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Towards Smart Port Infrastructures: Enhancing Port Activities Using Information and Communications Technology

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ABSTRACT In this digital age, ports face stiff competition in global supply chain. Smart ports, as high performing ports, utilize information and communications technology (ICT) to provide a wide range of smart applications, resulting in vastly improved vessels and container management among others, which subsequently improve the competitiveness and sustainability of the national economy. While various novel solutions, such as information system and locating system, have been proposed to improve smart port activities, there are several key issues pertaining to ports and port operations that warrant specific attention, particularly greenhouse gases emission, which has accelerated to an alarming level. The urgent need to address such issues is lacking. This article aims to offer a review of the research literature on smart ports, including Internet of Things platform, greenhouse gases emission reduction, energy efficiency enhancement, and so on. The objective is to establish a foundation of existing research conducted on smart ports in order to motivate new research interests in this area. Open issues are also presented to foster new research initiatives on smart ports.

INDEX TERMS Smart port, seaport, smart city, smart port city, computing, ICT, sustainability.

I. INTRODUCTION

With 80% of world trade being transported by sea [1], and the steady growth of 4% in international seaborne trade [2], the increased interest in developing a smart port ecosystem using information and communications technology (ICT) to handle port demands is evident. Figure 1 provides the top 50 container ports in the world in 2018 as according to the World Shipping Council [3]. Smart port, which is part of the smart city, aims to utilize technological innovations for enhancing port activities and services, and to provide a socio-economic boost to cities and regions with an improved international trade competitiveness. The smart port ecosystem minimizes energy consumption and traffic.

The ports have evolved over five generations [4]. The *first generation* served as a nodal point of land and sea transports and provided basic operations, such as logistic and transportation, cruise, fishing, and emergency rescue [5]. The *second generation* deployed equipment and infrastructures to reduce the dependency on manpower. The *third generation*, which serves as a cargo handling center, provides value-added services such as warehousing, packaging, and distribution [6]. The *fourth generation* connects physically-separated ports to serve as a networked port [7]. The *fifth generation* of ports [8], [9], the latest and current version, is a customer- and community-centric *smart port* that is distinguished by five main features:

(a) *smart port services and applications* such as vessel and container management;
(b) *technologies* such as data centre, networking and communication, and automation;
(c) use of *sustainable technology* to increase energy efficiency and reduce greenhouse gases emission;
(d) *cluster management* such as a shipping cluster that consists of geographically proximate companies and stakeholders with their main activity being shipping; and

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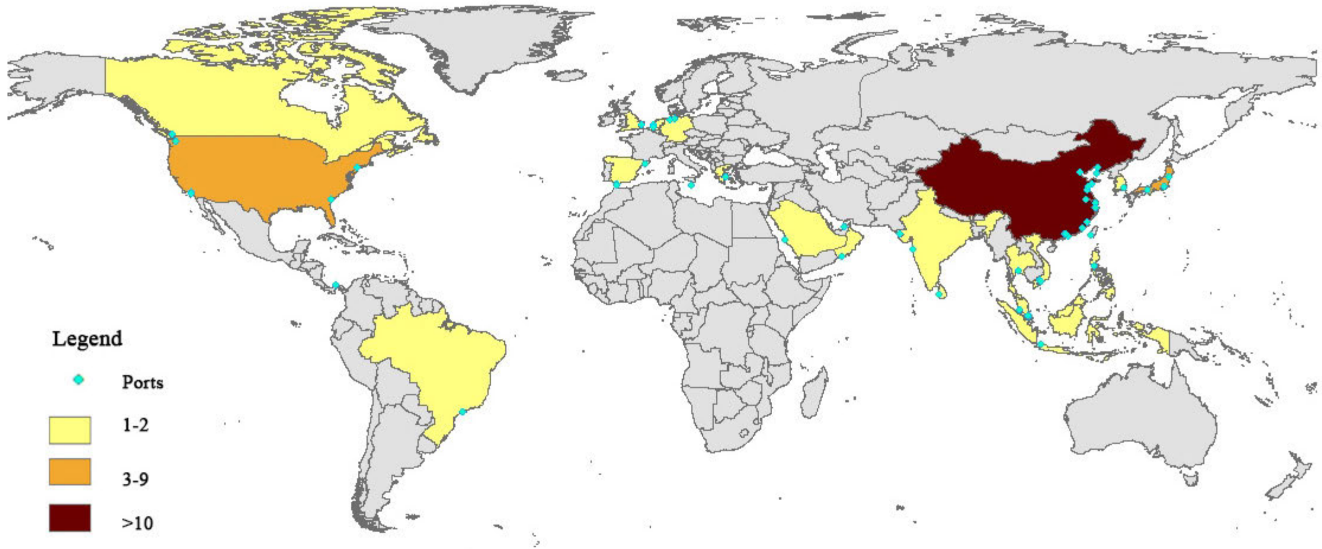


FIGURE 1. Countries and their respective number of top 50 busiest container ports according to the World Shipping Council [3]. Out of the top 50 busiest container ports in the world, there are 16 in China, 5 in United States, 3 in Japan, as well as 2 in Germany, India, and Malaysia, respectively.

(e) development of *hub infrastructures* to foster collaboration among different ports.

Equipped with these five features, smart ports adapt to the dynamic and unpredictable conditions of the ports to improve port activities and services.

A. OUR CONTRIBUTIONS

The urgent need to develop smart ports to improve the economic, social, and environmental aspects of nations has been limited by the lack of related investigation. Hence, we aim to present a comprehensive review of the limited work on smart ports with a focus on the role of ICT. While a review of the information systems for smart ports has been presented in [10], our article focuses on new areas of investigation in smart ports, including the use of Internet of Things (IoT) platform, techniques for greenhouse gases emission reduction, energy efficiency enhancement, and so on. In addition, this timely article explores various open issues, and it aspires to establish a foundation to spark research interests in this area.

B. ORGANIZATION OF THIS ARTICLE

Throughout this article, web resources are used to support discussions of mainstream literature. Specifically, web resources are used to: a) provide supporting points with real-life examples and cases, policies, as well as data and statistics provided by renowned organizations, such as International Maritime Organization (IMO) [11]; and b) provide references to technical websites of technologies and tools, such as PostgreSQL [12], COSMOS [13], and the MSP430F2272 processor [14].

The rest of this article is organized as follows. Section II presents the background of a port and a smart port. Section III introduces smart port research themes, including the use of IoT platforms, greenhouse gases emission reduction, energy efficiency enhancement, container management enhancement, the use of automatic identification system (AIS) data for operational efficiency enhancement, and resource management system, while Section III-G presents simulation and implementation of smart ports. Table 1 summarizes the investigations of smart ports in the literature. Section IV presents open issues and emerging technologies, and Section V concludes this article.

II. BACKGROUND AND MOTIVATING THE NEED FOR A SMART PORT

This section presents the port areas of a typical port or smart port, as shown in Figure 2, as well as the attributes of smart ports, including the components of an information system, smart applications, and performance measures, as shown in Figure 3. Finally, it presents a review of notable global smart port projects.

A. PORT AREAS

As shown in Figure 2, the main areas of a port are as follows:

- *Terminal* is a demarcated area of a port that handles a certain type of cargo, such as containers, oil, and gas, as well as cruise. A terminal may have several quays.
- *Quay (or berth)* is an area where vessels are moored,[1] and so it has loading and unloading equipment.
- *Yard* is a temporary storage area for containers. Each container, typically with a height of 2.62 m, is stacked on top of another with a maximum height of 16 m as according to the ISO standard [15]. The containers are stacked in a grid layout, and the container stacks are separated by 25-30 m to provide a path for the yard trailer. Light towers, which are higher than 30 m, are installed around the yard.

[1] To moor a vessel refers to fastening of the vessel to an anchor or the shore by attaching it by cable or rope.

TABLE 1. Summary of investigations of smart ports.

