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# Inter-terminal transportation: an annotated bibliography and research agenda

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**Abstract** The seemingly unlimited growth of containerized transport is nowadays associated with an increasing number of seaport container terminals and facilities as well as demand for port-centric value-added and just-in-time logistics services. Intense global and local competition as well as geographical limitations urgently require efficient means to handle inter-terminal transportation. Many factors influence the productivity and efficiency of inter-terminal transportation as well as its economic and environmental implications. In the last two decades, these aspects have led to a growing interest in research, in particular concerning decision analytics and innovative information technology aiming to better understand, improve, and operate inter-terminal transportation. In this paper, we present a chronological overview of related works as an annotated bibliography in order to reflect the current state of research. Furthermore, we identify future research issues and propose a respective research agenda.

**Keywords** Inter-termal transportation · Planning · Optimization · Simulation · Information technology · Survey · Research agenda

## 1 Introduction

Due to growing transport volumes, environmental restrictions, and port competition, the productivity and efficiency of port operations needs to be further enhanced to increase the competitiveness of seaports. Important determinants for a sustainable

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growth and competitiveness of ports include cost efficiency, physical and technical infrastructure (e.g., nautical accessibility, terminal infrastructure and equipment), geographical location (e.g., proximity/connection to the immediate and extended hinterland and important markets, links to main shipping lanes), interconnectivity (availability and frequency of deep-sea and feeder shipping services), inland transport services by truck, rail and barge (may include transports within the port), auxiliary services (e.g., customs, empty container depots), value-added logistics services (e.g., warehousing), port security and safety, information and communication technologies (e.g., availability of a port community system), and port reputation such as expressed by satisfactory rankings in benchmark (Wiegmans et al. 2008; Notteboom and Winkelmans 2001; Van Reeven 2010).

Some of those port characteristics have an essential impact on maritime transport costs and transport reliability (Wilmsmeier et al. 2006; Notteboom 2006a). Moreover, environment protection becomes an important factor for sustainable growth so that ports are required to reduce, for example, greenhouse gas emissions by means of avoiding traffic congestion or through the use of eco-friendly transport modes (Bailey and Solomon 2004). Consequently, ports need to determine economic and ecological goals to support sustainable growth and to remain competitive. All mentioned determinants play an essential role when it comes to transportation between terminals and/or dedicated service areas (e.g., logistics service areas, auxiliary services) within a port. In fact, growing transport volumes and the need for dedicated service areas will likely require a more efficient utilization of available infrastructure and resources, pooling of service areas, and efficient transportation means in between in order to ensure punctual and efficient deliveries of containers at the points of delivery where they are either further processed (e.g., customs control, packing activities) or further transported to the hinterland or to another port.

Related port operations are referred to as inter-terminal transportation (Duinkerken et al. 2006; Tierney et al. 2014). That is, inter-terminal transportation (ITT) refers to any type of land and sea transportation moving containers and cargo between organizationally separated areas (e.g., container terminals, empty container depots) within a seaport. In particular, ITT is important to compensate differences in the terminal infrastructure endowment and to improve the link between terminals and common auxiliary and value-added logistics facilities, as depicted in Fig. 1. Value-added services may include inventory, inspection, labelling, packing, picking, bar coding, customizing activities (United Nations 2002), and thus are essential to satisfy individual customer requirements. Auxiliary areas may include rail or feeder terminals that are used to bundle cargo for intermodal operations. Beyond the increasing number of auxiliary and value-added services demanding transports between container terminals and respective facilities, we also need to consider the considerable share of containers requiring repairs, cleaning, or storage in the port of destination.

As depicted in Fig. 1, ITT may be required between various origins and destinations within a port, which typically incorporates multiple terminals serving container vessels, railways, barges, and other forms of hinterland transportation (Tierney et al. 2014). This may include transports from and to dry port terminals,

