Inf Technol Manag (2017) 18:179–201
DOI 10.1007/s10799-016-0269-1

Information systems in seaports: a categorization and overview

Leonard Heilig[1] · Stefan Voß[1,2]

Published online: 1 November 2016

Abstract Information systems have become indispensable to the competitiveness of ports, facilitating communication and decision making for enhancing the visibility, efficiency, reliability, and security in port operations under various conditions. Providing value-added information services and analytics is increasingly important to maintain a competitive edge and to fulfill regulatory requirements. Consequently, it is necessary to survey current information systems both from an academic and practical standpoint. In this paper, we present a classification and a comprehensive survey of information systems and related information technologies applied in ports. As such, the paper provides a state-of-the-art information-centric view on port operations and aims to bridge the gap between industry solutions and academic works.

Keywords Port information systems · Port information technologies · Smart port · Intelligent port · Big data · Port operations · Maritime logistics · Survey

✉ Leonard Heilig
leonard.heilig@uni-hamburg.de

Stefan Voß
stefan.voss@uni-hamburg.de

[1] Institute of Information Systems (IWI), University of Hamburg, 20146 Hamburg, Germany

[2] Escuela de Ingenieria Industrial, Pontificia Universidad Católica de Valparaíso, Valparaiso, Chile

1 Introduction

Besides providing physical and technical infrastructure and being located in geographical proximity to important markets and hinterland connections, the competitiveness of ports is highly dependent on the costs, efficiency, reliability, availability, security/safety, and quality of the various offered services including transport services, value-added logistics services (e.g., packaging, warehousing, product finishing), and auxiliary services (e.g., pilotage, customs, etc.) [140]. As an essential gateway in global supply chains, ports need to integrate a variety of networks and involved actors in order to coordinate the flows of cargo, property rights, and payments [7]. In this regard, a port can be seen as a part of a cluster of organizations where the performance of the network, performing various activities in value-creating logistics chains, is a collective effort requiring an alignment of partners and business processes [68]. Information management and the process of digital transformation [56] play a critical foundation for such alignment, lower transaction costs, and may help to compensate constraints of ports like inadequate infrastructure, capacity bottlenecks, and accessibility problems (e.g., due to traffic congestion).

Regarding the development of port operations from the beginnings of containerization, we see that digitalization and integration, facilitated through the adoption of innovative information technology (IT) and information systems (IS), have enabled a high degree of automation and streamlining in port procedures, in particular in container terminals [56]. Due to the technological progress in recent decades, a near total dependence of day-to-day port operations on IT/IS can be recognized. Consequently, those systems have become an indispensable element of ports and play a critical role in the overall success of port operations [80]. Regarding the developments in IT/IS, however, we also see that ports are usually lagging behind and fail to fully integrate and utilize applied IT/IS for addressing current and future challenges. The latter includes handling increasing trade volumes and larger vessels, changing production patterns, growing transport volumes and peak demands as well as rapid urbanization [41, 133, 147]. On the other hand, ports are increasingly obliged to promote a higher visibility, enhanced environmental awareness, and improved responsiveness to avoid disruptions and cascading effects, having a negative impact on related logistics chains. This includes establishing an electronic single window to fulfill import, export and transshipment-related regulatory requirements[1]. In this regard, the role of IT/IS as a so-called strategic weapon[2] needs to be revisited.

The vision of intra- and inter-port logistics chains characterized through seamless collaboration and communication is increasingly pursued by ports. Several authors emphasize the enlarging role of cooperation and information sharing in ports (see, e.g., [7, 11, 68]). The value of actual and high-quality information for increasing the efficiency and reliability of port operations through dedicated information systems and related decision support systems is intensively discussed in recent works (see, e.g., [55, 148]). Current projects and research initiatives, such as *Erasmus SmartPort Rotterdam* [24] and *smartPort* in the Port of Hamburg (Germany) [48], demonstrate the growing interest in developing innovative solutions for the port community in academia and practice. Governmental and intergovernmental bodies and organizations, such as the European Union (EU) and United Nations (UN), invest a huge amount of resources for supporting research and development in intra- and inter-port networks.[3] Moreover, several student competitions have been launched to motivate students with backgrounds in information systems, data science, and engineering to develop innovative solutions for the port.[4] While those activities mainly focus on the intra-port logistics chains, we can observe that major ports, despite fierce competition, aim to establish inter-port networks and relationships to facilitate better connections in the logistics chain through information exchange, to share best practices, and to build joint ventures for developing innovative digital solutions.[5] Generally, the development of innovative IT/IS solutions is supported by major technology trends, such as related to cloud computing, internet of things, big data, and mobile computing.

Many challenges arise with the development of innovative IT/IS solutions for the port community, at the latest when it comes to the introduction of new solutions on the port level. These problems may arise, for example, through an uneven power balance and different IT/IS maturity levels between actors in the port community, missing standards, and a lack of understanding and willingness to participate [56].

Despite the important role of IT/IS and the growing interests in both academia and practice, we identify a lack of a comprehensive overview of IT/IS solutions used in port operations. In this paper, we present a categorization and survey of the current state-of-the-art IT/IS implementation in major ports based on a review of literature and applied industry solutions. The functionality, standards, and the role of identified IT/IS solutions in port operations is extensively examined. Rather than focusing exclusively on practical implementations, we also review related scientific works and innovative approaches in the context of respective solutions. Thereby, we aim to bridge the gap between applied industry solutions and promising ideas and approaches from academia. Therefore, this survey helps to better understand the current and future role of IT/IS for solving operational problems and for increasing the visibility, efficiency, reliability, and security in ports from both a scientific and practical perspective and thus promotes future research in this area. A teaching oriented companion article can be found in Heilig and Voß [59].

The remainder of this paper is organized as follows. Section 2 provides the necessary background on enabling technologies and standards currently utilized by information systems in modern ports. In Sect. 3, we present a classification of existing port information systems. Subsequently, we provide a comprehensive overview on their functionality and role in port operations. We further point to related academic works that propose innovative ideas and approaches in the context of the presented IT/IS solutions. Finally, we draw some conclusions in Sect. 4.

2 Key enabling technologies and standards

The collection of operational data is highly dependent on advanced IT solutions. In this section, we provide a general overview of main technologies and standards being applied

[1] See, e.g., EU-Directive 2010/65/EU on reporting formalities for ships arriving in and/or departing from ports.

[2] That is, the role of IT/IS is to efficiently maintain current business processes and to facilitate business innovations to gain competitive advantages.

[3] The EU programme Horizon 2020, for example, is funding research for developing the *Port of the Future*.

[4] See, e.g., Maritime Hackathon 2016 in the Port of Hamburg (http://maritimehackathon.com) for the latest edition of such an event.

[5] In 2016, for example, such an international port network has been founded by the ports of Antwerp, Busan, Felixstowe, Hamburg, Los Angeles, Shenzhen, and Singapore [142].

in ports to build a foundation for overlying information and decision support systems. Thus, we classify them as *enabling technologies* since they need to be integrated in IS solutions to unfold their value for improving port operations.

2.1 Global navigation satellite systems

Since the middle of the 1990s Global Navigation Satellite Systems (GNSS), effectively Global Positioning Systems (GPS), were installed in ports [125]. Generally, GPS enables position detection and tracking of movable objects such as containers, vessels, vehicles, and equipment [107]. For vessels, GPS has become the primary aid to navigation in and outside the port area. In port operations, real-time data on the position and status of objects becomes increasingly important to improve the visibility and to efficiently plan and coordinate activities involving multiple actors [41, 57]. The retrieved positioning data does not only allow to locate objects, but is also essential for forecasting (e.g., route prediction, arrival times) and for achieving contextual data about the individual object by combining positioning data with other data sources and points of interest (see, e.g., [3]; further, an overview on location-based services is provided in [71]). Given this functionality, the implementation of innovative concepts like synchromodality [124] and slow-steaming [31, 104] as well as measures to avoid and handle disturbances may hugely benefit from considering operational circumstances. Further, GPS can also be used in totally different areas, such as for measuring tides in port areas more accurately [109].

In container terminals, differential GPS (DGPS) technology was initially used to accurately identify and track container yard positions. That is, DGPS extends GPS by fixed reference stations that calculate the difference between the precisely known location and GPS positioning data. Assuming that object-related receivers will experience similar atmospheric errors, the calculated difference is used to correct the positioning data of objects, which is retrieved through DGPS receivers that are installed on top of the transport and stacking equipment, as depicted in Fig. 1a. Applied to container yards, the position of containers is measured, translated into yard coordinates, and transmitted to a respective information system whenever a container is lifted or dropped [125]. Thereby, it is generally possible to document the exact position of containers as well as to locate and track container, vehicle, and equipment movements within the terminal, as shown in Fig. 1b.

Due to its robustness and accuracy, DGPS can further serve as a navigation system for unmanned vehicles and equipment, particularly for automated guided vehicles (AGVs) [67]. As it also facilitates vehicle-to-vehicle communication, the safety in container terminals and ports in general can be improved, for instance, by implementing collision warning systems. According to Ioannou et al. [67], the installation of DGPS implies relatively low cost and few modifications to the port area. For the transport of containers between container terminals and inland terminals, Zhang et al. [146] propose an automated container transport system where unmanned trucks are equipped with DGPS and on-board sensors to fully automate container transports on dedicated roads [146]. Alternatives to DGPS are optical-based systems, especially laser and radar systems, which are sometimes combined to achieve an even higher reliability [125].

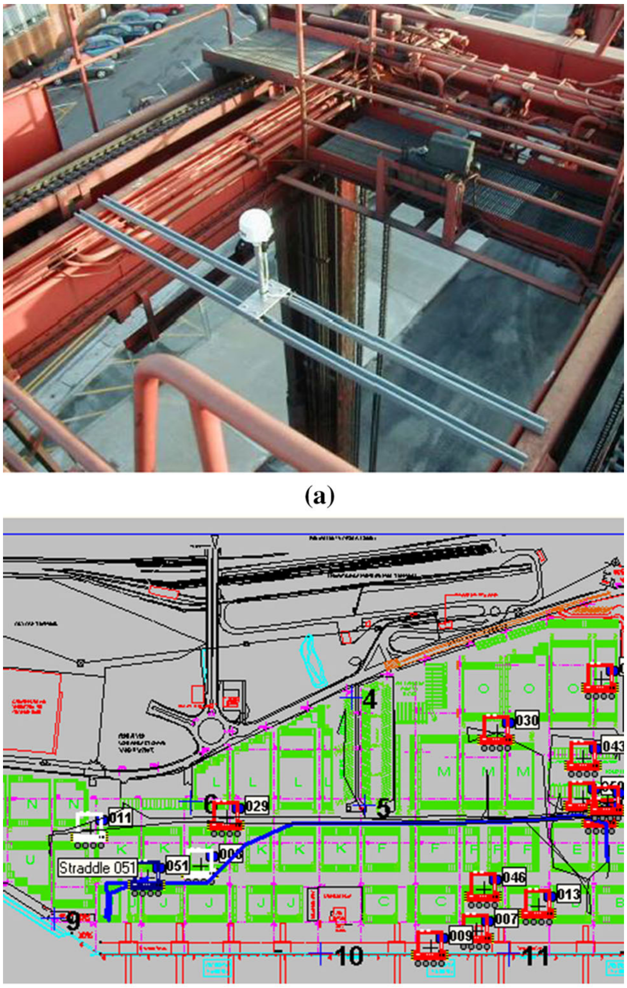
For example, the patented local positioning radar technology developed by Siemens, applied in several large container terminals like HHLA Container Terminal Burchardkai (CTB), substitutes GPS and provides a high accuracy; in particular in areas where GPS cannot be applied (e.g., due to spatial and harsh conditions), real-time location systems are used as an alternative (see Sect. 2.5). Further, satellite-based augmentation systems (SBAS), such as the European Geostationary Navigation Overlay Service (EGNOS), have been developed to complement existing GPS or more generally GNSS. Recently, Favenza et al. [33] presented a cloud-based SBAS architecture to better support correction algorithms and to provide enhanced localization services.

Due to cybersecurity threats (e.g., GPS jamming[6]), the General Lighthouse Authorities of the United Kingdom and Ireland have trailed enhanced Loran (eLoran) in the Port of Dover (UK) as an independent backup to GPS. eLoran has evolved from Loran-C, which is a hyperbolic, low-frequency radio navigation system using fixed ground stations transmitting radio signals to determine the position of vessels, referred to as local positioning system (LPS). Their results indicate that a comparable accuracy can be achieved with eLoran [141].

2.2 Electronic data interchange

A paperless and standardized communication is not only a prerequisite for efficient port operations being carried out by multiple stakeholders, but also for improving supply chain integration, coordination, and performance [60]. Major ports have adopted electronic data interchange (EDI) technologies (see, e.g., [77, 94, 97, 106, 143]) to enable a paperless communication between those stakeholders based on international EDI standards like UN/ EDIFACT

[6] In 2013, for instance, a research team of the University of Texas-Austin demonstrated how GPS signales can be manipulated to take the control of ships; see https://www.youtube.com/watch?v=uR0t3SUnO1Q.