Area of investigation	Proposed solution	Reference	Objective	Component of information system	Smart application	Performance measure
IoT platform	Interconnected and collaborative platform	[50]	Enable information exchange among heterogeneous entities to deploy smart applications	(C.1) Information gathering devices (C.2) Data centre (C.3) Networking and communication (C.4) Automation	General	–
Greenhouse gases emission reduction	Cold ironing	[25] [2] [51]	Connect vessels to land-side electrical power grid on land	–	(A.4) Smart energy management	(P.1) Lower greenhouse gases emission (P.2) Lower energy consumption; (P.4) Lower monetary cost;
	Renewable energy generation	[25] [51]	Generate energy using photovoltaic panels and wind turbines on land			
	Renewable energy storage	[25]	Use deep cycle batteries to maximize the energy storage capacity of vessels			
Energy efficiency enhancement	Energy management	[52]	Identify and evaluate the energy consumption of processes in land-side terminal operations	–	(A.4) Smart energy management	–
Container management enhancement	Locating system for containers	[28] [15] [29]	Identify and track the physical locations and trajectories of items and equipment	(C.1) Information gathering devices (C.3) Networking and communication (C.4) Automation	(A.2) Smart container management	(P.5) Higher accuracy of estimation
	Recognition of container codes	[27]	Recognize container codes with low readability	–		
Application of AIS data for operational efficiency enhancement	Data collection	[53]	Use AIS data to determine the number of different types of freight vessels at each terminal	(C.1) Information gathering devices (C.2) Data centre	(A.3) Smart port management	–
	Trajectory estimation	[26]	Use AIS data to determine the future location and trajectory vessels	(C.1) Information gathering devices (C.2) Data centre (C.4) Automation	(A.1) Smart vessel management	(P.5) Higher accuracy of estimation
Resource management enhancement	Resource management	[54]	Develop models for business processes and evaluate the impact of ICT	–	(A.5) Smart resource management	–

There are four main types of infrastructural facilities used on a smart port (see Figure 4), which we describe next:

- *Quay crane (QC)* loads/unloads containers to/from vessels at the quay.
- *Yard trailer (YT)* (or prime mover) transports containers via a path, or a guided platform, in an autonomous manner between the terminal and yard areas.
- *Rubber tire gantry crane (RTGC)* (or yard crane or transfer crane) loads/unloads containers to/from YT, and stacks the containers on top of each other at the yard. The crane, which is approximately 30 m high, runs along a predefined straight railway to stack and move containers.
- *Terminal operating system (TOS)*, being the brain of a smart port, is an integrated system that plans, manages, and controls a diverse range of tasks, from administrative to field operations, such as loading, unloading, determining storage locations, and transferring containers in the port.

Consider a vessel arriving at one of the quays at a terminal for unloading. The vessel is either moored at an allotted quay immediately, or must wait until a quay becomes available. When the vessel is moored, a number of QCs and YTs are allotted to the vessel. Based on an unloading sequence and schedule, the QCs pick-up containers from the vessel and put them on YTs. When there is a storage constraint at a yard, RTGC is used to stack up the containers. These loading and unloading activities are carried out with the help of a TOS that ensures the smooth running of the port.

B. INFORMATION SYSTEMS FOR SMART PORTS

Information systems have been deployed to manage, monitor, and store massive amounts of data (e.g., information from AIS, maritime traffic, and logistic data) and to provide large-scale computerized and paperless services in smart ports [10]. The diversity of the gathered data and information enables smart port applications to adapt to the dynamic requirements of a complex system handling diverse aspects (e.g., environment, energy, and traffic) and comprising different technologies (e.g., wireless communications and embedded systems for sensing operation).

There are four main components of an information system as follows:

C.1 *Information gathering devices* gather and integrate temporal and spatial data and information (e.g., temperature, humidity, and physical location) from heterogeneous sensing and detection devices such as video cameras, cameras, sensors, radio-frequency identification (RFID) tags and readers, bar codes and readers, and face recognition systems. Multiple sensors and detectors can be located at various areas—e.g., in terminal, quay, yard, warehouse, and customs—and may be embedded in various infrastructures (e.g., QC, RTGC, YT, and container) to monitor the operating environment and track cargo (particularly hazardous goods), and send information (e.g., damages) to the data center.

C.2 *Data centre* provides storage and computing capabilities to store, integrate, process, and analyze a

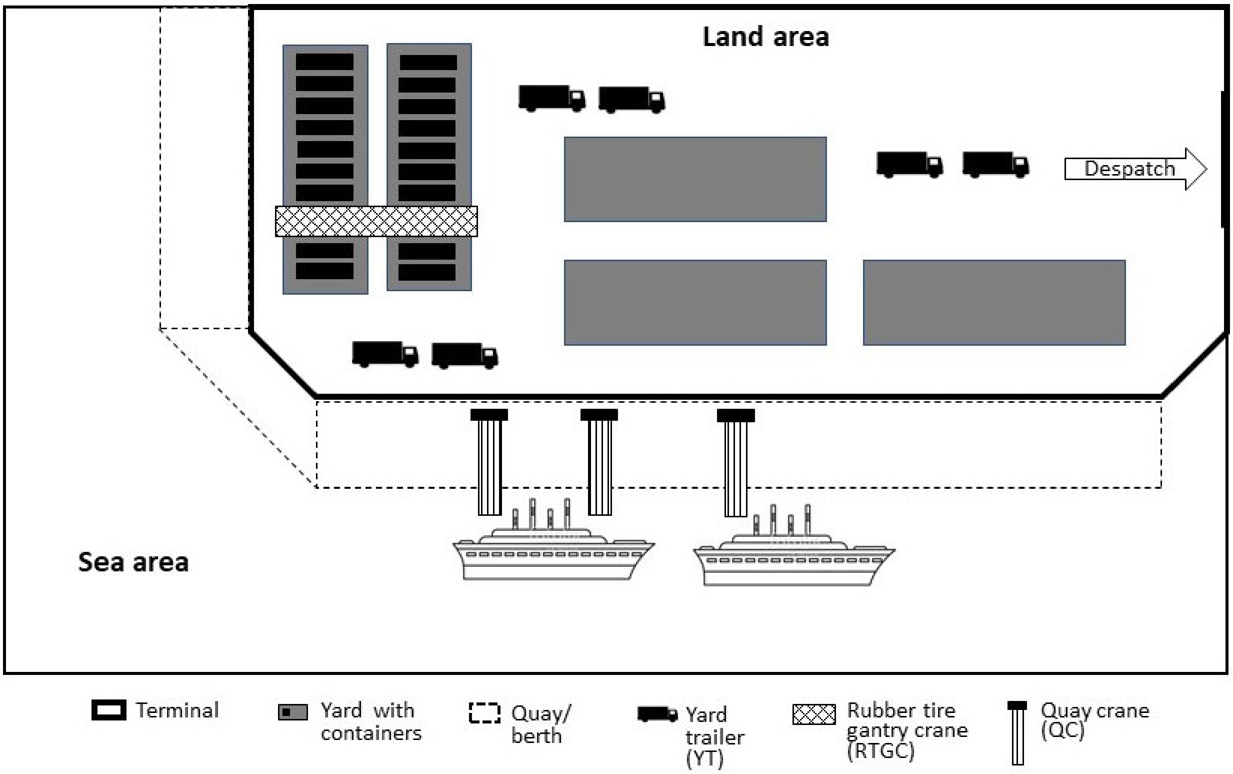


FIGURE 2. Port areas.

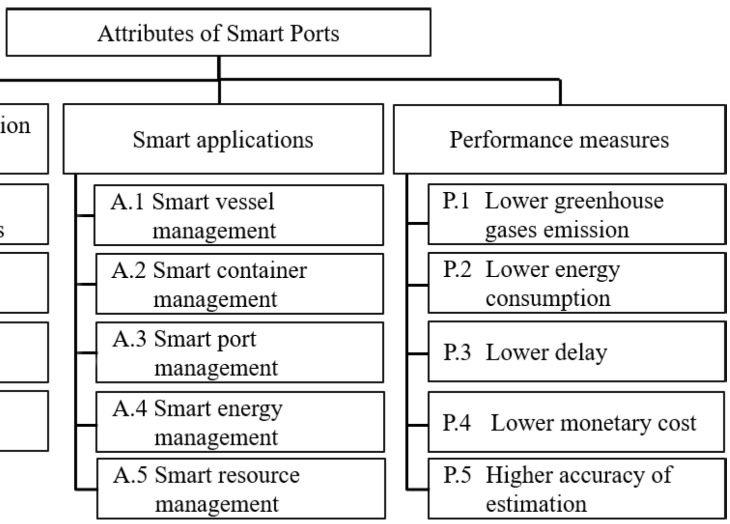


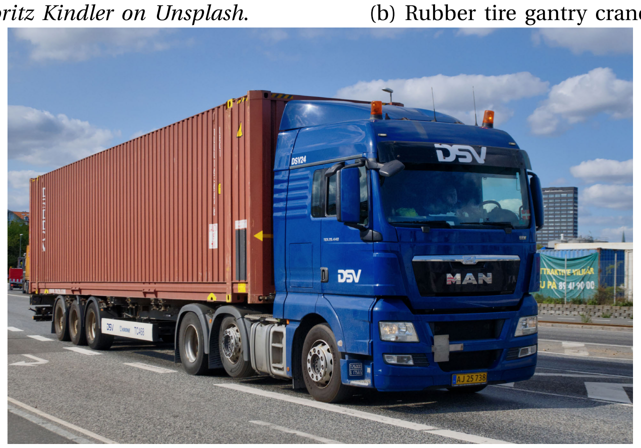
FIGURE 3. Attributes of smart ports.

massive amount of data and information in real time. Data centre can be realized through cloud computing and edge (or fog) computing [16]. Cloud computing is a network of servers hosted remotely on the Internet. Edge computing is a server that provides cloud computing service in a local network, and so it reduces the amount of data transfer between the local network and the cloud, which helps to improve network performance and data security.