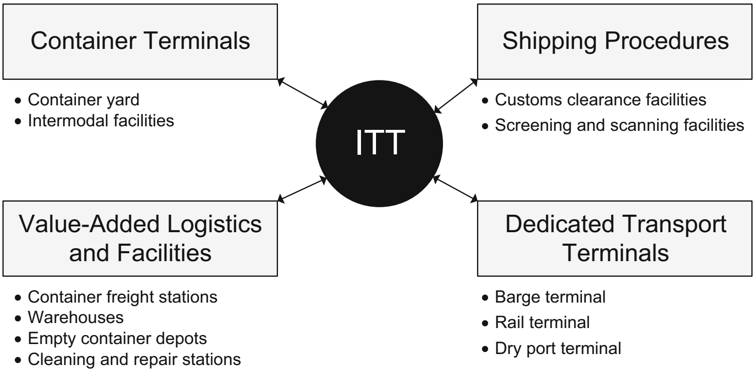


**Fig. 1** Role of ITT in seaports

further discussed in Sect. 2. Dedicated terminals allow to bundle cargo from different areas of the port for intermodal operations. This is in particular important for areas that do not have the necessary infrastructure (like rail and feeder connections); often, this is the case for logistics facilities within the port. Moreover, an ITT network connects service areas including container repair stations, empty container depots, and common areas for handling shipping procedures such as customs and security procedures. The latter procedures can be compulsory and thus naturally imply ITT.

Consequently, ITT forms a complex transportation network, which can represent a major source of errors and delays if not handled efficiently. As a consequence, the main objective of an efficient ITT system is to minimize transport delays and reduce, or ideally eliminate, delayed transports (Duinkerken et al. 2006; Tierney et al. 2014).

Other objectives can be a minimization of transport time and costs, minimization of handling times, high occupancy rates, minimization of empty trips, and the reduction or even avoidance of obstructive traffic congestion influencing both the productivity and efficiency of ITT operations. Ecological objectives could further aim at reducing the emissions produced through ITT. The use of port resources plays an essential role in those processes and needs to be optimized leading to decision problems on the strategic, tactical, and operational levels. Without appropriate decision and communication support, it is difficult, or even impossible, to achieve those objectives supporting sustainable growth and the competitiveness of ports.

Consequently, the design of efficient ITT operations represents a considerable challenge and will also be a challenging task for many large seaports in the future. ITT involves not only operational problems and related decisions, but also critical tactical and strategic decisions (Heilig and Voß 2014a; Tierney et al. 2014). To efficiently establish an ITT system, several factors must be taken into account including an appropriate choice of vehicle types and fleet size, transportation links, container priorities, locations of terminals, and service areas as well as the communication and collaboration among involved actors. Regarding the transport links, the port may opt to have a dedicated infrastructure for ITT, for instance by building non-public roads in order to be able to use more efficient and/or autonomous terminal equipment, such as multi-trailer systems (MTS) and automated guided vehicles (AGV), respectively. Furthermore, a multimodal transport may be necessary, for instance, involving barges and trucks. ITT might also involve the transport of different types of cargo with diverse requirements. Moreover, the deployment model needs to be specified to clarify whether transport operations shall be carried out natively by involved terminal operators, by specialized third-party ITT operators benefiting from order-bundling and resource pooling, or even as a mixed form, taking into account the autonomy of terminal operators as well as the competition between terminals within a port. Ports further have to find ways to efficiently handle frequently occurring peak demands, for instance, by occasionally leasing additional vehicles or through predictive peak leveling techniques. The latter refers to methods that aim at balancing under- and overutilization phases by predicting future workloads.

The coordination of inter- and intra-terminal operations represents another great challenge, requiring efficient collaborative planning techniques and means to communicate in real-time. The availability and quality of information, such as on ITT demand, container locations, destinations, time windows, available modes, and available connections (Tierney et al. 2014; Heilig and Voß 2014a; De Vries 2013), is essential to organize ITT operations. Often, this information is not available beforehand or owners only share the information at the last moment (De Vries 2013).

It might also be possible to avoid ITT between container terminals to some extent through means of collaboration between shippers (e.g., of an alliance) in the port of origin, for example by assigning containers to a foreign vessel with the right terminal or through a more flexible berth planning where competing terminals cooperate to reduce expensive ITT in order to compete with other ports. In general, this requires policies, advanced information and communication technologies (ICT) as well as interoperable information systems to better support information sharing and decision making.