(a)

(b)

Fig. 1 DGPS system at Southampton Container Terminals, Port of Southampton (UK). **a** Straddle carrier with DGPS receiver. **b** Terminal vehicle monitoring (*source/copyright*: effective-solutions.co.uk)

(EDI for administration, commerce and transport), which is a standard to structure and exchange data of commercial or administrative transactions. UN/EDIFACT defines several EDI message types supporting port operations, such as for covering berth management, bay/stowage plans, stowage instructions, gate in and gate out reports, stuffing or stripping orders, customs cargo reports, and dangerous goods notifications.[7] The exchange of those and multiple other messages during transportation is essential to enable seamless processes in which different actors can communicate and collaborate efficiently. However, one of the major adoption problems of traditional EDI systems is still a lack of standardization and high set-up costs, which can be a significant barrier for smaller organizations [38]. Internet technologies and standards were developed to format and transmit EDIFACT messages based on XML (Extensible Markup Language; referred to as XML/EDIFACT) enabling more inexpensive and flexible communication channels. Meanwhile, some port authorities established new Internet offerings supporting information exchange without the need of expensive EDI implementations. Nevertheless, EDI and in particular EDIFACT still builds the foundation for paperless communication and a more efficient integration of different stakeholders in many ports. In fact, the implementation of port community systems (PCS) is commonly based on EDI (see Sect. 3.2). An approach for assessing the value of EDI has been presented in [62].

2.3 Radio-frequency identification

Radio-frequency identification (RFID) is a contactless automatic identification (Auto-ID) technology that enables identification of tagged objects and exchange of information carried by radio waves without requiring a line of sight [37]. RFID systems consist of a data-carrying transponder, the RFID tag, and an interrogator, i.e., RFID reader. The RFID tag contains a radio antenna and an attached microchip incorporating rewritable information related to the tagged object [136]. Advanced transponders are further equipped with sensor technologies facilitating the measurement of physical variables (e.g., temperature, humidity, motion) [37]. Within the interrogation zone formed by the RFID reader, a bidirectional communication line between the tag and the reader is automatically established for receiving data [37]. Some readers are capable of reading multiple tags at the same time.[8] RFID readers forward the data to other systems for further processing [136]. For this purpose, a middleware is supposed to filter, convert, correct, and relay the data to a respective information system [54]. The middleware is installed either directly on the reader or on a server. To facilitate the integration, readers offer communication interfaces such as Ethernet, WiFi, and USB.

RFID tags can either be active or passive, depending on their source of electric power. Active RFID tags contain a power supply (e.g., on-board battery); passive tags gain electric power from an external RFID reader [37]. Due to the on-board power supply, active tags communicate at higher operating frequencies enabling longer distances. However, the costs for passive tags are significantly lower,

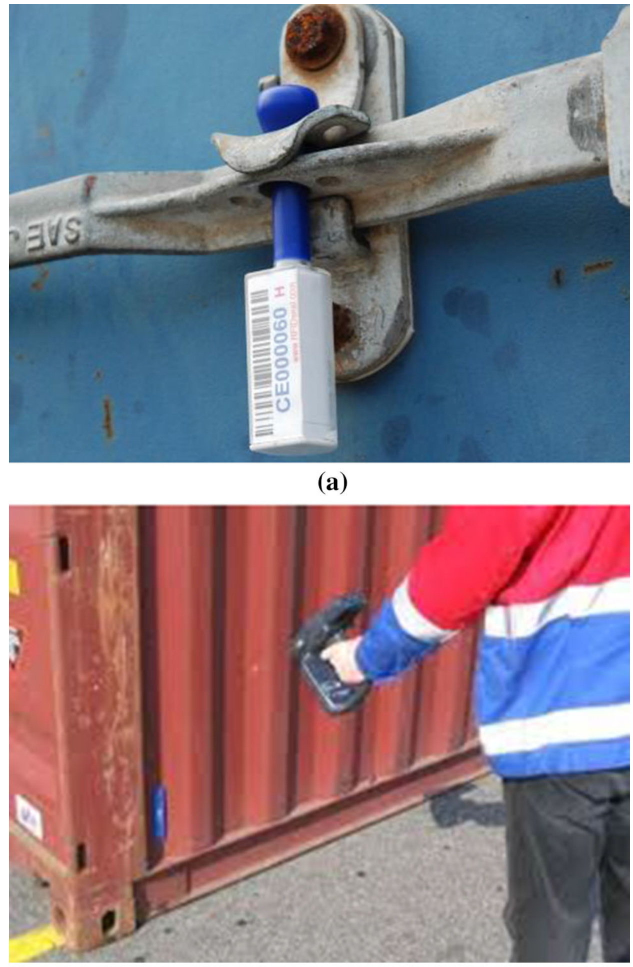
[7] EDI message specifications for the maritime industry are developed and promoted by the User Group for Shipping Lines and Container Terminals (SMDG). Specific EDI documentation within ports and related practical settings can be found, e.g., at www.dakosy.de.

[8] Basically, three types of techniques are used to coordinate data processing: Space Division Multiple Access (SDMA), Frequency Division Multiple Access (FDMA), and Time Division Multiple Access (TDMA) [54].

mainly due to low tag prices, maintenance costs, and because no batteries are used. In addition, the size of the tag is smaller so that it can be attached to practical self-adhesive labels (smart labels) [138]. As indicated, the frequency of RFID systems determines the data reading and transmission speed. At least, RFID readers must support one communication protocol to communicate with standard tags.[9] To protect the data against eavesdropping, different open and proprietary encryption mechanisms are available. Another form is near field communication (NFC), which is based on RFID, but limits its band range to about 10 cm (very short range). It basically enables tag reading and data exchange between two devices [37]. The integration of NFC into mobile devices offers novel application potentials such as for truck driver registration in the terminal gate area. For an extensive introduction to RFID and NFC the reader is referred to [37]. Hassan and Chatterjee [54] propose an RFID taxonomy that can be used to characterize RFID systems.

The application of RFID technologies in logistics and supply chain management has been intensively discussed both in research and practice (see, e.g., [85, 98, 112, 126]). Although the container transportation industry is still in the elementary stages regarding RFID applications, several application scenarios to improve efficiency of port operations can be identified including automatic coordination and handling of activities (see, e.g., [57, 117]). In addition, RFID enables an automated compliance to security regulations important to reduce the costs for fulfilling regulatory requirements promoted by major international security initiatives (e.g., specified in the International Ship and Port Facility Security Code; ISPS Code) [6]. In the following, an overview on major application areas is provided.

Shipping container security Security seals are devices that are used to seal shipping containers. The tamper indication device is attached to the locking mechanism of the container door (see Fig. 2a) in a way that an unauthorized or attempted removal can be detected. In addition, a security seal is limitedly resistant against intentional or unintentional physical attacks and intrusion, provides tamper evidence and thus increases the container security [116]. Usually, seals are made of plastic or metal and implement different locking mechanisms for different door designs. The international standard ISO 17712:2013 unifies requirements, procedures for the classification, acceptance, and withdrawal of mechanical container seals. To prove the integrity of containers, the state of each container seal has to be checked during import and export procedures. Manual checking[10] and reporting of the seal status imply high expenditures on personnel along with higher costs and loss of time. To significantly reduce those manual procedures, RFID-based electronic seals (referred to as e-seals or RFID seals) have been developed, which store mandatory data including the seal number[11], seal status, battery status if an active RFID tag is used, sealing and opening times, and protocol information [22]. The international standard ISO 18185:2007 uniforms the requirements and unique identification mechanisms for electronic container seals.



(a)

(b)

Fig. 2 RFID applications. **a** Container with RFID seal (*source/copyright*: rfidseal.com). **b** RFID container identification (*source/copyright*: isl.org)

Shipping container identification and tracking A general feature of RFID in logistics is the automatic

[9] RFID tags must comply with ISO (International Standards Organization) and/or EPC (Electronic Product Code) standards.

[10] For a manual check of a container seal, the examiner has to record the unique seal number, indicate an eventual tampering, and report the time when the seal had been opened and closed (e.g., during customs procedures).

[11] The seal number is a combination of the RFID tag number and its manufacturer number.

identification of tagged objects and their tracking by installing RFID readers at focal points in the logistic chain. Specific RFID shipping container tags may also include data about the transported cargo. The international standard ISO 10374:1991/Amd 1:1995 specifies requirements for an RFID-based automatic identification of shipping containers, such as requirements for the physical location of devices, frequency band, data format, operational requirements, and security features. ISO 17363:2013 defines the usage of RFID cargo shipment-specific tags, attached to shipping containers, for supply chain management purposes. The international standard specifies the implementation of sensors and makes recommendations on the data interface for GPS or GLS (global locating system) services. Further, recommendations about mandatory and optional, re-programmable information on the shipment tag are given. ISO 18186:2011 describes the composition, application requirements, and operational procedures of RFID cargo shipment tags that are used for improving transparency in transportation processes. A standard-conform RFID cargo shipment tag can be used separately or combined with e-seal and licence plate tags [5]. A licence plate tag, also referred to as *container tag*, specified in the international standard ISO/TS 10891:2009, is a permanently affixed, read-only tag containing limited data for the physical identification and description of a container. As depicted in Fig. 2b, RFID tag data can be accessed either directly with a handheld device or indirectly through an information system. RFID can further be integrated with GPS sensors or other environmental sensors [39], for instance, to enhance the tracking of containers in storage yards [25].

Gate operations The automatic collection and verification of truck and driver information based on RFID can further help to improve access controls in the gate area [117]. In some ports, such as in the Port of Seattle (US) [102], drayage trucks have to be registered (with company and driver information) and must affix a dedicated RFID tag on the truck in order to gain access to terminals. To also enhance identification and authentication of individuals (e.g., personnel, truck drivers), a contactless smart card can be used, additionally providing microcontroller processing capability and writable memory, for instance, to verify passwords and store digital signatures and job information. Application examples are given, e.g., in [51, 110]. Moreover, gate in and out controls may also involve checking the status of container seals, which can be fully automated based on RFID electronic seals. In this regard, Choi et al. [15] propose a non-stop automated gate system based on RFID.

Electronic toll collection Once RFID is adopted for identifying and tracking moving cargo and transport vehicles, it may also be used for electronic toll collection. Tolling is recognized as a means to decongest the port roads and related urban areas, which may result in reduced emissions [19, 28]. The Nhava Sheva Port (India), for example, recently introduced a toll charge for containers and other cargo arriving or leaving by road into or from the terminals, respectively [16].

Early RFID implementations such as in the Port of Shanghai (China), however, identified important aspects to be considered regarding the selection of RFID technology, costs of RFID tags, security of RFID systems [108], and the importance of global standards [137]. Past projects indicate that investment decisions play an essential role for the adoption of RFID. In this regard, Harder and Voß[53] propose a simple cost model for applying RFID in the container shipping industry. By considering relevant factors for evaluating respective business scenarios, the authors show that under reasonable assumptions RFID may provide moderately quick return on investment (ROI). Moreover, Wang et al. [137] emphasize the importance of information systems in adopting RFID in port operations, providing convenient and practical web-based information platforms that are compatible with existing information systems to efficiently share data with involved parties.

2.4 Optical character recognition systems

Optical character recognition (OCR) systems enable an automatic pattern recognition of alphanumeric and handwritten characters in scanned documents or images. To improve the text recognition rate, specific fonts have been developed, namely OCR-A (ISO 1073-1:1976) and OCR-B (ISO 1073-2:1976). Research and development in OCR systems has been active since the mid 1950s and has meanwhile reached a stage where those systems are able to recognize human faces, interpret words, and categorize documents. An overview on the historical development and OCR from both academic and industrial points of view is presented in [87].

In this regard, some studies propose methods for improving the automatic recognition of container numbers (see, e.g., [12, 42, 88]). Several applications of OCR exist in modern ports, which are briefly described in the following.

Identification of Intermodal Shipping Containers and Loading Units OCR systems are often installed at terminal gates to partially automate administrative and checking procedures, as depicted in Fig. 3a. Consequently, gates are able to handle more containers without needing extra staff. As terminal entry and exit gates are potential performance bottlenecks, producing congestion in front of the terminal gate, many terminal operators have implemented pre-gates, also referred to as automatic gates or OCR gates, in order to uncouple checking procedures and enable a guided access to the gate [9]. Further, automated OCR-based pre-

Fig. 3 Gate OCR systems. **a** Pre-gate OCR system (*source/copyright*: portstrategy.com). **b** Rail OCR system (*source/copyright*: Visy, visy.fi)

gates facilitate fast lane procedures thus improving not only the security, but also the management and efficiency of port operations [23]. Also incoming and outgoing rail wagons can be processed through OCR gate systems, as depicted in Fig. 3b. This extends to transports of containers between ship and shore and within the yard area, where OCR systems are commonly attached to ship-to-shore (STS) and yard gantry cranes (e.g., rail-mounted gantry crane—RMG), respectively. The real-time exchange of container identification data does not only build the basis for increasing the efficiency of procedures, but also helps to prevent and reduce errors, such as the unloading of a wrong container from a container vessel. To enable the identification of intermodal shipping containers and loading units, such as semi-trailers or swapbodies, the labeling of loading units is required. The standard for intermodal shipping containers is ISO 6346, which describes a BIC[12] code representing the owner, equipment category, and a container-specific serial number. OCR systems are able to capture and recognize such machine-readable codes, as depicted in Fig. 4a. In Europe, a new standard, EN 13044, has been introduced for labeling combined loading units (e.g., swap-bodies, non-ISO containers, and semi-trailers) with ILU (intermodal loading unit) codes, which are compatible with BIC codes. Rail wagons can be identified based on unique UIC[13] wagon numbers. Although RFID would likely reduce gate time over OCR [43], OCR has the advantage that vehicles and containers must not be equipped with respective technologies.