In addition, the data centre requires a middleware to handle the massive amount of data and information gathered from heterogeneous sensing and detection devices [17], [18]. For instance, in [18], the middleware is based on the EPCglobal architecture framework [19], which defines the standard for

(a) Quay crane. *Photo by Moritz Kindler on Unsplash.*

(b) Rubber tire gantry crane. *Photo by nnqooh on Pixabay*



(c) Yard trailer. *Photo by Lav Ulv on Flickr*

FIGURE 4. **Port infrastructures.**

RFID middleware, and it has four main functions to handle RFID data: a) converting data in different formats to a uniform data format; b) filtering data so that the filtered data conforms to rules (e.g., the data lies within an acceptable range); c) capturing events from the data and storing them in a database for retrieval in the future; and d) monitoring, aggregating, and reasoning the events based on business context for decision making.

C.3 *Networking and communication* provide seamless connection among heterogeneous network entities (e.g., information gathering devices and data centre) and stakeholders (e.g., shipping and logistics companies, freight forwarders, and commodity inspection bureau) via wireless and wired networks. The network entities exchange a massive amount of data and information in a real-time manner. However, containers and large infrastructures (e.g., QC) made of steel are stacked on top of each other. The port environment, therefore, is prone to reflection, scattering, and non-line-of-sight communication, resulting in lower network performance.

C.4 *Automation* enables automated decision making based on the massive amount of data and information in an unpredictable and dynamic environment.

C. SMART APPLICATIONS IN SMART PORTS

There are five main smart port applications as follows:

A.1 *Smart vessel management* manages vessels, including their choice of routes and ports, based on the location and traffic amount of the ports in order to improve their arrival punctuality at ports. Based on a study [20], 48% of the container ships arrive at least 12 hours behind schedule, which increases fuel consumption and causes underutilization of terminal resources. Hence, smart vessel management helps to reduce the waiting and inactivity time of vessels, which can be costly. For instance, reducing an hour of time spent in mooring a vessel can save up to US$80,000 [21], [22].

A.2 *Smart container management* manages the acquisition, tracking, transport, storage, and repositioning of containers [23], as well as transshipment in which containers are transferred from one vessel to another. This reduces the time a vessel spends in a port, and hence it optimizes the logistic services and can reduce up to 10% operating cost [22], [24]. It allows the conditions (e.g., temperature) of the containers to be tracked and monitored, and the events of the containers throughout their journey to be remotely detected. Examples of events are whether the containers are opened unexpectedly/expectedly and inspected properly/improperly; whether there are fluctuations in temperature; whether there are any emergency cases such as vibrations and falls of fragile goods; and whether there has been any exposure to fire or flood. The event information (e.g., the location and time of the event) can be tracked and monitored, and necessary actions (e.g., sending alert messages to stakeholders) can be taken immediately.

A.3 *Smart port management* optimizes port services, such as commodity inspection, customs clearance, transportation planning, procedures and applications (e.g., transshipment, trade license, as well as import and export permits), customer service, market information exchange, and insurance provisioning.

A.4 *Smart energy management* reduces the *fixed energy consumption* incurred by the operational infrastructures at port terminal, yard, and office areas; as well as the *variable energy consumption* that increases with the port activity level, such as those incurred by equipment and infrastructures (e.g., QC, RTGC, and YT). For instance, the Valencia and Hamburg ports are equipped with motion-sensitive lights that are illuminated when vehicles pass by—such lighting system has been shown to reduce energy consumption by up to 80% [22].

A.5 *Smart resource management* schedules and allocates resources, including equipment and infrastructures (e.g., container trucks, forklifts, suspension bridge, and cranes) to reduce congestion, and identify the sources of congestion, in order to optimize resource procurement and allocation in terms of time and cost. This helps to reduce resource wastage, and waiting and inactivity time.

D. PERFORMANCE ENHANCEMENT ACHIEVED BY SMART PORTS

There are five main performance enhancements achieved by a smart port as follows:

P.1 *Reduced greenhouse gases emission* in the order of ktone per year [2], [25].

P.2 *Lower energy consumption* increases the available (or residual) energy in the order of MWh [25], or increases the available energy generated in the order of MWh per year [2].

P.3 *Lower delay* reduces the access delay to database [26], and the processing delay incurred in recognizing container codes [27].

P.4 *Lower monetary cost* reduces the cost per energy unit in the order of cost per MWh [25], while also reduces the estimated investment cost (e.g., the number and cost of equipment and infrastructures) [2].

P.5 *Higher accuracy of estimation* increases the success rate of the prediction of vessel positions [26], equipment (i.e., YTs and RTGCs) positions [15], distance [15], [28], container codes recognition [27], and the trajectory of equipment such as YTs [29].

The efficiency of a smart port is captured by the above performance measures, particularly reduced greenhouse gases emission (P.1), lower energy consumption (P.2), lower delay (P.3), and higher accuracy of estimation (P.5). The performance enhancements are achieved by various investigations of smart ports in the literature as presented in Table 1. Some of the investigations present preliminary studies and conceptual solutions without performance enhancements, and so their performance measures are not shown in Table 1. Nevertheless, the technical descriptions of such investigations are included in this review article for comprehensiveness.

E. REVIEW OF GLOBAL SMART PORT PROJECTS

Smart port projects have been deployed in many parts of the world including in the ports of Le Havre (France) [17], Amsterdam [17], and Barcelona [17]. Smart application such as cold ironing has been adopted in the port of Long Beach (California, USA) [41], Gothenburg (Sweden) [42], Oslo (Norway) [43], Rotterdam (Netherlands) [44], [45], Hamburg (Germany) [17], [46], [47], Vigo (Spain) [48], and Tanjung Perak (Indonesia) [49]. Table 2 gives a description of some global smart port projects.

III. SMART PORT RESEARCH THEMES

This section presents preliminary and in-depth studies on this topic. While the in-depth studies (Sections III-B, III-D, and III-E) present technical solutions that show performance enhancements in Table 1, the preliminary studies (Sections III-A, III-C, and III-F) present conceptual solutions that provide insights for further investigations.

A. INTERNET OF THINGS (IoT) PLATFORM IN SMART PORTS

The use of IoT platforms has been proposed to establish an interconnected and collaborative platform that enables information exchange among heterogeneous equipment and infrastructures in order to deploy smart applications.

The IoT platform architecture typically consists of four main layers [50] to incorporate the four main components of an information system (see Section II-B).

- *Firstly*, the *data acquisition* layer (C.1) that consists of heterogeneous sensing and detection devices, which sense, recognize, and collect a diverse range of data, information, and objects.
- *Secondly*, the *transport and data processing* layer (C.2 and C.3) connects the data acquisition layer to the computing platform (e.g., cloud computing and edge computing), which serve as the management and information centers, in order to process the massive amount of collected data. The connection is made via the communication platform (e.g., wireless communication).

TABLE 2. Description of some global smart port projects.