To address current and future challenges in this area, innovative approaches, optimization models, and simulation models as well as other scientific means are required for evaluating different ITT configurations and for providing decision support. In this regard, interdisciplinary research combining the strength of different disciplines is important to provide more integrated solutions. Although a greater extent of research has been devoted to this area in the last two decades, a lot of issues and potentials for improvement still need to be investigated. In this paper, we explain the spectrum of issues related to ITT operations and present an annotated bibliography. This includes insights on the approach, scope, methods, and contributions of works. The aim of this work is not only to stimulate research in this area, but also to emphasize important aspects for decision makers who face a growing demand of ITT.

This leads us to three main research questions: (1) what are the main factors contributing to ITT in seaports and the concomitant problems, (2) how has recent research tackled those problems, and (3) what research gaps can be identified and how could they be addressed in the future? To the best of our knowledge, this paper comprises the first comprehensive overview on ITT-related research, extending widely recognized literature reviews on container terminal operations (see, e.g., Steenken et al. 2004; Vis and De Koster 2003; Günther and Kim 2006).

The remainder of this paper is organized as follows. First, an overview on related research is provided in Sect. 2. In Sect. 3, we describe and analyze works in the area of ITT. A table at the end of the section summarizes approaches, methods, and contributions using the introduced notation. Given the identified research gaps, we propose a research agenda in Sect. 4. Finally, some conclusions are given in Sect. 5.

## 2 Related research

Before presenting a comprehensive review of works specifically focusing on ITT, we strive to embed the topic into related research areas. Firstly, the area of ITT-based research is related to container terminals themselves. A detailed overview and categorization of container terminal operations as well as a comprehensive literature review on associated operations research models and applications is presented in Steenken et al. (2004). Moreover, ITT is adjacent to more specific topics of interest such as related to technical equipment, transport vehicles, port congestion, satellite terminals, transportation systems and hinterland accessibility. An overview on container terminal operations and terminal planning is given in Böse (2011). Further, intermodal freight planning between deep-sea terminals and hinterland terminals has been considered in recent studies (see, e.g., Li et al. 2015a). This also includes collaborative planning approaches, such as for coordinating the use of existing transport infrastructure by different container terminals to efficiently connect those terminals to the hinterland (Nabais et al. 2013). However, the connection between container terminals and ITT transport is not made explicit in those studies and surveys.

On a different scale we see several works focusing on the evaluation, design, and control of transport modalities and handling equipment. Vis and Harika (2004) and Yang et al. (2004) compare common vehicle types of automated container terminals. Surveys of research in the design and control of automated guided vehicles as well as strategies for an efficient use of AGVs are presented in Vis et al. (2001), Le-Anh and De Koster (2006), Vis (2006), and Grunow et al. (2006). Further, the application of automated gantry cranes is discussed in several works (see, e.g., Saanen and Valkengoed 2005; Dorndorf and Schneider 2010). A survey and classification of research on loading, unloading, and premarshalling of stacks in storage areas in given in Caserta et al. (2011) and, more recently, in Lehnfeld and Knust (2014). More general classifications of handling equipment for the horizontal and vertical transport of containers are also available in the literature (see, e.g., Steenken et al. 2004; Günther and Kim 2006). As vehicle and equipment configurations have an essential impact on the ITT performance in terms of productivity, efficiency, and environmental impact, the results and implications of those studies and surveys should be taken into account.

Some works provide an overview on infrastructural aspects of seaports and expansion strategies (see, e.g., Haralambides 2002; Olivier and Slack 2006; Dekker and Verhaeghe 2008; Liu and Medda 2009). Specifically, the impact of port congestion (see, e.g., Regan and Golob 1999; Fan et al. 2012), environmental impacts (see, e.g., Bailey and Solomon 2004; Giuliano and O'Brien 2007), and other influencing factors have been investigated in order to understand and improve the efficiency of container flows within a port and related areas concentrating, e.g., on terminal appointment systems (see, e.g., Giuliano and O'Brien 2007; Namboothiri and Erera 2008; Guan and Liu 2009), truck arrival time window optimization (Chen et al. 2013), and traffic inequality analysis (Notteboom 2006b). Insights from those studies may provide a starting point for developing new concepts and strategies for establishing and handling ITT operations more efficiently.