Identification of Vehicle Licence Plates In automatic number plate recognition (ANPR)[14] systems, OCR is used to read vehicle licence plates. Usually combined with video surveillance systems, these technologies enable an audit trail of vehicle movements within port facilities and are used for security checks. When a truck enters a container terminal, for instance, the licence plate data is minuted in order to constantly oversee the number of visiting vehicles. In some ports, the data is combined with driver card data enabling an unambiguous assignment of trucks to drivers. Additionally, the entry and exit logs for the vehicles and drivers as well as camera images can be used for forensic investigations in case of intended or unintended frauds or accidents. According to the ISPS Code, a valid identification of load, vehicles, and drivers is mandatory.

Damage Inspection The images produced for container identification further provide evidence of the condition of the container surfaces (roof, side, end walls) as they have arrived at or have left the terminal. A reproducible damage inspection is mandatory in order to check claims relating to material damage to goods, especially important for insurance companies. Many OCR systems provide features to document and report container damages. Based on a unique identification, the images of container conditions can be uniquely assigned to the respective container, as depicted in Fig. 4b. Some of these OCR systems are combined with laser technology (e.g., 2D/3D laser scanning) to detect damages, such as bulges, tears, and holes.

12 The BIC (Bureau International des Containers) code should not be confused with the ISO 9362 standard code used for payment transactions.

13 The rail wagon numbering system has been created by the International Union of Railways (Union Internationale des Chemins de Fer - UIC).

14 Several terms for these systems exist, such as automatic licence-plate recognition (ALPR) and licence-plate recognition (LPR). To be differentiated from this are automatic vehicle identification (AVI) systems, which use optical, microwave, or radio-frequency technologies to exchange data based on a transponder and interrogator.

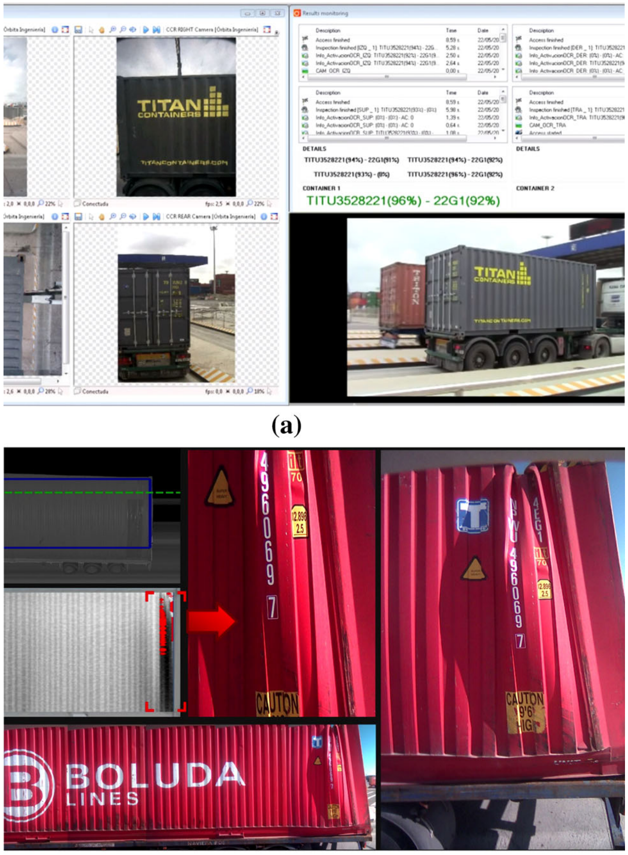


Fig. 4 OCR applications in automated container terminals. **a** OCR container recognition. **b** OCR damage inspection (*source/copyright*: orbitaports.com)

2.5 Real-time location systems

Real-time location systems (RTLS) are specific LPS that enable the identification and constant location tracking of tagged objects located in both indoor and outdoor environments. To detect the position of objects, RTLS often use RFID technology to establish a communication link between a locally installed base station and nearby objects. To determine the position of objects, RTLS readers receive data from the tag, determine the time-of-arrival and forward the data to an RTLS server which determines the respective tag location [99]. Consequently, RTLS technologies are not dependent on satellite systems and thus can be applied in confined spaces including warehouses and road tunnels [82]. Different techniques are proposed to enhance RTLS location estimation (see, e.g., [70, 91]). Some research studies specifically explore the application of RTLS technology in container terminals. Park et al. [99] presents an RFID-based RTLS for improving the coordination between vehicles and cranes for loading and unloading operations. Lee and Cho [76] propose a dynamic planning system (DPS) for yard tractors utilizing RTLS technology and analyze its performance based on simulations.

2.6 Wireless sensor networks

A wireless sensor network (WSN) describes a large-scale system consisting of interconnected wireless sensors deployed within an area of interest in order to cooperatively monitor large physical or environmental conditions, such as temperature, humidity, and position [1]. Sensors communicate with each other and with a base station connected to a remote system propagating sensor data for storage, processing, mining, and analysis [20].

Yet, the application of WSN technology in port operations is mainly explored from a theoretical perspective. Ngai et al. [95], for instance, propose a case study designing an intelligent context-aware decision support system for supporting vertical and horizontal transport operations in the container yard. Heilig and Voß [57] present a cloud-based system service-oriented architecture (SOA) that integrates context-aware information on transport vehicles and containers (e.g., to monitor internal and external conditions, such as position, temperature, humidity, status of e-seals, etc.) based on RFID, WSN, and mobile technologies. A METRANS project [83] investigates WSN security and aims to study the application of WSN in a pilot implementation program at one of the terminals of the Ports of Long Beach and Los Angeles. Besides, an increasing number of sensors is used in port-related road networks such as in-roadway sensors (e.g., inductive-loop systems, magnetic systems, weight-in-motion systems) and over-roadway sensors (e.g., infrared sensors, ultrasonic sensors) to obtain important traffic measurements.

Figure 5 shows a mesh topology enabling a multi-hop communication in which sensor nodes also serve as a relay for other sensors. As a result, multi-hop communication can cover large geographic areas, as found in ports, and utilizes the sensors' resources more efficiently (e.g., lower power consumption) in contrast to a single-hop communication on basis of a star topology. Due to multiple constraints of sensor devices that are usually battery-powered, various standards for wireless communication in WSN have been proposed. In contrast to other wireless network standards, such as the well-known IEEE 802.11 family of standards for implementing wireless local area networks (WLAN), communication standards for WSN aim to reduce energy consumption [8]. ZigBee has emerged as de facto wireless standard for the deployment of WSN. In contrast to Bluetooth, which is another wireless communication standard, ZigBee is simpler, uses lower data rates, and is more energy efficient so that ZigBee-based devices can operate anywhere between six months and two years

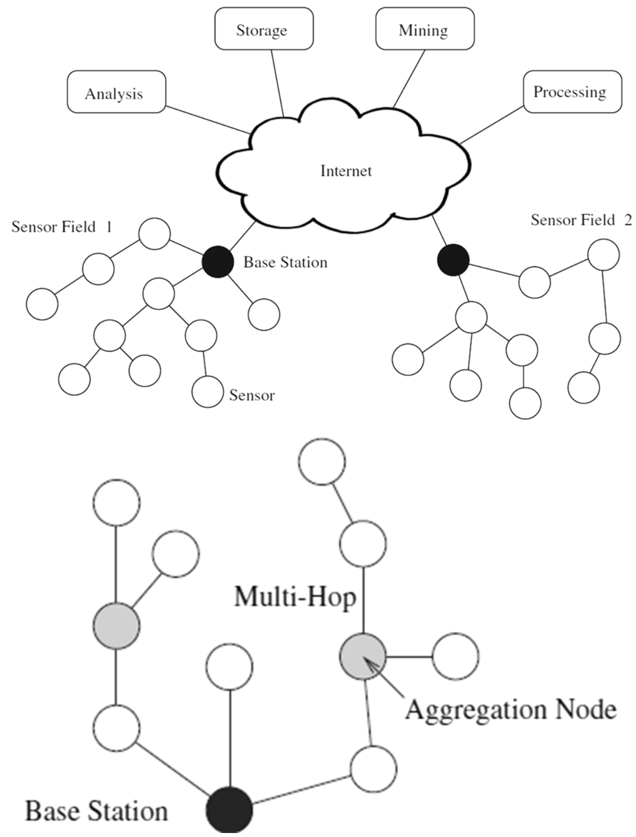


Fig. 5 Types of network topologies for wireless sensor networks [20]

on two common Mignon batteries. Moreover, ZigBee supports a large number of nodes (up to 65.000) and thus can be used to build a large scale WSN. ZigBee is based on the IEEE 802.15.4 standard which defines the lower network layers and furthermore supports mesh networking and automated routing, making it a highly reliable wireless communication standard [26].

Regarding its application in seaport and logistics operations, Yang et al. [144] present a hybrid ZigBee-RFID system architecture to increase the visibility of resources handled by distribution centres in a humanitarian supply chain. Schaefer [113] proposes a ZigBee sensor network solution allowing the tracking of containers and the increase of security of container shipments by implementing a tamper-resistant embedded controller with build-in sensors to detect door openings and measure light, temperature, humidity, acceleration, and the position of containers via GPS.

As an interaction with the environment is sometimes required, actuators are used in addition to impact the environment based on environmental conditions gathered by sensor nodes. For example, an actuator might be a stationary fire extinguisher, based on a smoke detector sensor, that automatically extinguishes a fire detected by the smoke sensor. In combination, actuators and sensors form the new generation of WSNs also referred to as wireless sensor actuator networks (WSAN) [93]. WSN and its extensions, such as mobile WSN [2] and underwater WSN [4], may lead to new innovative applications in ports, as seen in a recent project in the Port of Las Palmas (Spain) [35].

An interesting application of WSAN is the control of light. In large port areas, lighting consumes a severe amount of energy and costs. A lot of ports operate 24/7 requiring an appropriate lighting. In the context of port-related research, however, the optimization of lighting systems (and the corresponding energy consumption) based on real-time data has not been examined so far and thus requires more interdisciplinary research. Recently, the company Philips has developed a solution encompassing several intelligent and interconnected lighting systems that can be applied in the port area. The self-configurable, sensor triggered lighting is responsive to the movement and progression of an object through the area providing an appropriate level of illumination depending on the distance from the object [10]. Early research studies by Sandhu et al. [111] already indicate that the application of WSAN to lighting control may lead to huge energy savings by implementing intelligent self-configuration and learning techniques such as based on multi-agent systems. These approaches could be combined with other technologies, such as with smart video surveillance systems. To further improve the sustainability of lighting in ports, green energy supplied by port-related photovoltaic systems and/or wind power plants could be used, combined with smart grids, which were extensively examined by the research community in recent years (see, e.g., [32]).

2.7 Mobile devices

Nowadays mobile devices, such as smart phones and tablets, are equipped with powerful computing, communication, and sensing capabilities including GPS, RFID, and mobile data services to receive and transmit data over mobile networks [57]. Different standards are used for communication including GSM (Global System for Mobile Communications), UMTS (Universal Mobile Telecommunications System), and LTE (Long-Term Evolution). The evolution and availability of mobile devices provides many opportunities in the logistics sectors and specifically in the port industry [13].

Yet, the adoption of mobile devices in port communities is still in its infancy, which also applies to research in this area. Heilig and Voß [57] propose a system architecture that utilizes mobile device capabilities to integrate GPS-based positioning data and WSN sensor data from containers. In this regard, mobile devices act as base stations and data gateways, allowing to forward contextual data from a connected WSN that links one or multiple containers. Other meaningful adoptions may involve the mobile device owner by providing mobile applications that enable not only the exchange of information, but also features to interact with and/or assist the owner, for instance, a truck driver when approaching a port by considering information on the individual position, traffic congestion, parking spaces, etc. (see, e.g., [55]). Vice versa, individual data from involved actors can be utilized to enhance port operations. Pilot projects, such as the smartPORT logistics project in the Port of Hamburg [48], demonstrate the growing trend of utilizing mobile devices and thereby support real-time information exchange in port operations.

2.8 Communication technologies

Without a highly reliable wireless network, it is difficult to scale the deployment of mobile devices, sensors, and actuators requiring an ongoing communication link. Therefore, many ports aim to establish WiFi networks covering a large area with a high bandwidth network while being equipped for harsh environments, such as by a weatherproof enclosure supporting extended temperature ranges. Common routers are equipped with different connectivity options including LTE with backup to UMTS and GSM, and often include redundant routing and meshing capabilities. For connecting specific equipment, for instance STS gantry cranes, dedicated data transmission systems, e.g., to allow the communication of signals between moving and fixed parts of the equipment using mobile transceivers, have been developed.[15]

3 A survey of information systems in seaports

While the presented enabling technologies are essential for the measurement, collection, and transmission of data, integrated information systems are required to store, manage, analyze, and disseminate information and knowledge to support decision processes of various stakeholders. Existing information systems in the port area can be simply classified according to their scope of operations. In Fig. 6, a classification of information systems in ports is presented. We distinguish between information systems that are accessible by the overall port community and external stakeholders, providing auxiliary information services for port and administrative procedures in general, and information systems that focus on either terminal, seaside, or hinterland operations. Therefore, we decouple those distinct areas of port operations at important transfer points. In this regard, a terminal connects to distinct areas and further implements, dependent on its access to the land or seaside, internal information systems to handle operations at those interfaces. For seaside and hinterland operations, we thus focus on auxiliary information services accessible by all actors involved in respective port operations.