Continent	Country	Port	Reference	Features
America	USA	Los Angeles (TraPac Terminal)	[30]	Integrates shipping data from across port ecosystem with data analytics to enhance supply chain performance through real-time data.
Europe	France	Le Havre	[31]	Embarks on projects which address mobility issues (i.e., traffic monitoring and coordination), energy management (i.e., energy production and collection), data management (i.e., data processing and analytics), and environment issues (i.e., air quality improvement).
	The Netherlands	Amsterdam	[32]	Improves management of assets, and develops unique expertise in waste management.
	The Netherlands	Rotterdam	[33]	Uses IoT to create a digital twin and data analytics to determine optimal conditions and timing for the berthing and passage of ships.
	Spain	Barcelona	[34]	Implements storm forecasting system and enables quantification of its customers' cargo environmental footprint.
	Spain	Seville	[35], [36]	Uses IoT-based system for intermodal transshipments, and mobile network technology for supply chain management.
	Germany	Hamburg	[37]	Monitors navigation in real-time, sources shore power supply from renewable energy, and uses mobile GPS sensor for intelligent fleet management.
	Belgium	Antwerp	[36], [38]	Uses blockchain technology to enhance security in digital exchange for transfer of rights between competing parties, digital cameras, and sensors to ensure ships moored at the correct berth, and optimizes preventive maintenance via automatic image recognition.
Asia	China	Shanghai (Yangshan Port Phase 4)	[39]	Implements automated container terminal with remotely controlled bridge cranes, rail-mounted gantry cranes, and auto-guided vehicles.
	Singapore	Tuas Megaport	[40]	Will implement (to be completed by 2040) automated wharf and yard functions, and full-electric automated guided vehicles.

- *Thirdly*, the *business* layer (C.4) implements smart applications. For instance, RFID data is used to register a container when it approaches an access gate.
- *Fourthly*, the *presentation* layer consists of user devices, such as smartphones, for communication.

In spite of the urgent need to deploy and support various smart applications, there is relatively little work on the design of IoT platforms for smart applications in smart port. Further investigations could be pursued to design IoT platforms to deploy and support various smart applications that can perform various tasks, such as smart vessel, container, port, and energy management.

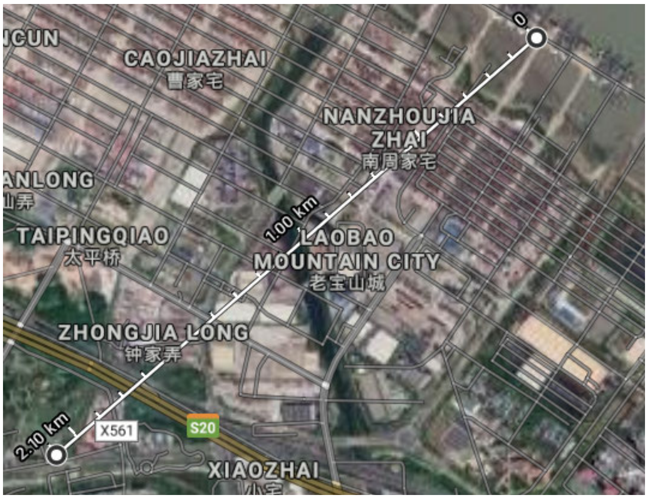
B. GREENHOUSE GASES EMISSION REDUCTION IN SMART PORTS

This section presents mechanisms to reduce greenhouse gases (GHG) emission and the carbon footprint in order to mitigate climate change and environmental impacts, as well as improve air quality, while also contributing to smart energy management (A.4). When vessels are moored at quays for loading and unloading, their main and auxiliary engines run on low-grade fuel or bunker oil, particularly low-grade diesel, to provide continuous power for onboard usage, such as heating, cooling, lighting, loading and unloading containers, and so on. The low-grade fuel has a sulphur content of 3,000 times higher than that of conventional diesel in the emission from vehicles [2]. This issue is compounded by the failure to comply with standards imposed on the chimney filters of vessels.

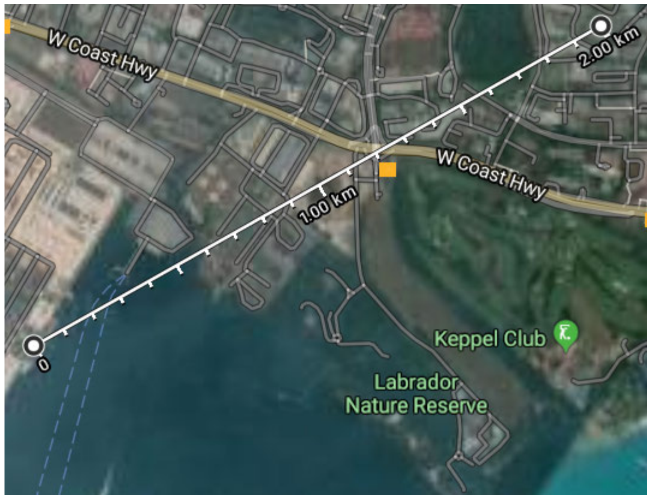
Consequently, harmful air, including sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), and particulate matters whose diameter is less than 10 μm (PM), is emitted from vessels due to incomplete carbon combustion [55]–[57]. The SO_2 and NO_x emissions cause acidification that is harmful to ground level zone, human health, vegetation, and built environment. PM can reach lungs, causing respiratory irritation and worsening heart disease, asthma, and lung cancer [58], [59]. Based on an estimation [60], vessels have contributed to 2.8 million tons of NO_x, 1.7 million tons of SO_2, and 195,000 tons of PM per annum. Each vessel emits between 5 and 6.9 tons of NO_x, between 4.7 and 6.5 tons of SO_2, as well as between 1.2 and 1.6 tons of PM per annum [61], [62]. In short, the maritime transportation system is accounted for 1 billion tons of GHG emission, or 3% of the GHG emission worldwide, from 2007 to 2012 [11]. GHG emission is expected to increase to 25% by 2050 [11], which is a significant contribution to climate change. Some studies indicate that certain pollutants, particularly SO_2 and NO_x, exceed the inland sources.

Long-term exposure to emission from vessels at ports has been shown to increase hospital admissions, years of life lost, and healthcare cost [2]. The effect of the emission on inland air pollution level is approximately reduced by half and to a negligible level at 18 km and 37 km, respectively [63]. However, the distance from a port to a nearby city is generally significant less as shown in Figure 5. Meanwhile, the higher energy cost on land discourages vessels from connecting to the land-side electrical power grid. Hence, cold ironing, along with the deployment of clean and renewable energy sources, have been proposed to reduce emission and energy cost.

Cold ironing (see Section III-B1) connects vessels moored at quays to landside electrical smart grid, which has shown to reduce GHG emission by up to 70% [41]; and the use of renewable energy sources (see Section III-B2) can further reduce GHG emission to a negligible level. The proposed schemes have shown to reduce greenhouse gases emission (P.1), energy consumption (P.2), and monetary cost (P.4).

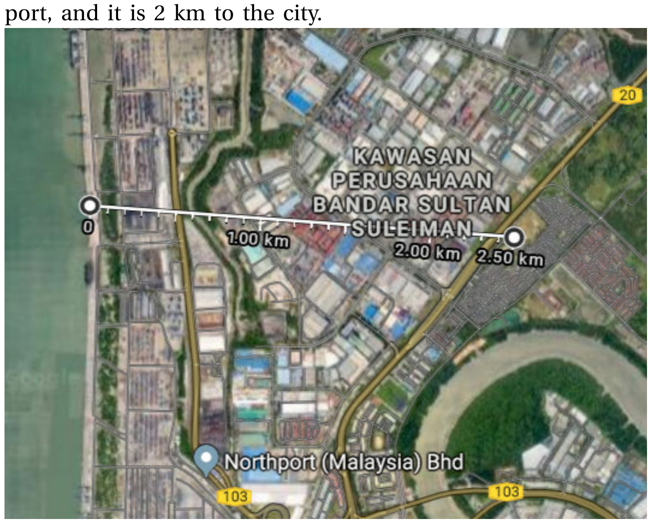


(a) The port of Shanghai in China is the world's busiest container port, and it is 1 km to the city.



(b) The port of Singapore is the world's second busiest container port, and it is 2 km to the city.

(c) The port of Busan in South Korea is the world's sixth busiest container port, and it is 600 m to the city.



(d) The port of Klang in Malaysia is the world's twelve busiest container port, and it is 2.45 km to the city.