Another concept discussed in research is the concept of dry ports (see, e.g., Roso et al. 2009). The dry port concept refers to terminals that are connected with additional intermodal terminals (i.e., dry port terminals), for instance, to solve space problems and mitigate congestion issues by shifting import and export container transports from road to more efficient transport modes. Consequently, the connection between terminals and dry ports may also require ITT. In this context, Roso (2007) evaluates the dry port concept from an environmental perspective. In Kovacs et al. (2008), factors influencing the implementation of a dry port are discussed. Combined efforts taking into account both dry ports and ITT are not existing in the current literature. Specific requirements of dry ports as well as implications from dry port studies could help to provide more universal ITT approaches.

The application of intelligent transport systems (ITS) is also discussed in this context (see, e.g., McGinley and Murray 2012; McGinley 2014). A classification of information technologies and information systems in seaports together with a comprehensive entry into related literature is given in Heilig and Voß (2014b). An overview on port community systems is provided in Posti et al. (2011). Data exchange and real-time data access (e.g., provided by an ITS) is of vital significance for the improvement of ITT operations as it not only facilitates coordination and collaboration between actors, but also increases the visibility of operations important to prevent or react to certain circumstances. In addition, innovative approaches have been discussed in the literature. Rijsenbrij et al. (2006) present an assessment of different manned and automated freight transportation systems, such as roller and belt conveyors, automated trucks, underground tube systems, and AGVs. In this context, a cooperative distributed collision avoidance controller has been proposed for waterborne AGVs in Zheng et al. (2015).

Daduna et al. (2012) analyze and evaluate various transport systems for linking container terminals and dedicated satellite terminals including shuttle trains, guided transport vehicles on dedicated roads, heavy-load ropeway systems, and underground transport systems. These new transport technologies and systems need to be evaluated in terms of feasibility and benefits for ITT.

## 3 Annotated bibliography

After providing links to related topics, we analyze academic works in the area of ITT research in order to comprehensively reflect the research progress and recent state of the art. To provide a complete review covering all relevant literature, we used a comprehensive backward and forward search regarding the large number of publications on ITT known to us, appended by a structured literature review approach as described in Webster and Watson (2002). In the following subsections, we provide a concise summary and an assessment of simulation studies (Sect. 3.1), optimization approaches (Sect. 3.2), and information system approaches (Sect. 3.3). In Sect. 3.4, additional case studies and concepts are surveyed. Used abbreviations are summarized in Table 1. A chronological overview of all approaches, used methods, and contributions is presented in Table 2. The overview further contains the considered transport vehicles and infrastructure elements as well as the application area.

**Table 1** Abbreviations for entities, solution methods, and contributions

| | | | |
|---|---|---|---|
| A | Algorithm | PoLB | Port of Long Beach |
| AGV | Automated guided vehicle | PoR | Port of Rotterdam |
| ALV | Automated lifting vehicle | PoS | Port of Singapore |
| AT | Automated truck | PoT | Port of Tianjin |
| B | Barge | PT | Patented technology |
| BAP | Berth allocation problem | QC | Quay crane |
| BT | Barge terminal | QT | Queuing theory |
| C | Conceptual | RE | Requirements engineering |
| CA | Cost assessment | RT | Rail terminal |
| CS | Case study | RW | Rail wagon |
| GA | Genetic algorithm | S | Simulation |
| H | Heuristic | SA | Systems architecture |
| IP | Integer programming | SCT | Sailing container terminal |
| IV | Inland vessel | SM | Simulation model |
| LP | Linear programming | SOA | Service-oriented architecture |
| LSC | Logistics service centre | SOQN | Semi-open queuing network |
| M | Method | SP | Stochastic programming |
| MILP | Mixed-integer linear programming | T | Truck |
| MTS | Multi-trailer system | TEU | Twenty-foot equivalent unit |
| MV | Maasvlakte | TL | Terminal layout |
| PA | Performance assessment | TN | Transport network |
| PN | Petri net | TS | Tabu search |
| PoA | Port of Antwerp | TYAP | Terminal and yard allocation problem |
| PoH | Port of Hamburg | | |