Commonly, information systems on lower layers are vertically aligned and integrated with information systems on overlying layers. For example, automated gate systems access a terminal operating system that receive and store information from external parties through a PCS. As a result, a scalable horizontal integration of multiple information systems is possible facilitating a basis for smooth information flows. In the following, an overview of existing information systems and applied technologies in the port area is given according to the proposed classification.

3.1 National single window

A national single window (NSW) is defined "as a facility that allows parties involved in trade and transport to lodge standardized information and documents with a single entry point to fulfill all import, export, and transit-related regulatory requirements." [132] Main objectives of NSW implementations are the streamlining, harmonization, and coordination of reporting formalities and procedures mainly by electronic means. Therefore, the adoption of IT/IS greatly enhances its implementation [132]. The stage of an NSW implementation is dependent on its current scope of connecting involved companies, authorities, and countries through the exchange of information, as depicted in Fig. 7.

A PCS, which is further described in the next subsection, can be assigned to the third stage of development, providing an information system integration on a local port level [131]. Consequently, a PCS builds a foundation to establish a NSW or can be integrated into one by considering certain standards and interfaces [29, 65].

In the higher development stages, national and transnational information platforms can be established to better facilitate global trade and transnational administrative procedures. In the maritime shipping industry, e-marketplaces (also referred to as *e-logistics platforms*) have been established to form transnational networks among companies involved in the shipping process, including ocean carriers, freight forwarders, and shippers. INTRAA[16] is the leading e-marketplace in the shipping industry, offering various functionalities, e.g., to select ocean carriers, book and track containers, and manage invoicing processes. According to company information, the platform

[15] See, e.g., http://www.conductix.com.

[16] See https://www.inttra.com.

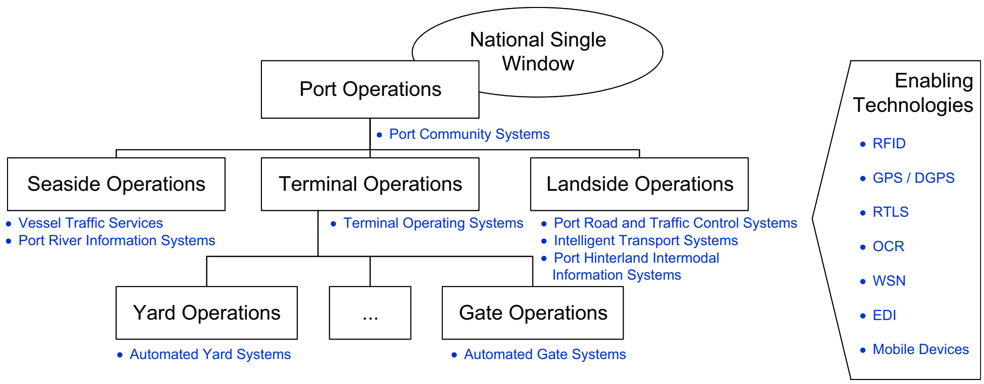


Fig. 6 Classification of port-related information systems and enabling technologies

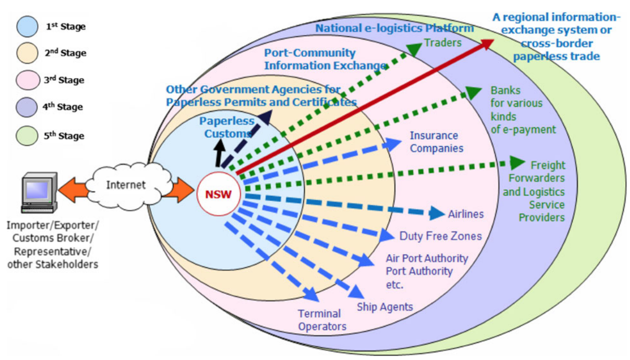


Fig. 7 NSW development stages [131]

is currently used to handle nearly one-quarter of the world's ocean container traffic. Recently, the functionality of INTRAA was extended to comply with the new IMO[17] SOLAS VGM regulations, requiring shippers to submit a verified gross mass (VGM) declaration to carriers before a container is loaded onto a vessel.

Besides this large business network, new e-marketplaces have emerged in recent years. The Boston Consulting Group (BCG), for example, developed *xChange*, a platform to avoid container repositioning by balancing, i.e., exchanging empty container capacities among carriers. A similar platform has been developed by the startup company *Find-Box* in Santiago (Chile). Following the common approach for empty equipment repositioning, *SynchroNet* offers a platform for finding inexpensive ways to transport empty equipment to demand locations (e.g., by utilizing otherwise unused space on vessels and vehicles). As problems like empty container repositioning have been extensively addressed in academic literature since decades (see, e.g., [118, 121]), it would be interesting to analyze the current gap between industry solutions and scientific approaches. Regarding the value of those attempts in general, electronic integration in the maritime shipping industry is positively associated with logistics cost performance according to empirical findings of [74]. However, studies assessing the value of innovative national and transnational solutions, combining IT/IS with problem solving methods and innovative business ideas, need to be comprehensively evaluated in terms of their economic, ecological, and social impact on port operations.

Besides trading, cross-border standards and channels for covering and harmonizing the exchange of information on specific cargo (e.g., dangerous goods, waste, etc.) or other specific requirements of the shipping process between different ports and national authorities have been developed (see, e.g., EDI message standard PROTECT[18] for dangerous goods declaration; import control system (ICS) specifications for EU-wide entry summary declarations, etc.). This includes single window approaches to better manage customs procedures. The e-customs initiative, initiated by the European Commission, aims to establish a single EU-wide single window that interconnects local customs systems in order to harmonize and ease customs procedures allowing, for instance, that import/export operations can be started in one EU member state and can be completed in another one without re-submission of the same information.[19]

Due to the huge interest and governmental support, such as in terms of funding, the topic has gained much attention in academia in recent years. Urciuoli et al. [134] conducted an empirical global survey with customs administrations in order to analyze drivers and barriers affecting the usage of e-customs. A survey with Swiss enterprises considering cost aspects and business requirements has been presented by Hintsa et al. [61]. Raus et al. [105] propose an e-government model and discuss the diffusion of standards as well as the political and societal impact of e-customs solutions.

[17] Abbr. International Maritime Organization.

[18] See http://www.protect-group.org.

[19] The Customs 2020 programme, for example, supports national customs administrations to build up expertise and develop future electronic customs systems.

Meanwhile, PCS operators and customs-related service providers have formed cooperations (e.g., to exchange customs data via EDI, see, e.g., the DAKOSY-Portbase cooperation) and alliances (e.g., EurTradeNet) to facilitate an effective EU-wide implementation of the envisioned e-customs procedures. Baron and Mathieu [7] envision full interoperability among several PCS, especially beneficial for customs authorities, and assume that industrialization of related software systems will lead to a higher market penetration by certain PCS operators linking different ports. In the following, we discuss PCS in more detail.

3.2 Port community systems

A PCS is an inter-organizational system (IOS) that electronically integrates heterogeneous compositions of public and private actors, technologies, systems, processes, and standards within a port community [73, 135]. Thereby, a PCS provides mission-critical IT/IS services and builds an electronic communication link between organizations that operate in the port environment including shippers, shipping lines and ocean carriers, terminal operators, drayage companies, and various authorities (e.g., port authority, customs authorities, water police, veterinary office, etc.). The number of ports that are connected to a PCS varies from one to many and is often dependant on the size of ports [65]. The core aim of a PCS is to facilitate paperless procedures by providing a common information platform used to exchange port-related information and documents that are required for efficiently managing port operations and procedures, such as related to customs handling, import and export declarations, transport orders, dangerous goods declarations, etc. Thus, the objective of a PCS is to improve administrative and logistics processes on a long-term basis [73].

The value of PCS is dependent on the number of actors using the system, known as network effect, as well as on the quality of information and associated benefits for all actors involved. A fundamental challenge for the success of PCS is the adoption of a single information platform among port community actors and the willingness of those actors to share information [135]. Regardless of different roles, interests, and power structures, it is therefore important to achieve a common understanding between different parties in the port community whereby they agree to adopt a PCS to improve the overall performance [21]. Thus, a PCS should be able to promote the autonomy of all involved actors, while incorporating and supporting activities in different port-related business processes [129]. For this purpose, the integration of existing IT/IS plays an essential role, but also leads to several challenges as documented as lessons learned in [122], where also other experiences within the development life cycle of PCS are discussed. Furthermore, special workshops are required to establish a good collaboration and to train end users among the key stakeholders [65]. Tsamboulas et al. [130] propose a methodology to evaluate the introduction of PCS. The authors provide KPIs for port authorities and stakeholders to measure financial and operational indicators as well as functional aspects and impacts on supply chains. Given this methodology, it is possible to evaluate to which extent a PCS generates an added value to a port's performance. Carlan et al. [11] further propose a framework to assess costs and benefits of PCS based on a review of existing literature. In a case study, the authors evaluate costs and benefits of stakeholders using the Export Control System (ECS), providing customs clearance functionality, within the Antwerp Port Community System (APCS). Tijan et al. [129] outline important factors, requirements, and measures for supporting disaster recovery and business continuity in the context of PCS. Baron and Mathieu [7] discuss the evolution of local PCS towards an interconnected maritime information network of interlinked locations.

From a technical perspective, PCS are individual platforms that were commonly built upon EDI standards, in particular EDIFACT. The range of functionality and applications is organized in a set of separate modules covering different aspects of port operations. According to the International Port Community Systems Association (IPCSA) [65], key functionality covers an easy, fast, and efficient information exchange and management, customs clearance, dangerous goods declaration, and tracking and tracing for all types of cargo as well as the processing of maritime and other statistics. Posti et al. [103] indentify over 30 different PCS in different countries including DAKOSY PCS (Hamburg), Portbase (Amsterdam and Rotterdam), eModal (several ports in the US), and PORTNET (Singapore, Seattle). Functionality and services offered by those different PCS varies and is usually under development to be further expanded [11, 72]. For a detailed overview on various existing PCS and key functions, the reader is referred to Posti et al. [103] and Carlan et al. [11].

Specifically regarding customs handling, the PCS must comply with certain requirements in terms of information exchange between customs administrations and economic operators, and with national and supranational authorities. For Europe, for example, the PCS must facilitate a single window by implementing a link to the EU-wide ICS, which complies to safety and security requirements of the European community customs code, in order to allow carriers or their authorized representatives to transmit mandatory documents such as an entry summary declaration (ENS) using a single interface. Moreover, national governments may have additional systems and procedures that must be supported by the PCS. In Germany, for instance, this refers to the EMCS (Excise Movement and Control System) procedure for controlling duty suspension within German tax territory [34]. That is, an electronic administration document (e-VD[20]) under the EMCS is required to move goods under duty suspension. Procedural instructions specify the requirements and conditions for the information exchange over the EMCS between individuals (e.g., carriers) and customs authorities.

3.3 Vessel traffic services

As one of the most critical information systems at the seaside in terms of both safety and efficiency, a vessel traffic service (VTS), i.e., vessel traffic information system (VTIS), includes functionality to collect, analyze, and disseminate information, in particular to navigate vessels in busy, confined waterways and port areas [81]. One of the main aims is to reduce the risks of accidents, especially the risk of hazardous collisions of vessels with dangerous goods and/or loaded tankers, which increasingly occur in port areas with an increased vessel traffic density. Thus, a VTS is essential to technically support waterway safety in ports [36].[21] For this purpose, different enabling technologies are used to gather, process, and communicate information of and to involved actors (e.g., vessel operator). This includes vessel movement reporting systems (VMRS), radar systems, radio communication systems, traffic signals, and video surveillance systems. In this regard, an automatic identification system (AIS) is one of the most used technologies for tracking vessel positions and therefore substitutes radar systems, for example, to avoid collisions on waterways as imposed by the IMO [27]. Recently, new satellites were launched to better support real-time monitoring of vessels based on AIS.[22] A comparison between ARPA radar systems and AIS is provided in [78]. GPS-based devices enable an identification and exchange of positioning data between circumjacent ships and AIS base stations, which are commonly connected to a VTS. The application of WSN technologies might be an interesting extension of common AIS.

As depicted in Fig. 8, several screens display VTS information to constantly oversee the vessel traffic situations in a respective port area and beyond.[23] The VTS

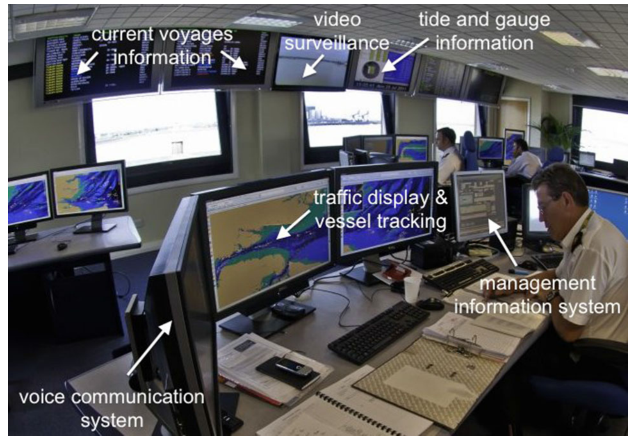


Fig. 8 Port of London Authority VTS centre and workstations (adopted from [100], *copyright*: A. Wallace, Port of London Authority)

personnel must be trained according to international standards (e.g., given by the Maritime and Coastguard Agency - MCA). To distribute information (such as water traffic, water levels, dangerous spots, clearance heights and widths, planned underwater operations, and construction sites) not only to personnel but also to actors on the water, the use of mobile devices and apps will play a crucial role in the future.[24] Recently, a mobile app called *Mobile Port Monitor* has been introduced in the Port of Hamburg, distributing corresponding information in real-time to involved actors [46]. The basis for this mobile app are huge efforts to integrate various information systems into a central control station, i.e., information gateway that will also include road and rail information systems.