FIGURE 5. **Distance from major ports to their nearby cities (e.g., residential and commercial areas, and school) is less than 18 km and 37 km, where the effects of the emission from vessels at ports is approximately reduced by half and to a negligible level, respectively.**

1) COLD IRONING IN SMART PORT

Cold ironing connects vessels moored at quays to land-side electrical smart grid, and supply shore side electrical power to them [2], [25], [51]. This allows the vessels to shut down their diesel engines, which reduces emission. Vessels are installed with bidirectional points of delivery and energy meters to exchange energy with smart grid. Smart grid provides a more reliable energy source due to the intermittency and unpredictability of the renewable energy sources. The infrastructures from the smart grid to a vessel are [51]: a) *smart grid*; b) *step-down transformer* reduces the high-voltage level of smart grid to a mid-voltage level (e.g., from 35 kV to 10 kV [64]); c) *power converter* converts the grid frequency (e.g., 50 Hz in Europe and 60 Hz in North America) to the required level of the vessel; d) *step-up transformer* increases the voltage level to the required level (e.g., 6.6 kV or 11 kV [64]) of the vessel; e) *switchboard (on shore)* that manages and measures electrical energy; f) *shore-to-ship cable*; and g) *switchboard (on vessel)*. Further research could be pursued to expand the smart grid with clean and renewable energy sources.

2) DEPLOYMENT AND STORAGE OF CLEAN AND RENEWABLE ENERGY

The deployment of clean and renewable energy sources reduces the dependency on traditional energy sources (e.g., fossil fuel).

Renewable energy source has been proposed to generate energy and form a smart port microgrid, which can be connected to the electrical smart grid. In [25], three photovoltaic panels and a wind turbine on land are used to produce 438 kWh and 876 kWh per year, respectively. In [51], a large number of photovoltaic panels and wind turbines on land are proposed to be deployed to meet the energy demand of the vessels moored at quays at the port of Barcelona. The power demand is estimated by $P_i = P_{i-1} + P_a - P_d$, where P_{i-1}, P_a, and P_d are the power demand of vessels moored at quays at the previous time instant, arriving vessels, and the departing vessels. The estimated power demand is $P_i = 221.9$ MWh. The power supply of a photovoltaic panel is estimated by $P_s = \eta V_s I_s T_s$, where η is photovoltaic panel efficiency, V_s and I_s are the voltage and current at the maximum power point respectively, and T_s is peak sun hours. The power supply of a wind turbine is estimated by $P_w = 1/2 \times \rho c_w A_w v_w^3$, where ρ is air density, c_w is the power coefficient of the wind turbine, A_w is the area swept by the rotor of the wind turbine, and v_w is the wind speed. The energy supply generated by the proposed 29,137 photovoltaic panels and 177 wind turbines is estimated based on solar irradiation and wind speed, where photovoltaic panels and wind turbines generate 25% and 75% of the power supply, respectively. In [2], sea wave energy converters are installed along the port of Naples to convert wave energy to electrical energy. The converters use: a) turbines that generate up to 10,250 MWh per year (or 6,000 MWh per kilometer), or b) floats, which generate a pitching movement, that generate up to 4,500 MWh per year (or 150 MWh per float). Other sea wave energy converters have been proposed in [65]–[70].

In [25], *energy storage* uses deep cycle batteries, rather than the widely-used lead-acid batteries, Li-ion batteries, and hydrogen storage, to maximize the storage capacity on vessels. The vessels moored at quays are connected to the electrical smart grid on land to recharge its batteries.

Further research could be pursued to provide an accurate prediction of renewable energy generation, and to optimize the deployment of renewable energy sources, storage, and backup.

C. ENERGY EFFICIENCY ENHANCEMENT IN SMART PORTS

This section presents mechanisms to improve energy efficiency in smart ports, contributing to smart energy management (A.4). The container terminal of a port consumes a high amount of energy, which is estimated to be approximately half of the electricity consumed in a port [71]. This section presents mechanisms—including energy management and port automation—to improve energy efficiency and sustainability of smart ports.

In [52], an energy management framework is proposed to identify and evaluate the energy consumption of processes in land-side terminal operations. This helps to monitor and compare energy consumption across different ports worldwide in a consistent manner. Each process is a cascade of terminals (e.g., containers, oil, gas, and cruise), services (e.g., import, export, transshipment), activities (e.g., load, unload, transport, and shuffling of containers), energy consumers (e.g., equipment and infrastructures, such as QC, RTGC, and YT), and energy sources (e.g., electricity, diesel, and renewable solar energy). For instance, a container *terminal* uses a transshipment *service* that has quay-side, yard, and administrative *activities*, and uses QCs, which are *energy consumers*.

There are two main steps in the framework proposed in [52]. *Firstly*, it identifies processes and the energy-efficient mechanisms for their services, activities, and energy consumers. *Secondly*, the framework evaluates the energy efficiency of the processes based on four sustainability evaluation criteria, including: a) *transparency* (e.g., energy consumption measurement and its accuracy and granularity, the accountability of stakeholders, the auditability of reports, and the adherence to international standards such as ISO 9001 for quality management, ISO 28000 for security of supply chain, as well as ISO 14001 and EMAS III for environmental management [55]); b) *policies* (e.g., policies imposed by international bodies and local port authorities, and certification such as green mark); c) *best practices* (e.g., black and white paints for oil storage tanks for natural heating and cooling effects); and d) *energy-efficient technologies* (e.g., a generator that adapts the speed of an engine to carrying load). The proposed framework can support business decision making by incorporating throughput measurement into the evaluation criteria. This helps to achieve a balanced tradeoff between energy efficiency and operational efficiency (or productivity).

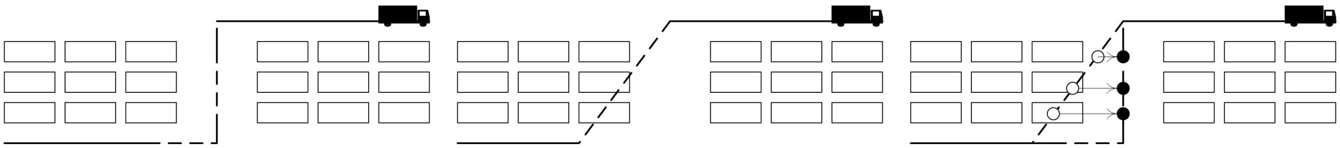
While port automation using autonomous vehicles and equipment, and leveraging redundant resources can improve operational efficiency (e.g., the turnaround time for loading and unloading containers is reduced), it increases energy consumption. While labor force reduces energy consumption, it reduces operational efficiency. Therefore, in port automation implementation, the tradeoff between operational efficiency and energy efficiency need to be considered. Further investigation could be pursued to design energy-efficient automation and the use of clean and renewable energy.

D. CONTAINER MANAGEMENT ENHANCEMENT IN SMART PORTS

Terminals handling containers are normally overwhelmed with loading, unloading, and operations. Congestion at a terminal can be a bottleneck to the global supply chain. This section presents mechanisms to improve container management, contributing to smart container management (A.2).

1) LOCATING SYSTEM FOR CONTAINERS

In [15], [18], [28], [29], a real-time locating system is proposed to identify and track the physical locations and trajectories of various items and equipment, including containers and YTs. In general, containers can be identified using RFID whereby fixed and mobile readers with known physical location are used to read tags at certain physical locations. However, the physical location of the containers at terminals cannot be identified using RFID thus human intervention is still required to handle anomalous situation. In other words, staff must search for containers that are out of place. This is because location and trajectory information is important in



(a) Trajectory loss, represented by the dotted line, due to radio signal loss at a hidden area.

(b) Trajectory estimation, represented by the dotted line, at the hidden area based on linear interpolation.

(c) Trajectory smoothing, represented by the arrowed lines, at the hidden area based on Kalman filter.

FIGURE 6. Estimation of an incomplete trajectory of a YT between two known points in the yard, where containers are stacked on top of each other in a grid layout. A solid line represents an estimated trajectory. Shown in the figure is a scenario under investigation in [29].

resource management so that tasks can be scheduled to the nearest available equipment. The best possible routes, and their arrival times, of tasks can be planned and estimated.

There are two challenges in communication that hinder radio signals from reaching some areas, which are also known as hidden areas, causing packet loss, and so the trajectory information becomes incomplete. *Firstly*, mobile items and equipment experience a dynamic and unpredictable operating environment due to the presence of static and mobile obstacles. *Secondly*, the containers which are stacked on top of each other, and large infrastructures (e.g., QC), are made of steel that can cause reflection, scattering, and non-line-of-sight communication. The path between the container stacks, which is 25-30 m wide, is too narrow for line-of-sight communication.

Traditional localization approaches are not suitable. *Firstly*, multilateration-based approaches require a target to collect at least three distances with different readers, which may not be possible due to packet loss. *Secondly*, global positioning system (GPS) requires radio signal to reach the area, including the hidden area which may not be possible [18], [72]. *Thirdly*, conventional approaches, including received signal strength indicator (RSSI), time-of-flight (TOA), time-difference-of-arrival (TDOA), and angle-of-arrival (AOA) [73], require time synchronization that can increase overhead.

