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Appendix

Table A1. Gaseous emissions and energy consumption indicators for forklift vehicles with different engine types [*Source*: Fuc et al. (2016)].

AGV Type	Vehicle Status	mPt Emissions Factor (mPt/km)	Global Warming Impact Factor (kg CO2-eq/km)	Respiratory Inorganics Factor (kg PM2.5-eq/km)	Electricity Factor (kWh/km)	Primary Energy Factor – Non-renewable Energy (MJ primary/km)	Secondary Energy Factor – Non-renewable Energy (MJ secondary/km)
LPG	Unloaded	2.0100	2.1000	0.0029	0.0000	33.4700	0.0016
	Loaded (1 t)	5.8600	5.5400	0.0070	0.0000	88.1400	0.0040
ELE	Unloaded	0.1200	0.4200	0.0003	0.3200	4.9900	0.0008
	Loaded (1 t)	0.1200	0.4300	0.0004	0.3300	5.1500	0.0008
DSL	Unloaded	0.8400	1.7400	0.0022	0.0000	26.0700	0.0011
	Loaded (1 t)	1.2600	2.4500	0.0030	0.0000	36.3900	0.0015

Symbol: 'LPG' – liquefied gas-powered vehicle; 'ELE' – electric-powered vehicle; 'DSL' – diesel-powered vehicle.
Note: The characterised impact category indicators were calculated for the coverage of 1-km distance by the selected forklifts.

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Thank you.

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