The availability of more accurate information on vessel movements and sea traffic can be further used to improve vessel scheduling and terminal planning activities, such as berth allocation. By that, the estimated time of arrival of vessels can be refined, which allows a more efficient planning of subsequent port operations, critical for increasing the port's efficiency and for reducing vessel waiting and turnaround times.

For scheduling and navigating vessels, in particular in restricted waterway corridors, tidal windows and turnaround manoeuvres need to be taken into account. Tidal windows are used to schedule vessels with a certain draught and speed dependent on the current time, location of the vessel, and geospatial information [128]. In restricted waterways, such as on rivers, large vessels might

[20] Abbr. elektronisches Verwaltungsdokument (engl. electronic administration document).

[21] Several other organizational measures have been implemented to regulate sea traffic including traffic separation schemes (TSS) and IMO regulations for preventing collision at sea.

[22] See, e.g., http://blog.orbcomm.com/ais-new-og2-satellites-enable-near-real-time-vessel-monitoring.

[23] In 2007, for instance, the Port of London Authority introduced Thames AIS as a key safety tool supporting the navigation of vessels on the River Thames and transmitting safety critical information to the London VTS [101].

[24] Note that the use of information systems on board of the vessel, such as ECDIS (electronic chart display and information system), are not directly affected. However, the use of mobile apps might improve the communication between vessel operators and the port, in particular to deliver additional, more accurate information and assistance.

demand one-way traffic. In this context, Lalla-Ruiz et al. [75] tackle the waterway ship scheduling problem in the Yangtze Delta (China) to improve the waiting times of ships accessing or leaving the port.

Other circumstances and obstacles, such as locks and movable bridges, require a coordination of infrastructure elements and vessels aiming to pass respective areas [128]. Due to a lack of real-time coordination and adaptable planning, however, those circumstances often lead to maritime traffic congestion [120]. Delays and over-punctual vessel arrivals as well as weather conditions, equipment breakdowns, and a change of vessel priorities, for example, cause changes to the berthing planning [79]. To accommodate flexibility, intelligent decision support systems need to take into account those dynamic aspects, e.g., by incorporating analytics based on real-time data (for an extensive survey on berth allocation problems, the reader is referred to Bierwirth and Meisel [79]). This might also involve the utilization of favorable tidal window. Vice versa, it might be beneficial to leave the port earlier in case of favorable tides, even though the unloading and loading process is not yet completed [96]. Besides vessel characteristics, information systems and related decision support need to further take into account vessel priorities and appointments [63].

Planning functionality using real-time information is not only important to increase the efficiency of port operations, but also to avoid severe accidents and cascading effects.[25] We further see that the interface between seaside and terminal exhibits several potentials for improving the flow of cargo and information. Regarding the availability of academic works, we see that more research is required in this area taking into account the various aspects, in particular real-world dynamic factors, for developing innovative decision support systems. This is not limited to optimization approaches, but also includes analytics to better utilize various available (real-time) data sources.

In the practical context, we already find first implementations of information systems taking into account specific geographic and tidal requirements. In this regard, a port river information system is a specific VTS, also including functionality to ensure a safe entry and exit of vessels through rivers using real-time data. This includes real-time data from sensors and external information providers on the current maritime traffic, weather, and tides. Besides basic VTS functionalities, the information system aims to connect all parties involved in operative and administrative procedures necessary to handle the arrival and departure of vessels in the port. In the Port of Hamburg, PRISE (Port River Information System Elbe) has been introduced to link terminal operators, pilots, shipping companies and shipping agents, tugs, and mooring staff. The objective of the information platform is to improve handling processes, in particular for large vessels, having specific requirements (e.g., regarding the navigation on the river Elbe) and need to be carried out within narrow time windows (e.g., due to tidal time windows). This requires an efficient scheduling of activities and allocation of resources (e.g., berth allocation) according to current circumstances. In this regard, real-time water level forecasts are provided by the German Federal Maritime and Hydrographic Agency [52]. Figure 9 shows the backend of the web-based PRISE application depicting data on vessels, berthing places, and a topographic map of the Port of Hamburg.

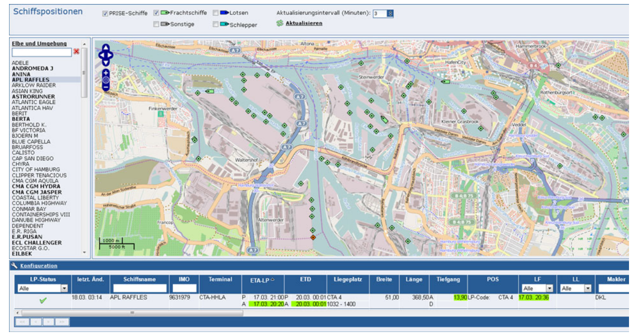


Fig. 9 PRISE vessel, berthing and position data (*source/copyright*: DAKOSY)

3.4 Terminal operating systems

Container terminals manage the flow of goods and materials between the waterside and the hinterland of a port. According to Steenken et al. [125], a container terminal consists of three main operation areas: ship operation area, yard operation area, and truck and train operation area. Different types of handling equipment (e.g., quay cranes, stacking cranes) and transport vehicles (e.g., automated guided vehicles, straddle carrier, multi-trailer systems) are used to serve different types of container vessels and to satisfy certain requirements (for an extensive overview, the reader is referred to [125]). An efficient management of terminal operations, facilities, and equipment requires advanced planning activities. Ship operations involve decisions on berth allocation, stowage planning, and crane split. In the yard operation area, which decouples waterside and hinterland operations, storage planning and stacking decisions play an important role for the performance of a terminal. To enable an efficient flow of goods and materials between all areas of operations, horizontal and vertical transport activities must be planned and optimized. The

[25] In 2016, for example, one of the worldwide largest container ships, the CSCL Indian Ocean, grounded on the river Elbe due to a failure in the navigation system, which resulted in severe restrictions in the overall port operations for several days.

need for optimization has led to a considerable amount of operations research approaches and solutions in recent years (a survey of methods is provided in [123, 125]). The application of those methods for supporting timely and cost-effective decision making heavily relies on information systems that deliver accurate information on the current situation. A sustainable management of terminals further requires management functions (such as booking, accounting, reporting, etc.), means to measure performance based on KPIs, to facilitate effective information flows and to provide an integrated view on operations and resources/inventory.

Information systems that support terminal-related planning and management activities are commonly referred to as terminal operating systems (TOS). Similar to the concept of enterprise resource planning (ERP) systems, a TOS provides a set of applications to collect, store, manage, analyze, and disseminate information from different terminal activities in order to provide an integrated view on core terminal processes and ensure an efficient use of resources for handling cargo. Thus, a TOS focusses on the integration of other technologies, information systems, and applications being installed in a container terminal. Further, different enabling technologies are integrated to monitor and handle the flow of cargo, such as OCR, GPS, RTLS, and RFID. Moreover, data exchange with external parties (e.g., shipping lines, agents, forwarders, truck and rail companies, governmental authorities like customs, waterway police, and port authority) must be supported [125]. Common TOS support EDI standards, such as UN/EDIFACT. Often, a link to the port's PCS is established to enable the interchange of certain information over a shared platform. An analysis of existing TOS, however, has shown that many TOS lack of integration with external parties, system integration, management decision support, and information services for customers [14]. Besides ERP functionality, common TOS provide means for decision support, such as simulation tools and advanced planning and scheduling (APS) modules. In general, the TOS can be regarded as a backbone for the automation in container terminals, for example, containing all work orders for (semi-) automated terminal procedures [56].

In recent decades, several commercial TOS have been developed. The current market leader is Navis SPARCS N4 [92], which provides extensive means to customize the TOS according to individual requirements of terminal operators and has been adopted by many huge terminal operators around the globe. TOS service providers have acquired valuable domain knowledge and developed modules enhancing the planning and management of terminal operations. Another popular TOS is CITOS (Computer Integrated Terminal Operations System), developed by PSA International and implemented in the Port of Singapore. It integrates different modules and expert systems to cover key terminal activities such as berth allocation, stowage planning, and resource allocation. A communication link to Singapore's TradeNet PCS has been established to facilitate cross-terminal communications [44].

In recent years, a trend towards collaborative planning approaches can be observed in terminal software solutions. XVELA, for example, is a multi-tenancy cloud-based collaboration platform and network linking terminal operators and ocean carriers built upon PowerStow, the stowage planning and management system provided by Navis.[26] Meanwhile, TOS providers started to offer their solutions as cloud-based software as a service (SaaS).[27] In the light of cloud implementations, however, implemented planning components and methods need to be revisited in order to fully utilize cloud capabilities, in particular with respect to computing scalability (for an extensive introduction into the field of cloud computing, the reader is referred to [58]). This includes making use of big data for analytics. Also in this regard, we see first solutions in the market, for example, Kalmar Insight aggregating operational data from the TOS, terminal equipment, maintenance systems, etc.[28]

3.5 Gate appointment systems

Gate appointment systems are commonly implemented on the port level to better schedule the handover of cargo by providing a platform to negotiate transport appointments. One of the main objectives is to balance truck arrivals and avoid peak hours at terminal gates in order to reduce congestions at the gate and in the port area. This is not only important for improving cargo flows and avoiding waiting times for drayage trucks within the port, but also for reducing vehicle emissions. Therefore, several terminal operators and port authorities have developed gate appointment systems (see, e.g., [41]).

The terminal operator uses the scheduled appointments to adjust gate and terminal operations accordingly. Drayage companies serving different terminals use appointment systems to determine cargo availability [41]. Consequently, an appointment system aims to reduce information asymmetries and uncertainties in order to facilitate a smoother flow of cargo. Several theoretic works examine the implementation of gate appointment systems. Giuliano and O'Brien [41] evaluate the use of gate appointment systems, which were implemented by many terminals due to state regulations at the ports of Los Angeles and Long Beach. By

[26] See, e.g., http://navis.com/news/in-news/navis-launches-xvela.

[27] See, e.g., http://www.rbs-emea.com/wp-content/uploads/2016/06/TOPS_Expert_Cloud.

[28] See, e.g., https://www.kalmarglobal.com/services/kalmar-insight.

conducting a survey, the authors reveal that appointment systems only impact queuing at terminal gates and hence emissions (1) if those systems provide a clear benefit for truckers and trucking companies, (2) are utilized for a large portion of trips, and (3) if terminal operators efficiently integrate appointments into their operational strategy. As none of these factors were satisfied, the results indicate that appointment systems at the ports of Los Angeles and Long Beach failed to meet expectations to significantly improve traffic flows at the terminal gates.

Another study concluded that appointment systems and extended gate hours implemented at North America West Coast ports (e.g., Port of Vancouver, Canada) have some positive effects in reducing truck emissions dependent on the factors that are producing congestions [86]. Other studies are focused on improving the utilization of gate appointment systems from a perspective of a terminal operator [45, 64], a drayage company [90], or from both perspectives [66, 147]. Zhao and Goodchild [147] emphasize the importance of updating truck arrival information in real-time and real-time decisions for gaining benefits. In their study the authors improve crane efficiency by significantly reducing container re-handling based on more accurate arrival information. They conclude that information sharing requires collaboration between terminal and trucking companies and propose to use existing gate appointment systems to retrieve truck arrival information. However, static truck arrival time windows are often missed due to foreseeable and unforeseeable external events, as reported in mentioned surveys. Thus, information systems that support efficient real-time communication and propagation of truck locations for estimating more reliable and exact truck arrival times and availabilities need to be developed. Other cases can be found, e.g., in Hong Kong [89] and San Antonio (Chile) [115].

3.6 Automated gate systems

Terminal gates handle landside inbound and outbound cargo flows. Therefore, it is essential that information about container and vehicles movements are recorded and verified accurately using respective gate information systems that are integrated with the terminal's TOS. The gate procedures involve checking container damages and cargo hazard classifications as well as the permissions of the truck driver to enter/exit the terminal with a certain container. For this purpose, enabling technologies, such as OCR and RFID, are installed to automatically identify vehicle, driver, and container data and check relevant records in the TOS.

External parties can provide those information through a PCS in advance to avoid paperwork. In this case, the gate personnel only needs to verify and confirm the correctness of data. Otherwise, gate personnel must record relevant information manually, which is very time consuming. Especially in peak hours, this may lead to a major performance bottleneck. That is, the availability of prior information is critical to ensure a fast processing of inbound and outbound cargo flows. As a consequence, some terminal operators have subdivided gate operations into two stages. In the first stage, pre-gate operations identify drivers, vehicles, and containers. If prior information is completely available, the truck driver can directly move on to a check-in gate, where gate personnel can verify information and check the container conditions.

Moreover, some ports have introduced self-service stations allowing truck drivers to manually input missing data prior to arriving at the gate (e.g., at pre-gates or dedicated port parking spaces). As depicted in Fig. 10, self-service stations in the Port of Hamburg enable truck drivers to access the system by using a valid trucker smart card. After typing the relevant container number, the driver is able to specify missing data. The application of the self-service stations contributes to a lower workload and processing time at container gates and thus leads to more efficient terminal operations. Recently, mobile applications for truck drivers have been developed enabling a similar registration procedure and further inform the truck driver on the status and errors during the process (see, e.g., [18]).