To provide and enhance locating systems for containers, *three* main solutions have been proposed.

1) In [29], two stages are proposed to estimate the incomplete trajectories of items and equipment (e.g., YTs) between two known points (see Figure 6). *Firstly*, *trace estimation* uses linear interpolation to construct new points between the two known points based on an incomplete set of information (see Figure 6b). However, the new points may be located at prohibited areas, such as the containers, which trajectories cannot pass through. *Secondly*, *trajectory smoothing* uses Kalman filter to estimate an optimal trajectory statistically based on inaccurate sets of information in a recursive manner in order to reduce location and trajectory errors, including the avoidance of the prohibited areas.
2) In [28], the two-way ranging mechanism of IEEE 802.15.4a is proposed to estimate distance using trilateration based on round-trip time without time synchronization. The signal transmission and propagation time between a transmitter and a receiver is given by one-half of the round trip time. There are three components in the architecture. *Firstly*, *tags* are embedded in items and equipment, and their physical locations and trajectories are to be identified. *Secondly*, *readers*, which are connected to the local area network and equipped with directional antennas, are embedded in light towers. Being stationary, the readers with known physical location serve as reference points. In addition, assistant tags, which are tags with known physical location, also serve as reference points. *Thirdly*, an *engine*, which is connected to the local area network, determines the location of tags while preventing collision among transmission and addressing hidden areas. There are six main steps for a tag to determine its physical location:
   - a tag broadcasts short messages (or beacons) to readers every random time interval;
   - a reader measures the distance to the tag and sends a message to the engine;
   - the engine gathers messages from at least three readers;
   - the engine sends a list of readers and assistant tags to the readers and the tag;
   - the readers and assistant tags in the list are involved in determining the distance to the tag, and the last reader in the list sends the location information to the engine; and
   - engine uses the location of the readers and the assistant tags to determine the location of the tag.
3) In [15], the two-way ranging mechanism [28] is enhanced so that: a) there are stationary and mobile readers; and b) trajectory estimation based on previously known location and existing paths is used when multilateration-based approaches cannot be used (i.e., there are less than three distances received from different readers).

The proposed solutions have been deployed and investigated in the Hutchison Korea terminal in Busan, South Korea, and have shown to improve the accuracy of location and trajectory (P.5).

2) RECOGNITION OF CONTAINER CODES

In [27], template matching and deep learning are used to recognize container codes with low readability, such as nonuniform and unclear fonts. There are three main tasks involved.

Firstly, the *location* of the code characters is identified based on their vertical edges. There are three main steps: a) horizontal high-pass filter detects the vertical edges; b) Otsu algorithm calculates a threshold, which is subsequently used to obtain binary images; and c) morphological operation connects a series of binary images to provide a preprocessed image, which contains the container code.

Secondly, each character is isolated from the background. There are two main steps: a) projection method isolates characters from the background; and b) connected component analysis locates connected components (or characters) based on the shape features of the container code in the preprocessed image.

Thirdly, the characters are extracted, recognized, and transferred to actual characters. Template matching is used to recognize characters in two main steps: a) extracting the character features (e.g., strokes and contours) from high-quality images; and b) comparing the similarity between the extracted features of the images and those from test images. Deep learning uses convolutional neural network, which is robust to noise and distortion, to recognize container codes. Finally, characters are combined according to the credibility of each character, and are verified using the verification rule of the container code.

The proposed scheme has shown to improve the accuracy of the recognition of container codes (P.5).

E. APPLICATION OF AIS DATA FOR OPERATIONAL EFFICIENCY ENHANCEMENT

AIS is an automatic vessel tracking system, which has been mandated by IMO since 2004 [74]. Each vessel is installed with an AIS transponder that exchanges spatiotemporal data (e.g., destination, longitude, latitude, speed of ground, heading, and estimated arrival time of vessels at ports) and sensor data (e.g., temperature, sea depth, and wind speed) with surrounding vessels and AIS base stations on land. Vessels use AIS data to track their locations for navigation and safety (i.e., accident prevention) purposes. In smart ports, AIS data has been used to estimate the arrival time of vessels [53], [75] and analyze traffic [76].

1) APPLICATION OF AIS DATA TO GATHER VESSEL INFORMATION AT TERMINALS OF SMART PORT

In [53], an AIS data collection system is implemented to collect AIS data of the traffic, remove its inaccuracy, verify its checksum, and store the data at the port of Le Havre, which is one of the main ports in France. Subsequently, the AIS data is used to determine the types of freight vessels based on their sizes (i.e., twenty-foot equivalent units, TEUs) and the number of different types of freight vessels at each terminal, contributing to smart port management (A.3). The information is important to understand the port operations, such as the waiting and handling times of vessels, and hence the congestion level of different terminals. Therefore, the information can be used to identify the popular quay positions for different types of freight vessels. For instance, a quay that provides loading, unloading, and transshipping operations to a large number of large freight vessels does not serve small vessels, which can increase the waiting time and cost of large freight vessels. Further investigation could be pursued to design a scheduling scheme to allocate different types of freight vessels to different quays at a terminal.

2) APPLICATION OF AIS DATA TO ESTIMATE VESSEL TRAJECTORIES

In [26], an AIS data collection system is implemented to collect and store the AIS data of the vessel traffic at the ports of Long Beach and Los Angeles. Subsequently, the AIS data is used to predict the future location and trajectory of vessels at heavily trafficked fairways at ports based on the attributes and current trajectories of the vessels, contributing to smart vessel management (A.1). There are three types of data that characterize the attributes and current trajectories of the vessels. *Firstly*, *static data* that includes the type (e.g., passenger and cargo vessels have different routes) and the draft (i.e., vessels with different drafts require fairways with different depths) of the vessels. *Secondly*, *dynamic data* that includes the current location (i.e., longitude and latitude), the trajectory and speed of ground, and the current status (e.g., moving or being moored) of the vessels. *Thirdly*, *voyage-specific data* that includes the country of origin and destination (i.e., vessels with different destinations have different routes) of the vessels.

In general, vessels with similar attributes have the same trajectories, and are likely to reach the same destination within the same time period. Suppose, given the current location of a target vessel at time t, the future location of the vessel at time $t + \Delta t$ is estimated. *Firstly*, a certain number of the nearest neighboring vessels are identified based on the current location of the target vessel. *Secondly*, for each of the nearest neighboring vessels, the estimated location of the target vessel is calculated based on the trajectory of the vessels; specifically: a) the distance between the target vessel and a neighboring vessel at time t; and b) the location of the neighboring vessel at time $t + \Delta t$. *Thirdly*, the central location of the estimated locations of the neighboring vessels is calculated in order to provide the future location and trajectory of a target vessel. The proposed scheme has been shown to improve the accuracy of trajectory estimation (P.5).

F. RESOURCE MANAGEMENT SYSTEM FOR SMART PORTS

In [54], the business process model and notation (BPMN) is used to represent business processes (i.e., terminal processes), covering tasks, resources (e.g., human resources, equipment, and infrastructures), and decision makings. Subsequently, the BPMN model is translated into a computer simulation model to simulate realistic scenarios of business processes in the Port of Leghorn, Italy, in order to evaluate the efficiency of resource management, contributing to smart resource management (A.5). There are two types of BPMN models, namely a traditional model and a novel model integrated with ICT. Each business process has multiple paths from the start event to the end event. Multiple tokens traverse along the multiple paths, in which each distinctive path represents a unique scenario. The tokens compete among themselves to use the available resources. Several variables are being monitored, including the performance measures (e.g., the duration of and resources required by each task in the business flow) and the cost (e.g., the wage of the human resource, and shipping cost).

The impact of ICT to smart port operations, as well as their relationship, is investigated. In other words, the extent to which smart ICT solutions improve the efficiency of operations in smart port is investigated. Subsequently, suggestions on the changes and improvement are made to mitigate resource under- and over-utilization (or bottleneck) of the processes in order to reduce processing time and resource wastage in resource management. There are two business processes. *Firstly*, a smart port management (A.3) mechanism is investigated to facilitate truck check out. Traditionally, there are a number of manual steps, in which the hardcopy documents are passed from the truck driver to the access gate. However, using RFID, the process becomes automated, whereby the RFID registers and controls the containers when the truck approaches the access gate. Simulation using the BPMN model shows that RFID reduces processing time. *Secondly*, a smart container management (A.2) mechanism is investigated to identify the physical location of containers. Containers are embedded with sensor nodes, and so the containers form a wireless sensor network (WSN) that enables the containers to communicate with neighboring containers. The base station constantly gathers information (e.g., location information) from containers to determine and track their physical locations, as well as their relative locations. Simulation using the BPMN model shows that the WSN-based container management system reduces the duration of (i.e., up to 53.2%), and resources (i.e., up to 95.24% of human resource) required by smart container management.

G. SIMULATION AND IMPLEMENTATION OF SMART PORTS

1) SIMULATION OF CONTAINER MANAGEMENT IN SMART PORTS

In [18], a simulation platform is proposed to investigate container management at a port. There are four main components: a) *planning* estimates the number of required equipment and infrastructures; b) *modeling* models the port using object-oriented based libraries for different areas (e.g., quay, terminal, and yard), as well as equipment and infrastructures (e.g., QC, YT, and containers); c) *simulation* runs simulation to evaluate and analyze equipment and operation rules at the terminal; and d) *reporting* presents results.

2) IMPLEMENTATION OF DATABASE AND WEB PLATFORM FOR BIG DATA IN SMART PORTS

In [28], [77], databases and web platforms are proposed to manage and support big data applications, as well as perform reactive actions, at the Las Palmas port in Spain [77] and the ports of Long Beach and Los Angeles in United States. There are static (e.g., the location data of the infrastructures) and dynamic (e.g., the temperature and wave height) data, as well as AIS data, gathered by information gathering devices (e.g., sensors) (C.1). The database is a data centre that provides storage and processing capacities for a massive amount of data and information [26], [77].

In [77], two different databases are used for static and dynamic data, respectively. For the static data, a quantum geographic information system (QGIS) digitizes the data, stores it in a relational database management system (RDBMS) called PostgreSQL [12], and converts it into the GeoJSON format [78], which encodes different geographical data structures. For the dynamic data, an open source cloud platform called FIWARE stores the data in databases called Orion and COSMOS [13], uses an abstraction layer in JavaScript and XML to perform data query, and caches the query results in RDBMS in case similar query is made in the future. The proposed system is used to understand wave height in different seasons of the year; subsequently, fuzzy logic is used to make decisions whether to relocate vessels to a safer location or not. When events of particular interest (i.e., the gathered data is less than, equal to, or greater than predefined thresholds) are detected, Orion generates and sends an alert to the web platform for display via a custom application programming interface (API) and the MySQL database for storage.

In [26], Apache Hadoop is used to store and process a massive amount of static, dynamic, and voyage-specific AIS data (see Section III-E2) in the order of tens of gigabytes [79]. There are two main components. *Firstly*, a Hadoop distributed file system called HBase stores data. HBase is a scalable database stored in a set of distributed machines comprised of 11 Linux machines, each has 8 cores Intel central processing unit (CPU) and 24 gigabytes RAM. HBase provides real-time read and write accesses to support big data. The row and column keys of HBase are defined to enable fast response to queries. The row key is defined by the name, type, draft, and status of a vessel. The column key is defined by the single-dimensional geohash [80], which is based on the two-dimensional information (i.e., longitude and latitude) of a target vessel, for prefix searching. *Secondly*, Hadoop MapReduce processes and analyzes the data.

Next, web platform processes queries and displays data using web applications. In [77], the Glob3 mobile framework (G3M) [81] displays a three-dimensional port layout that consists of equipment and infrastructures (e.g., sensors, cranes, vessels, and containers), and landscape, so that users can explore the port and its surroundings virtually. In [26], Java-based open source GIS software displays vessel trajectories.

The proposed database and web platforms have been shown to reduce the response delay for data and information retrieval from database (P.3) in [26], [77].

3) IMPLEMENTATION OF LOCATING SYSTEM IN SMART PORT

In [28], the locating system enables a tag (e.g., embedded in a YT) to measure the distance to a reader with known location (e.g., embedded in a light tower). Subsequently, engine uses the location of the readers and assistant tags with known locations to determine the location of the tag. More description about the locating system [28] is found in Section III-D1.

The locating system consists of three main types of components. *Firstly*, *tag* consists of a MSP430F2272 processor [14] connected to a NA5TR1 transceiver [82]. *Secondly*, *reader* consists of a PXA255 processor [83] connected to two NA5TR1 transceivers installed with directional antennas so that it can broadcast RF signals to different areas. *Thirdly*, *engine* consists of two software modules connected to a local area network and a serial interface for communication.

The server module consists of: a) packet analyzer that analyzes messages and distance values of readers; b) cell list manager that checks a reader's status (e.g., either idle or estimating distance values) to determine whether it should transmit the information (i.e., a set of readers) to the readers or not in order to minimize collision among radio frequency (RF) signals; c) reader list pool; and d) data pool. The calculation module consists of: a) TOA-based positioning that estimates the location of a tag; b) data filter that uses a median filtering method to estimate the location of a tag; and c) 2.5 dimension that corrects the estimation errors caused by the different heights between readers and tags.

IV. OPEN ISSUES AND FUTURE WORK

Since there is limited work in the literature that attempts to improve smart port, there is much left to be explored. This section presents open issues that can be addressed in the ICT aspect of smart port.

A. EXPLORING NEW APPLICATIONS FOR SMART PORT

In order to improve the competitiveness and productivity of a smart port, further investigation could be pursued to design and deploy the following applications:

- *Smart marine traffic management* can be designed to manage the navigation of the maritime traffic, and ensure the safety of the maritime traffic. Both land and sea intelligent transportation systems can be integrated to provide a holistic solution that can smoothen the traffic flows on land and sea, which is important in busy ports.
- *Smart logistics* can be designed to track, monitor, and manage traffic, logistic, containers, and inland depots in an adaptive manner in order to optimize the local and global supply chains in an unpredictable and dynamic environment. This is because the right inputs, in terms of quality and quantity, must be provided to the production and manufacturing systems at the right times and places in order to facilitate Industry 4.0. Equally important is a smooth flow of goods to customers.
- *Smart security service* can be designed to ensure the availability, confidentiality, integrity, and traceability of data, information, and systems, in the presence of malicious entities in order to optimize the security of smart port. While security services, such as video surveillance, face recognition, trajectory tracking, and RFID-based electronic seals for securing containers have been proposed in the literature [84], RFID-based smart gates [85]–[87], security services, and best practices can be proposed to secure the above new applications and those presented in Section II-C. For instance, the AIS, maritime traffic, and logistic data and information can be manipulated by the heterogeneous malicious network entities, equipment, and infrastructures, affecting the marine traffic and resource management.

B. COLLABORATION PLATFORM FOR DIFFERENT PORTS

A collaboration platform is proposed to foster cooperation among ports in different physical locations despite the different standards and policies of different countries. The platform promotes transnational cooperation, which helps to coordinate and reduce business and administrative processes, and pool and share data, information, resources, and best practices, in order to enable coordinated effort in achieving optimal joint decision and improving operational and energy efficiency in an automated manner. Shared information, such as truck, warehouse, and special handling and packaging (e.g., for grains and resins) cost and availability, is important to cater for the increasingly complex port operation in order to ensure supply chain to run smoothly. This helps the partner ports to achieve economies of scale and improve their competitiveness for mutual benefit, while reducing handovers, unnecessary handling, and waiting time in order to achieve an integrated end-to-end voyage and container management. As an example, partner ports can reposition (e.g., long-term and short-term lease, as well as purchase) empty containers and chassis, whose availability depends on the unpredictable supply and demand of containers at the ports and inland depots.

Both major ports, despite their established capabilities to handle heavy traffic, and smaller ports can seek real-time collaboration to create a stronger bond to compete as a team, rather than compete against each other [88]. Collaboration can also be made with inland depots. In addition, legal issues would need to be addressed to ensure appropriate compliance as it may be complex due to locality with differing governing laws and jurisdiction clause [89], [90]. Hence, further investigation could be pursued to design and deploy essential applications and the underlying digital back-end that enable an effective collaboration platform for achieving a win-win collaboration.

C. ENHANCED TERMINAL OPERATING SYSTEM

Enhancements to TOS are proposed to provide a smart platform for planning, controlling, and managing port operations. As an example in resource management, there are two main potential enhancements. *Firstly*, TOS gathers a pool of resources, including items and equipment such as QCs and YTs. The information about the resources is pertinent, and locating systems (see Section III-D1) can be used to identify the location of the mobile equipment and infrastructures. *Secondly*, TOS allots the resources to tasks. Scheduling mechanisms allocates resources based on the pool of resources efficiently.