3.7 Automated yard systems

After identifying the truck at the bay, a safety laser scanner is used to measure the position of the truck and uses light signals to instruct the driver to move forward or backwards. Additional mechanisms are implemented to ensure the safety of the driver, as depicted in Fig. 11. For instance, the driver must leave the truck cabin and confirm this by pushing a button or swiping a driver's card through a bay station. The latter enables the identification of containers based on job data stored on the smart card. Besides implementing methods to advance re-marshaling and re-handling activities for optimizing the location of containers in yard blocks, an information system is essential to register new containers and track their position within the container yard. Therefore,

Fig. 10 Self-service stations (*source*: adopted from [51], *copyright*: HHLA)

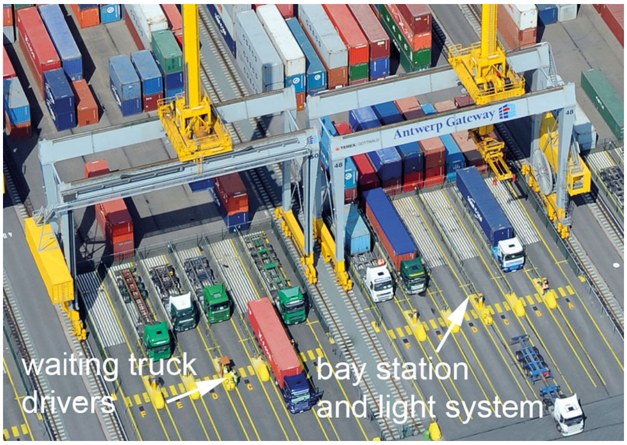


Fig. 11 Bay stations for automatic stacking crane operations at the Port of Antwerp, Belgium (*source/copyright*: adopted from Terex Port Solutions [127])

yard operation technologies are integrated with a TOS. Automated transfer cranes (ATC) heavily rely on the availability and correctness of job and container data to autonomously perform respective yard moves.

3.8 Port road and traffic control information systems

After reviewing approaches for supporting seaside and terminal operations, the following subsections are devoted to give an overview on solutions supporting landside operations. Growing international trade volumes, changing patterns of production, and an increasing seaside container throughput due to larger vessel sizes have resulted in significantly increased volumes of freight traffic at and around ports in urban areas [41, 147]. While an increasing freight volume positively impacts the economic development of a country, e.g., accounting for many jobs in respective port areas and significant tax revenues, its impact on urban congestion and environmental problems becomes increasingly visible [41].

A large portion of import, export, and transshipment goods is moved by trucks before and after, respectively, loading or discharging vessels. An increased truck traffic in metropolitan areas highly contributes to congestion, traffic accidents, and increased vehicle emissions [41]. Besides environmental issues, congestions in port areas affect the productivity of container terminals, lead to frustration and reduced wages for drayage drivers [147], higher fuel and maintenance costs due to stop and go traffic, cause a higher degree of uncertainty leading to scheduling problems, and increase the transport time of goods between origin and destination [147].

Some ports have implemented port road and traffic control systems to measure and control current traffic flows within the port area and inform vehicle drivers about the situation. For this purpose, different enabling technologies in form of sensors and actuators are applied (e.g., video/infrared/laser vehicle detection systems, induction loops, etc.). The collection of real-time data allows more accurate predictions and build the basis to timely react to certain conditions, e.g., by adapting electronic traffic signs and signals (see also Sect. 3.9). It further helps to determine traffic-related vehicle emissions. The Hamburg Port Authority (HPA), for instance, introduced DIVA (Dynamic Information on Traffic Volumes in the Area of the Port) based on one of the most advanced traffic control systems providing integrated traffic information for the traffic control center, as depicted in Fig. 12a, and through LED signboards on the road side, as depicted in Fig. 12b.

As current sensor-based control techniques have some considerable disadvantages, such as related to their maturity, installation, sensitivity to weather conditions, and fixed detection spots, research has been devoted to the application of WSN technology (for an overview see, e.g., [145]) enabling a more accurate monitoring and measurement of vehicle numbers and speed in real-time [139]. Based on a more accurate prediction of vehicle

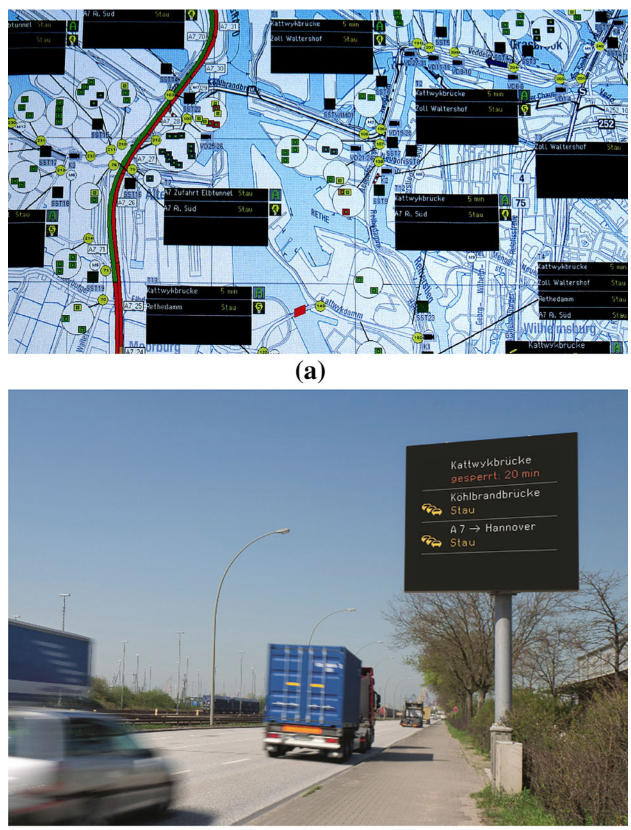


Fig. 12 Port road management system in the Port of Hamburg. **a** Port-related traffic information. **b** DIVA Traffic Signboard (*source*: adopted from [47], *copyright*: HPA)

movements, techniques for controlling the traffic, such as signal control mechanisms, can be improved. Advanced applications for different modes of transport involve intelligent transport systems (ITS), further discussed in Sect. 3.9. Some of those traffic control systems integrate floating car data (FCD) to enhance traffic control [114]. The implementation of traffic systems further build a foundation for truck acceleration programs in the port area. For instance, traffic routing systems can be used to establish an additional communication link between the truck drivers' mobile devices and the road network [40]. While a truck is approaching, nearby traffic lights get a signal to allow the truck to pass without impairment. Given a mobile application, it is also possible to send instructions to the truck driver, for instance, to adjust the current speed in order to enable phased traffic lights.

Strong weather conditions, such as dense fog or extreme winds, increase the risks of accidents and freight damages. More accurate weather data and forecasts could be used to better control the traffic and warn vehicle drivers according to certain weather conditions, e.g., via electronic signboards or mobile apps.

Moreover, the demand for an efficient service area and parking space management is growing. During peak hours with an increased traffic density, truck drivers may prefer to rest at a service area instead of waiting on a congested road. Considering the actual availability of parking space as well as the priority or gate appointment of certain drayage transport activities, an intelligent real-time scheduling could be used to better handle traffic loads. While access to the port area is given to transports with a higher priority, other vehicles have to wait outside the port in times with an increased traffic volume. By better utilizing those facilities, emissions can be reduced and traffic jams disappear more quickly. According to the HPA, a dynamic parking space management is a valuable component for future traffic management strategies. The HPA currently develops a parking space management system for heavy goods vehicles providing information on the availability of parking capacities and enabling the administration and detection of parking areas. A mobile application informs truck drivers about the availability and supports the booking of parking spaces [49].

3.9 Intelligent transportation systems

An ITS embraces a range of advanced sensor and IT systems applied to transport vehicles and infrastructure [84] to improve the performance of transportation systems. In Europe, a legal framework (Directive 2010/40/EU) and a corresponding action plan were designed in 2010 to accelerate the deployment of ITS in order to contribute to cleaner, safer, and more efficient transport systems [28]. To reduce overall emissions, relieve congestion and enhance productivity based on analytical techniques, an ITS collects and handles data from road-based, vehicle-based, and transport network data sources, for instance, by applying automatic vehicle identification (AVI), FCD, and wireless vehicular ad hoc network (VANET) technologies [69]. Subsequently, the collected data is verified, transformed into compatible formats, combined with external data (e.g., from external agencies like highway maintenance organisations, police departments), and processed in order to gain insights into several traffic patterns and to offer context-aware services. This includes the prediction of travel times, traffic, electronic road tolling, automatic incident detection (AID), vehicle location and advanced driver assistance that works with and without satellites, and to display location-based services [69]. In this context, Simroth and Zähle [119] present an algorithm for long-range trip travel time prediction using FCD applied to logistics planning. Moreover, ITS may build a foundation for fully automated transport (see, e.g., [84]) on individual routes without requiring dedicated roads. Cargo-oriented traffic data is further important to evaluate the performance of truck movements, to explore movement bottlenecks and to determine the frequency, costs, and environmental burden of recurring events, such as traffic congestion or accidents [57]. Thus, the use of ITS becomes increasingly important in multimodal logistics and has the potential to significantly shape the future of port operations. In particular promising are VANET technologies that establish a mobile connection among vehicles as a foundation for enabling ubiquitous and real-time information access and exchange [17].

3.10 Port hinterland intermodal information systems

In order to further improve the efficiency and visibility of cargo movements between ports and the hinterland, dedicated information systems shall facilitate the integration of port systems with inland logistics networks. FutureMed is a EU-funded project (futuremedproject.eu) that investigates options to develop a port hinterland intermodal information system (PHIIS) pilot based on interoperable and flexible standards. This involves the development of related PCS services. Consequently, the project aims to extend existing PCS capabilities (see Sect. 3.2) to better integrate involved parties (terminal operators, railway operators, forwarders, etc.), improve information exchange, and reduce the administrative burden between the port and logistics companies. Such projects are important to implement and extend NSWs that incorporate not only the ports, but also airports, logistics service providers, banks, traders and insurance companies (see Sect. 3.1).

Besides the truck transport, a large part of cargo movements is handled via rail transport requiring data access to efficiently manage rail operations and maintain the information exchange between railway undertakings (RUs) and railway operators or other parties in the port area. An example for a corresponding information system is transPORT, which is a new rail traffic management system of the Hamburg port railway [50]. The web-based information system allows, for example, to obtain information on train movements, wagon sequences, track occupations, wagon destinations, loading schedules, and vehicle locations. Furthermore, it can be used to schedule wagons and/or loadings, create transport orders, and transmit dangerous goods data. To harmonize automatic train protection (ATP) systems in Europe, the initiative European Rail Traffic Management System (ERTMS) aims to replace the existing individual member state rail systems with a single system in order to enhance cross-border interoperability [30]. A basic component of this undertaking is an interoperable data communication between the tracks and trains based on standard GSM technology using dedicated rail frequencies (GSM-R)[29]. Although the harmonized system has rather the general purpose of improving overall railway operations and safety, it represents an important step towards interoperable and cross-border data access, which is essential for ports that are linked to multinational transport corridors.

Moreover, the planning of hinterland operations needs to be supported by ports. The port authority of Zeeland Seaports (Netherlands), for example, has developed a web-based search engine to support the planning of intermodal transports and provides an overview of intermodal terminals and their connections using dynamic data from transport operations (barge, rail, feeder), terminals, and connections in Europe. As depicted in Fig. 13, the user can specify an origin and destination and gets possible connections in the next step. Once a connection and related operators have been selected, information about the route, including schedules and an estimation of transport times, are provided.

In recent years, many innovative cloud-based applications have been developed to better coordinate available truck capacities and demanded container transports. MatchBack, for example, offers a cloud-based SaaS solution to match the demand for transports of import and export containers in order to reduce empty trips. A solution developed at the University of Hamburg, *port-IO* [55], aims to better coordinate truck movements by providing a multi-tenancy cloud-based web platform for managing and planning container transport orders taking into account the

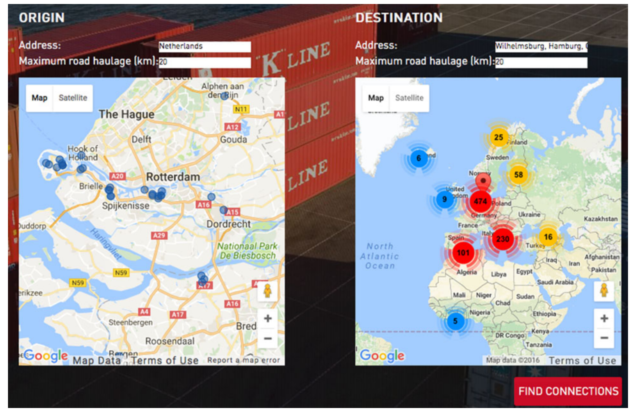


Fig. 13 Intermodal planner (*source*: intermodalplanner.eu)

current positions of trucks and real-time traffic information in order to minimize costs and empty trips. As the truck drivers are equipped with a mobile app, updated planning results can be synchronized immediately making it possible to react to certain events by replanning truck routes. In general, the development of location-based services draws more and more attention in modern ports.