With the introduction of digitalization and automation in ports, TOS must: a) allow optimal decisions to be made either by operators or by artificial intelligence-enhanced system in an autonomous manner; b) operate with a diverse range of devices and equipment; c) collect and share real-time information with public and private shareholders; and d) integrate with other smart initiatives, such as smart city and intelligent transportation system, to improve a nation's economic, social, and environmental aspects. Further investigation could be pursued to design and deploy TOS that cater for such requirements, while ensuring that its traditional performance measures, including high stability, availability, scalability, accuracy, and reliability, are upheld.

D. ENHANCING PORTS BY COLLABORATING WITH SMART SHIPS

Smart ships use ICT, such as big data, sensing and detection devices, and IoT, to reduce environmental impact and enhance ship safety, operations, and maintenance in various aspects, such as energy efficiency management, communication network, and navigation. Examples of smart ships include *Great Smart* that provides intelligent ship operations, maintenance, and navigation [91], and *Telenor Maritime's Smart Ship* that provides smart communication network for digital lifestyle onboard a cruise [92], [93]. Examples of smart ship projects are the *Ishin Next - MOL Smart Ship Project* that aims to enable safe autonomous sailing and to reduce environmental impact [94], and the Hyundai Heavy Industries and Accenture project that aims to enable data-driven decision making for efficient operations [95].

While smart ships have been deployed, the relationship between smart ports and smart ships, and the roles of smart ports to support smart ships, are largely undiscovered. Likewise, the ways in which smart ships can improve the efficiency of smart ports are much to be explored. Both smart ports and ships must share and use land-side and onboard resources efficiently, respectively. This means that both smart ports and ships collect real-time data, perform large-capacity calculations and analytics on new and historical data, visualize ship movement, predict the availability of resources, and perform remote control. Nevertheless, smart ports must perform intelligent tasks at the regional or global level, rather than at the individual ship level, so that they can optimize scheduling for stowage and terminal operations, coordinate the arrivals of vessels, and so on, in a real-time manner. As an example, while a smart ship issues real-time alerts to ensure its safety, such warnings can be used by smart ports to handle emergencies at the surrounding areas. In addition, real-time communication and data transmission between smart ports and ships can be enhanced to support remote services.

E. COMPLETELY DIGITIZED AUTONOMOUS SMART PORTS

In a completely digitized and autonomous port, various terminal and inland operations are wholly automated. Firstly, existing and new applications can be integrated into the smart port ecosystems to provide holistic, process-driven and future-proof solutions supported by the underlying digital backend. As an example, container tracking is a smart container management system (A.2) integrated with smart logistics to ensure that containers are transferred to the destination timely and safely. Secondly, self-driving and self-loading trucks, or even self-driving containers, transport containers to inland distribution centers or yard with reduced waiting and inactivity time, which can be costly, particularly at loading and unloading sites. Thirdly, sensors and detection devices (C.1) monitor conditions (e.g., temperature) and detect vibrations and falls of fragile goods, and send data over seamless connections (C.3). Fourthly, cloud and edge computing (C.2) process the massive amount of collected data, and make automated decisions (C.4) whenever there are any emergency cases, such as fluctuations in temperature.

Various application scenarios can be explored. As an example, at the destination, a vacant lot is identified, or an occupied lot is pre-cleared by a YT, for a container while it is being transported from the terminal. As another example, a supplier management system is a smart port management system (A.3) that enables customers and suppliers to interact with each other for procurement, and so an underlying collaboration platform for different ports is important to facilitate collaboration. Further investigation could be pursued to drive port digitization, and such investigations can be process-driven involving various stakeholders and the use of various technologies in order to improve end-to-end processes in smart ports.

F. BIG DATA ANALYTICS FOR SMART PORTS

A massive amount of real-time data and information is generated from heterogeneous sensing and detection devices in an unpredictable and dynamic environment. With today's state-of-the-art aircraft generating up to a terabyte of data per flight, ships are expected to generate data comparable to this amount. Nevertheless, the adoption of big data analytics in the maritime sector lags behind other transport sectors.

Big data analytics enable a better usage of data, from making essential decisions (e.g., identifying the quickest route and the preferred ports) to generating detailed statistics at a pace faster than human beings can do. This helps to improve the competitiveness and productivity of ships and ports. Accessing different kinds of real-time data, including traffic, weather, and currents, from different stakeholders (e.g., vessel owners and port authority) helps to visualize information (e.g., ship and container movements) and make optimal decisions, to predict the availability of resources (e.g., containers), and to optimize stowage and terminal operations, voyages, and coordination of the arrivals of vessels at ports in a real-time manner. Coupled with sharing of data among ports, big data analytics can help to provide an optimized and integrated flow management that improves the efficiency and flexibility of supply chain, which has been increasingly complex, at the global level. The underlying digital backend, enhanced using cloud computing and edge computing, is deployed to process the massive amount of data.

As an example, big data can provide a preventative model for operations (e.g., scheduling) and maintenance to increase port efficiency and cost savings. Operational data collected by sensors can be used to understand the current stage in the life cycle of a part and predict when it needs to be changed, as opposed to the standard suggestions given by manufacturers. Not only does this reduce cost, but also prevent from unexpected failure. Various potential applications of big data analytics have been proposed in [96], including service planning and chartering (i.e., finding the right ship at the right price). Further investigations could be pursued to design and deploy an information system enhanced with big data analytics to make good use of the massive amount of data.

G. USING BLOCKCHAIN FOR LOGISTICS

The emergence of blockchain technology has raised the interest of smart port as this technology could potentially upgrade the traditional port ecosystem with a complete disintermediation and enhance end-to-end process visibility. As an example, using blockchain, verification and transfer ownership of goods would no longer require third party intermediaries to act as guarantors as this new technology is capable to handle transactions in a secure manner since the ledger is duplicated in a large number of identical databases [97]. As another example, global cargo distributed through blockchain technology can help to reduce paper work [98], [99], and hence reduces overhead cost and increases revenue. Whilst blockchain benefits are promising and aplenty, the technology is at its infancy [100]. Further effort is needed for a cultural mind shift from a highly competitive to collaborative logistics environment in order for the blockchain technology to succeed because most main stakeholders may be reluctant on information sharing due to market competitiveness reasons and lack of trust.

H. CYBER SECURITY OF SMART PORTS

Automated smart port infrastructures and ships open up an attack front that can result in new security risks in the cyberspace of smart ports. It is well known that connected important cyber physical systems with digital technology in the cybersphere comes with great risks [101], [102]. Greater complexity of an automated system demands tighter security, which may be challenging. Further investigation could be pursued to develop resilient and intelligent security systems which could predict imminent attacks. As such leveraging the power of artificial intelligence [103], [104] may revolutionize all aspect of security which has become increasingly complex. Nevertheless, the use of artificial intelligence can cause security vulnerabilities as attackers can manipulate learned knowledge, and so proper rules should be designed and imposed [105].

V. CONCLUSION

This article presents a review of the limited number of works on the application of information and communications technology (ICT) in smart ports and proceeds to discuss a number of open issues ripe for research. The enhancement of ICT can be explored and exploited to improve smart port activities and services, including smart vessel, container, and port management, in order to increase the competitiveness of the national economy. More importantly, ICT can be applied to reduce greenhouse gases emission in order to increase the sustainability of the environment, which has been a pressing issue for the past decade and the decade to come. The use of information system, including information gathering devices, data centre, networking and communication, and automation, is an integral part of smart port. Although there is an urgent need to develop smart ports, there is only a perfunctory effort to investigate this topic, particularly in the past few years. This is despite the potential of smart ports to reduce greenhouse gases emission, energy consumption, processing delay, monetary cost, and to increase the accuracy of estimation, which is essential in port activities such as predicting the position of vessel and equipment. Recent works on smart ports revolve around the application of Internet of Things, cold ironing, renewable energy generation and storage, energy management, locating systems and code recognition for containers, the use of AIS data for trajectory estimation, and resource management. Future investigations could be made to explore, design, and develop new smart port applications, collaboration platform among different ports, enhanced terminal operating system, collaboration with smart ships, completely digitized autonomous smart ports, as well as big data analytics, blockchain, and cyber security solutions. This article has laid a strong foundation and stimulated new research interests in smart port for further investigation.

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