4 Conclusion

Port-related information systems and enabling technologies are an inherent and essential part of port operations enabling the collection, exchange, analysis, and dissemination of important information among different stakeholders. Combined with optimization methods, these systems provide a foundation for extracting process-related knowledge and for supporting long- and short-term decision making thus enabling smarter port operations. Consequently, the importance of integrated information systems will continue to grow, in particular because of current challenges faced by many ports around the globe. Recent technological developments, such as with respect to cloud computing and big data technologies, open new doors for improvement based on an integration of multiple data sources, decision analytics, and meta-analytics[30], but also imply huge requirements on the underlying IT/IS landscape. Consequently, the focus should be put on the integration of legacy systems and enabling technologies acting as data sources for highly scalable and distributed computing platforms using cloud computing, which are able to collect, store, process, and analyze data in real-time and thus provide advanced decision support.

[29] The specifications of GSM-R are available at http://www.uic.org/spip.php?rubrique874.

[30] Meta-analytics aims to unify metaheuristics and analytics by applying both optimization and machine learning tools, which may benefit from one another, in order to better address practical applications.

In this paper, we have presented a classification of state-of-the art enabling technologies and information systems being applied in maritime ports. To the best of our knowledge, this paper provides the first comprehensive overview of port-related IT/IS and is therefore important to better understand port operations from an information-centric point of view. We demonstrate the role of integrated information systems for enhancing the performance of ports as well as to comply with regulatory requirements. The survey also shows that more interdisciplinary research is required to further understand the requirements and implications of integrated electronic logistics platforms and further outlines innovative application potentials. In this regard, we bridge the gap between current industry solutions and academic approaches, which seem to be developed more or less independently from each other. To address current and future challenges, however, cooperation and collaboration between industry and academia may lead to innovative solutions as discussed in this survey.

References

1. Akyildiz IF, Su W, Sankarasubramaniam Y, Cayirci E (2002) Wireless sensor networks: a survey. Comput Netw 38(4):393–422
2. Amundson I, Koutsoukos XD (2009) A survey on localization for mobile wireless sensor networks. Mobile entity localization and tracking in GPS-less environments. Springer, Berlin, pp 235–254
3. Ashbrook D, Starner T (2003) Using GPS to learn significant locations and predict movement across multiple users. Pers Ubiquitous Comput 7(5):275–286
4. Ayaz M, Baig I, Abdullah A, Faye I (2011) A survey on routing techniques in underwater wireless sensor networks. J Netw Comput Appl 34(6):1908–1927
5. Bao Q (2010) Cargo shipment tags: making transport more transparent, efficient and safe. ISO Focus+ 1(4):29–30
6. Barletta GL, Bichou K (2007) Planning and implementing RFID technologies to enhance security in port operations. In: Bichou K, Bell MGH, Evans A (eds) Risk management in port operations, logistics and supply chain security. Informa, London, pp 63–82
7. Baron ML, Mathieu H (2013) PCS interoperability in Europe: a market for PCS operators? Int J Logist Manag 24(1):117–129
8. Baronti P, Pillai P, Chook VW, Chessa S, Gotta A, Hu YF (2007) Wireless sensor networks: a survey on the state of the art and the 802.15.4 and ZigBee standards. Comput Commun 30(7):1655–1695
9. Böse JW (ed) (2011) Handbook of terminal planning, operations research/computer science interfaces series, vol 49. Springer, New York
10. Bourquin S, Hortsing D, Johnston B (2009) Intelligent area lightingsystem. Google Patents, WO 2009003279:A1
11. Carlan V, Sys C, Vanelslander T (2016) How port community systems can contribute to port competitiveness: developing a cost-benefit framework. Res Transp Bus Manag 19:51–64
12. Chao SL, Lin YL (2010) Applying fuzzy AHP to select an automatic container number identification system in port terminals. In: Proceedings of the 8th international conference on supply chain management and information systems (SCMIS), pp 1–7. IEEE
13. Chen JV, Yen DC, Chen K (2009) The acceptance and diffusion of the innovative smart phone use: a case study of a delivery service company in logistics. Inf Manag 46(4):241–248
14. Choi HR, Kim HS, Park BJ, Park NK, Lee SW (2003) An ERP approach for container terminal operating systems. Marit Policy Manag 30(3):197–210
15. Choi HR, Park BJ, Shin JJ, Park NK (2007) Development of non-stop automated gate system. In: Proceedings of the 11th WSEAS international conference on systems, pp 259–265
16. CMA CGM: Toll charges for containers other cargoes passing through Nhava Sheva Port eff 01st May 2016 (2016). https://www.cma-cgm.com/local/india/news/289/toll-charges-for-containers-other-cargoes-passing-through-nhava-sheva-port-eff-01st-may-2016
17. Mondragon Coronado AE, Lalwani CS, Coronado Mondragon ES, Coronado Mondragon CE, Pawar KS (2012) Intelligent transport systems in multimodal logistics: a case of role and contribution through wireless vehicular networks in a sea port location. Int J Prod Econ 137:165–175
18. DAKOSY: Neue Truck-App für die schnelle Terminal-Anmeldung (2014). http://www.dakosy.de/presse/pressemitteilungen/presse-detailansicht/artikel/neue-truck-app-fuer-die-schnelle-terminal-anmeldung/
19. Daniel JI, Bekka K (2000) The environmental impact of highway congestion pricing. J Urban Econ 47(2):180–215
20. Dargie W, Poellabauer C (2010) Fundamentals of wireless sensor networks: theory and practice. Wiley, Chichester
21. Diaz MF (2003) Port community system: a key component of the future vision for cargo and port security. Gov Supply Chain 1(3):28–29
22. Dontharaju S, Tung S, Hoare RR, Cain JT, Mickle MH, Jones AK (2008) Design automation for RFID tags and systems. In: Ahson S, Ilyas M (eds) RFID handbook: applications technology, security, and privacy. CRC Press, Boca Raton, pp 35–64
23. Elovic P (2003) Implementation of gate and crane OCR systems for container terminal automation and security. In: Proceedings of terminal operations conference ASIA (TOC ASIA), pp 1–7
24. Erasmus University: SmartPort (2014) http://www.erim.eur.nl/research/centres/smart-port/
25. Ergen E, Akinci B, Sacks R (2007) Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS. Autom Constr 16(3):354–367
26. Ergen SC (2007) ZigBee/IEEE 802.15.4 summary. http://home.iitj.ac.in/~ramana/zigbee
27. Eriksen T, Hoye G, Narheim B, Meland BJ (2006) Maritime traffic monitoring using a space-based AIS receiver. Acta Astronaut 58(10):537–549
28. Commission European (2011) Intelligent transport systems in action: action plan and legal framework for the deployment of intelligenttransport systems (ITS) in Europe. Tech. rep, European Commission, Directorate-General for Mobility and Transport
29. European Port Community Systems Association (EPCSA): how to develop a port community system (2011). http://www.epcsa.eu/port-community-systems/pcs-services
30. European Rail Industry: ERTMS in brief (2015). http://www.ertms.net/?page_id=40
31. Fan Y, Schwartz F, Voß S (2016) Flexible supply chain planning based on variable transportation modes. Int J Prod Econ. doi:10.1016/j.ijpe.2016.08.020
32. Fang X, Misra S, Xue G, Yang D (2012) Smart grid–the new and improved power grid: a survey. IEEE Commun Surv Tutor 14(4):944–980

33. Favenza A, Rossi C, Pasin M, Dominici F (2014) A cloud-based approach to GNSS augmentation for navigation services. In: Proceedings of the 7th IEEE/ACM international conference on utility and cloud computing (UCC), pp 489–490. IEEE
34. Federal Ministry of Finance: movement of excise goods under duty suspension (2015) http://www.zoll.de/EN/Businesses/Movement-of-goods/Movement-of-goods-within-the-EU/Procedures/Movement-of-excise-goods-under-duty-suspension/movement-of-excise-goods-under-duty-suspension_node.html
35. Fernández P, Santana JM, Ortega S, Trujillo A, Suárez JP, Domínguez C, Santana J, Sánchez A (2016) SmartPort: a platform for sensor data monitoring in a seaport based on FIWARE. Sensors 16(3):417–441
36. Filipowicz W (2004) Vessel traffic control problems. J Navig 57(1):15–24
37. Finkenzeller K (2010) Fundamentals and applications in contactless smart cards, radio frequency identification and near-field communication, 3rd edn. Wiley, Chichester
38. Garstone S (1995) Electronic data interchange (EDI) in port operations. Logist Inf Manag 8(2):30–33
39. Gaukler GM, Seifert RW (2007) Applications of RFID in supply chains. In: Jung H, Jeong B, Chen FF (eds) Trends in supply chain design and management. Springer, New York, pp 29–48
40. Ginsberg ML, Austin MM, Chang PA, Mattison SC (2009) Traffic routing using intelligent traffic signals, GPS and mobile data devices. Google Patents, US Patent App. 12/639,770
41. Giuliano G, O'Brien T (2007) Reducing port-related truck emissions: the terminal gate appointment system at the ports of Los Angeles and Long Beach. Transp Res Part D Transp Environ 12(7):460–473
42. Goccia M, Bruzzo M, Scagliola C, Dellepiane S (2003) Recognition of container code characters through gray-level feature extraction and gradient-based classifier optimization. In: Proceedings of the 12th international conference on document analysis and recognition (ICDAR), pp 973–973. IEEE
43. Goodchild A, Mohan K (2008) The clean trucks program: evaluation of policy impacts on marine terminal operations. Marit Econ Logist 10:393–408
44. Gordon JR, Lee PM, Lucas HC (2005) A resource-based view of competitive advantage at the Port of Singapore. J Strateg Inf Syst 14(1):69–86
45. Guan CQ, Liu RR (2009) Modeling gate congestion of marine container terminals, truck waiting cost, and optimization. Transp Res Rec J Transp Res Board 2100(1):58–67
46. Hamburg Port Authority (HPA): Infrastruktur. Tech. rep., Hamburg Port Authority (2014). http://www.hamburg-portauthority.de/de/smartport/logistics/infrastruktur/Seiten/default.aspx
47. Hamburg Port Authority (HPA): port of Hamburg—digital gateway to the world. Tech. rep., Hamburg Port Authority (2014)
48. Hamburg Port Authority (HPA): smartPORT logistics (2014). http://www.hamburg-port-authority.de/en/smartport/logistics/
49. Hamburg Port Authority (HPA): system to depict an integrated traffic situation—effective depiction of the traffic situation (EVE) in the Port of Hamburg (2014). http://www.hamburg-port-authority.de/en/smartport/logistics/traffic-flows/Seiten/default.aspx
50. Hamburg Port Authority (HPA): transPORT rail (2015). http://www.hamburg-port-authority.de/en/port-customers/port-railway
51. Hamburger Hafen und Logistik AG (HHLA): HHLA launches first self-service terminal (2011). http://hhla.de/en/press-releases/overview/2011/07/hhla-launches-first-self-service-terminal.html
52. Hamburger Hafen und Logistik AG (HHLA): PRISE optimises sequencing and arrival of mega-ships on the river Elbe and at the Port of Hamburg (2014). http://hhla.de/en/press-releases/overview/2014/03/it-platform-optimises-harbour-processes.html
53. Harder FC, Voß S (2012) A simple RFID cost model for the container shipping industry. Int J Shipp Transp Logist 4(2):172–181
54. Hassan T, Chatterjee S (2006) A taxonomy for RFID. In: Proceedings of the 39th annual Hawaii international conference on system sciences (HICSS), pp 1–10. IEEE
55. Heilig L, Lalla-Ruiz E, Voß S (2016) port-IO: a mobile cloud platform supporting context-aware inter-terminal truck routing. In: Proceedings of the 24th European conference on information systems (ECIS)
56. Heilig L, Schwarze S, Voß S (2017) An analysis of digital transformation in the history and future of modern ports. In: Proceedings of the 50th Hawaii international conference on system sciences (HICSS) (in press). IEEE
57. Heilig L, Voß S (2014) A cloud-based SOA for enhancing information exchange and decision support in ITT operations. Lect Notes Comput Sci 8760:112–131
58. Heilig L, Voß S (2014) A scientometric analysis of cloud computing literature. IEEE Trans Cloud Comput 2(3):266–278
59. Heilig L, Voß S (2017) Port-centric information management in smart ports: a framework and categorization. In: Geerlings H, Kuipers B, Zuidwijk R (eds) Ports and networks: strategies, operations and perspective. Routledge (to appear)
60. Hill CA, Scudder GD (2002) The use of electronic data interchange for supply chain coordination in the food industry. J Oper Manag 20(4):375–387
61. Hintsa J, Männistö T, Urciuoli L, Granqvist M (2012) Future development of e-Customs: a survey study with Swiss companies. Int J Elect Govern Res 8(4):1–13
62. Hoogeweegen MR, Streng RJ, Wagenaar RW (1998) A comprehensive approach to assess the value of EDI. Inf Manag 34(3):117–127
63. Hu Q, Yong J, Shi C, Chen G (2010) Evaluation of main traffic congestion degree for restricted waters with AIS reports. Int J Marit Navig Saf Sea Transp 4(1):55–58
64. Huynh N, Walton C (2008) Robust scheduling of truck arrivals at marine container terminals. J Transp Eng 134(8):347–353
65. International Port Community Systems Association (IPCSA): port community systems (2014). http://ipcsa.international/pcs
66. Ioannou P (2006) Cooperative time window generation for cargodelivery/pick up with application to container terminals. Tech.rep, METRANS Transportation Center
67. Ioannou PA, Jula H, Liu CI, Vukadinovic K, Pourmohammadi H, Dougherty E (2000) Advanced material handling: automated guided vehicles in agile ports. Tech. rep., Center for advanced transportation technologies, Univ. Southern California, Los Angeles
68. Islam S, Olsen T, Daud Ahmed M (2013) Reengineering the seaport container truck hauling process: Reducing empty slot trips for transport capacity improvement. Bus Process Manag J 19(5):752–782
69. Jarašūnienė A (2007) Research into intelligent transport systems (ITS) technologies and efficiency. Transport 22(2):61–67
70. Jeong SH, Lee HJ, Lee JS, Oh CH (2006) Performance analysis of location estimation algorithm using an intelligent coordination scheme in RTLS. In: Gabrys B, Howlett RJ, Jain LC (eds) Knowledge-based intelligent information and engineering systems. Springer, Berlin, pp 829–835
71. Jiang B, Yao X (2006) Location-based services and GIS in perspective. Comput Environ Urban Syst 30(6):712–725
72. Keceli Y (2011) A proposed innovation strategy for Turkish port administration policy via information technology. Marit Policy Manag 38(2):151–167
73. Keceli Y, Choi HR, Cha YS, Aydogdu YV (2008) A study on adoption of port community systems according to organization

size. In: Proceedings of the 3rd international conference on convergence and hybrid information technology (ICCIT), pp 493–501. IEEE
74. Lai KH, Wong CW, Cheng T (2008) A coordination-theoretic investigation of the impact of electronic integration on logistics performance. Inf Manag 45(1):10–20
75. Lalla-Ruiz E, Shi X, Voß S (2016) The waterway ship scheduling problem. Transp Res Part D. doi:10.1016/j.trd.2016.09.013
76. Lee SY, Cho GS (2007) A simulation study for the operations analysis of dynamic planning in container terminals considering RTLS. In: Proceedings of the 2nd international conference on innovative computing, information and control (ICICIC), pp 116–119. IEEE
77. Lee-Partridge JE, Teo TS, Lim VK (2000) Information technology management: the case of the Port of Singapore Authority. J Strateg Inf Syst 9(1):85–99
78. Lin B, Huang CH (2006) Comparison between ARPA radar and AIS characteristics for vessel traffic services. J Mar Sci Technol 14(3):182–189
79. Lokuge P, Alahakoon D (2007) Improving the adaptability in automated vessel scheduling in container ports using intelligent software agents. Eur J Oper Res 177(3):1985–2015
80. Long DC (2004) International logistics: global supply chain management, 2nd edn. Kluwer, Dordrecht
81. Lynch WD (1982) Vessel traffic services. Master thesis, University of Rhode Island
82. Ma X, Liu T (2011) The application of Wi-Fi RTLS in automatic warehouse management system. In: Proceedings of the IEEE international conference on automation and logistics (ICAL), pp 64–69. IEEE
83. Maples TB (2011) Wireless ad hoc sensor networks for port security. METRANS Transportation Center, California StateUniversity, Tech. rep
84. McGinley K (2014) Preparing port container terminals for the future: making the most of intelligent transport systems (ITS). Urban Transp XX 138:419–427
85. Michael K, McCathie L (2005) The pros and cons of RFID in supply chain management. In: Proceedings of the international conference on mobile business (ICMB), pp 623–629. IEEE
86. Morais P, Lord E (2006) Terminal appointment system study. Tech.rep, Roche Ltée, Groupe-conseil and Levelton Consultants
87. Mori S, Suen CY, Yamamoto K (1992) Historical review of OCR research and development. Proc IEEE 80(7):1029–1058
88. Mullot R, Olivier C, Bourdon JL, Courtellemont P, Labiche J, Lecourtier Y (1991) Automatic extraction methods of container identity number and registration plates of cars. In: Proceedings of the international conference on industrial electronics, control and instrumentation (IECON), pp 1739–1744. IEEE
89. Murty KG, Wan Y-W, Liu J, Tseng MM, Leung E, Lai K-K, Chiu HWC (2005) Hongkong International Terminals gains elastic capacity using a data-intensive decision-support system. Interfaces 35(1):61–75
90. Namboothiri R, Erera AL (2008) Planning local container drayage operations given a port access appointment system. Transp Res Part E Logist Transp Rev 44(2):185–202
91. Narzullaev A, Park Y, Yoo K, Yu J (2011) A fast and accurate calibration algorithm for real-time locating systems based on the received signal strength indication. AEU Int J Electron Commun 65(4):305–311
92. Navis: Navis SPARCS N4—the industry standard terminal operating system (2014). http://navis.com/solutions/container/sparcs-n4
93. Nayak A, Stojmenovic I (eds) (2010) Wireless sensor and actuator networks. Wiley, Hoboken
94. Neo BS (1994) Managing new information technologies: lessons from Singapore's experience with EDI. Inf Manag 26(6):317–326
95. Ngai E, Li CL, Cheng T, Lun YV, Lai KH, Cao J, Lee M (2011) Design and development of an intelligent context-aware decision support system for real-time monitoring of container terminal operations. Int J Prod Res 49(12):3501–3526
96. Notteboom TE (2006) The time factor in liner shipping services. Marit Econ Logist 8(1):19–39
97. Notteboom TE, Winkelmans W (2001) Structural changes in logistics: how will port authorities face the challenge? Marit Policy Manag 28(1):71–89
98. Pacciarelli D, D'Ariano A, Scotto M (2011) Applying RFID in warehouse operations of an Italian courier express company. Netnomics 12(3):209–222
99. Park DJ, Choi YB, Nam KC (2006) RFID-based RTLS for improvement of operation system in container terminals. In: Proceedings of the Asia-Pacific conference on communications (APCC), pp 1–5. IEEE
100. Port of London Authority (PLA): About London VTS (2014). http://www.pla.co.uk/Safety/About-London-VTS
101. Port of London Authority (PLA): What is Thames AIS? (2014). http://www.pla.co.uk/Safety/Thames-AIS
102. Port of Seattle: RFID tags required to enter container terminals (2014). http://www.portseattle.org/Cargo/SeaCargo/Pages/RFID.aspx
103. Posti A, Häkkinen J, Tapaninen U (2011) Promoting information exchange with a port community system–case Finland. Int Supply Chain Manag Collab Pract 4:455–473
104. Psaraftis HN, Kontovas CA (2010) Balancing the economic and environmental performance of maritime transportation. Transp Res Part D Transp Environ 15(8):458–462
105. Raus M, Flügge B, Boutellier R (2009) Electronic customs innovation: an improvement of governmental infrastructures. Gov Inf Q 26(2):246–256
106. Reiners T, Voß S (2000) Costs and benefits of EDI integrationin supply chains and networks. Technische Universität Braunschweig, Tech. rep
107. Reynolds JC, Denaro RP, Kalafus RM (1990) GPS-based vessel position monitoring and display system. In: Proceedings of the position location and navigation symposium (PLANS), pp 601–607. IEEE
108. Rieback MR, Crispo B, Tanenbaum AS (2006) The evolution of RFID security. IEEE Pervasive Comput 5(1):62–69
109. Rivas MB, Martin-Neira M (2006) Coherent GPS reflections from the sea surface. IEEE Geosci Remote Sens Lett 3(1):28–31
110. Rodon J, Pastor JA, Sese F, Christiaanse E (2008) Unravelling the dynamics of IOIS implementation: an actor-network study of an IOIS in the seaport of Barcelona. J Inf Technol 23(2):97–108
111. Sandhu JS, Agogino AM, Agogino AK (2004) Wireless sensor networks for commercial lighting control: Decision making with multi-agent systems. In: Proceedings of the AAAI workshop on sensor networks, pp 131–140
112. Sarac A, Absi N, Dauzere-Peres S (2010) A literature review on the impact of RFID technologies on supply chain management. Int J Prod Econ 128(1):77–95
113. Schaefer S (2006) Secure trade lane: a sensor network solution for more predictable and more secure container shipments. In: Companion to the 21st ACM SIGPLAN symposium on object-oriented programming systems, languages, and applications, pp 839–845. ACM
114. Schäfer RP, Thiessenhusen KU, Wagner P (2002) A traffic information system by means of real-time floating-car data. In: Proceedings of the ITS world congress, pp 1–8

115. Schulte F, Gonzalez RG, Voß S (2015) Reducing port-related truck emissions: Coordinated truck appointments to reduce empty truck trips. Lect Notes Comput Sci 9335:495–509
116. Seidelmann C (2007) Developing and implementing global interoperable standards for container security. In: Bichou K, Bell MGH, Evans A (eds) Risk management in port operations, logistics and supply chain security. Informa, London, pp 55–60
117. Shi X, Tao D, Voß S (2011) RFID technology and its application to port-based container logistics. J Organ Comput Electron Commer 21(4):332–347
118. Shintani K, Imai A, Nishimura E, Papadimitriou S (2007) The container shipping network design problem with empty container repositioning. Transp Res Part E Logist Transp Rev 43(1):39–59
119. Simroth A, Zähle H (2011) Travel time prediction using floating car data applied to logistics planning. IEEE Trans Intell Transp Syst 12(1):243–253
120. Smith LD, Sweeney DC, Campbell JF (2008) Simulation of alternative approaches to relieving congestion at locks in a river transportion system. J Oper Res Soc 60(4):519–533
121. Song DP, Carter J (2009) Empty container repositioning in liner shipping. Marit Policy Manag 36(4):291–307
122. Srour FJ, van Oosterhout M, van Baalen P, Zuidwijk R (2008) Port community system implementation: lessons learned from international scan. In: Transportation research board 87th annual meeting
123. Stahlbock R, Voß S (2008) Operations research at container terminals: a literature update. OR Spectr 30(1):1–52
124. SteadieSeifi M, Dellaert NP, Nuijten W, Van Woensel T, Raoufi R (2014) Multimodal freight transportation planning: a literature review. Eur J Oper Res 233(1):1–15
125. Steenken D, Voß S, Stahlbock R (2004) Container terminal operation and operations research–a classification and literature review. OR Spectr 26(1):3–49
126. Tajima M (2007) Strategic value of RFID in supply chain management. J Purch Supply Manag 13(4):261–273
127. Terex Port Solutions: automated equipment (2017). http://www.terex.com/port-solutions/en/about-us/news/photo-gallery/automated-equipment/index.htm
128. Thiers GF, Janssens GK (1998) A port simulation model as a permanent decision instrument. Simulation 71(2):117–125
129. Tijan E, Kos S, Ogrizović D (2009) Disaster recovery and business continuity in port community systems. Sci J Marit Res 23(1):243–260
130. Tsamboulas D, Moraiti P, Lekka AM (2012) Performance evaluation for implementation of port community system. Transp Res Rec 2273:29–37
131. Tsen JKT (2011) Ten years of single window implementation: lessons learned for the future. In: Proceedings of the global trade facilitation conference, pp 1–30
132. United Nations: Recommendation and guidelines on establishing a single window to enhance the efficient exchange of information between trade and government: recommendation no. 33. Tech. rep., United Nations, Centre for Trade Facilitation and Electronic Business, New York (2005)
133. United Nations: World urbanization prospects. Tech. rep., United Nations, Department of Economics and Social Affairs (2014). https://esa.un.org/unpd/wup/Publications/Files/WUP2014-Highlights
134. Urciuoli L, Hintsa J, Ahokas J (2013) Drivers and barriers affecting usage of e-customs-a global survey with customs administrations using multivariate analysis techniques. Gov Inf Q 30(4):473–485
135. Van Baalen P, Zuidwijk R, van Nunen J (2009) Port inter-organizational information systems: capabilities to service global supply chains. Found Trends Technol Inf Oper Manag 2(2–3):81–241
136. Wamba SF, Chatfield AT (2009) A contingency model for creating value from RFID supply chain network projects in logistics and manufacturing environments. Eur J Inf Syst 18(6):615–636
137. Wang W, Yuan Y, Wang X, Archer N (2006) RFID implementation issues in China: Shanghai Port case study. J Internet Commerce 5(4):89–103
138. Want R (2006) An introduction to RFID technology. IEEE Pervasive Comput 5(1):25–33
139. Wenjie C, Lifeng C, Zhanglong C, Shiliang T (2005) A real-time dynamic traffic control system based on wireless sensor network. In: Proceedings of the international conference workshops on parallel processing (ICPP), pp 258–264. IEEE
140. Wiegmans BW, Hoest AVD, Notteboom TE (2008) Port and terminal selection by deep-sea container operators. Marit Policy Manag 35(6):517–534
141. Williams P, Basker S, Ward N (2008) e-Navigation and the case for eLoran. J Navig 61(03):473–484
142. World Cargo News: Hamburg launches ChainPORT (2016). http://www.worldcargonews.com/htm/w20160406.776974.htm
143. Wrigley CD, Wagenaar RW, Clarke RA (1994) Electronic data interchange in international trade: frameworks for the strategic analysis of ocean port communities. J Strateg Inf Syst 3(3):211–234
144. Yang H, Yang L, Yang SH (2011) Hybrid Zigbee RFID sensor network for humanitarian logistics centre management. J Netw Comput Appl 34(3):938–948
145. Yick J, Mukherjee B, Ghosal D (2008) Wireless sensor network survey. Comput Netw 52(12):2292–2330
146. Zhang J, Ioannou PA, Chassiakos A (2006) Automated container transport system between inland port and terminals. ACM Trans Model Comput Simul 16(2):95–118
147. Zhao W, Goodchild AV (2010) The impact of truck arrival information on container terminal rehandling. Transp Res Part E Logist Transp Rev 46(3):327–343
148. Zuidwijk RA, Veenstra AW (2014) The value of information in container transport. Transp Sci 49(3):675–685