**Table 2** Overview of approaches, methods, and contributions in the area of ITT

| References | Approach | Vehicle | Infra. | Location | Method | Contrib. |
|---|---|---|---|---|---|---|
| Ottjes et al. (1994) | Self propelled floating platform for ITT | SCT | - | PoR | S | C, PA |
| Kurstjens et al. (1996) | Planning method to reduce ITT trips with multi-trailer system | MTS | - | MV1, PoR | IP, H, S | A, SM |
| Duinkerken et al. (1996, 2006) | Evaluation of ITT transport vehicles and equipment | MTS, AGV, ALV | BT, RT | MV1, PoR | S | SM, PA, CA |
| Evers and Koppers (1996) | AGV traffic control modeling technique | AGV | QC, TN | PoS | QT, S | M, PA |
| Konings (1996) | Layout and position of logistics service centres in ITT networks | - | LSC | MV1, PoR | CS | C |
| Ottjes et al. (2002, 2006) | Evaluation of different container terminal configurations for ITT | AGV | TL, Quay, Stack | MV1+2, PoR | S | SM |
| Hansen (2004) | Self-driven rail wagons for ITT | RW | - | MV1, PoR | CS | C, PT |
| Evers (2006) | Vehicle sharing between container terminals to reduce empty ITT trips | - | - | - | LP | C, M |
| Zhang et al. (2006) | Automated unmanned trucks for ITT | AT | QC, TN | | PN, S | C, SM, PA |
| Hendriks et al. (2007a, b, 2012) | Multi-terminal berth allocation for reducing ITT | - | QC | PoA | MILP, CS | C, A, PA, CA |
| Lee et al. (2012) | Multi-terminal and yard allocation for reducing ITT | - | TL | PoS | IP, TS | A, PA |
| Mishra et al. (2013) | Evaluation of different ITT container flow types by considering uncertainties | MTS, AGV, ALV, B | TN | MV1+2, PoR | QT, SP, S | M, PA |
| He et al. (2013) | Vehicle sharing between terminals to handle peak demands and reduce transport costs | T | TL | PoT | IP, GA | A, SM, PA, CA |
| Tierney et al. (2014) | Optimization of vehicle configurations to minimize ITT delays | MTS, AGV, ALV, B | TN, Traffic | MV1+2, PoR; PoH | IP | M, PA |
| Nieuwkoop et al. (2014) | Extension of Tierney et al. (2014) to consider vehicle and penalty costs | MTS, AGV, ALV, B | TN, Traffic | MV1+2, PoR | IP, CS | M, PA |
| Heilig and Voß (2014a) | Development of a cloud-based information platform to manage resources in real-time | Generic | Generic | - | RE | C, SA |

**Table 2** continued

| References | Approach | Vehicle | Infra. | Location | Method | Contrib. |
|---|---|---|---|---|---|---|
| Schroër et al. (2014) | Evaluation of ITT vehicle configurations using different infrastructure and equipment settings | MTS, AGV, ALV, B, T | TN | MV1+2, PoR | QT, S | SM, PA |
| Li et al. (2015b) | Collaborative planning for coordinating ITT flows of different inland vessels using coordination rules | IV | - | - | MILP, S | M, PA |

### 3.1 Simulation approaches

Ottjes et al. (1994) investigate implications of an SCT used to transship small contingents of containers between container terminals in the PoR. The approach intends to operate a self propelled floating platform that collects, stores, and delivers containers between container terminals and vessels on a daily roundtrip as an alternative for barges and truck transports over roads, which is increasingly affected by port-related traffic congestion. The authors propose a generic SM and demonstrate the feasibility of an SCT service by evaluating the performance in terms of average ship turnaround time and container throughput. The component classes of the SM refer to important information that must be available to efficiently handle ITT operations such as related to the ITT consignment (e.g., number of containers, arrival time, due time of delivery, destination) and ITT streams between container terminals (e.g., interarrival time, destination distributions). In this regard, the SM uses synthetic data produced by a separate generator model. As input parameters and assumptions are not presented, it is difficult to reproduce the experiments. To fully evaluate this innovative ITT approach, however, the technical and economical feasibility must be assessed.

Duinkerken et al. (1996) present the first extensive ITT simulation study to investigate the performance of transport vehicles (AGV, ALV, MTS). The proposed SM considers an ITT transport network connecting container terminals with different facilities of the PoR MV area including barge terminals, rail terminals, empty depots, and the MV Distripark. Barge and rail terminals are not equipped with a container stack; thus, the containers are loaded directly onto the barge and trains, respectively. For the latter, timetables of the railway operator are used to determine time windows for loading and unloading activities. The SM further considers demand fluctuations and different ITT flows. However, road capacities and effects of traffic congestion are not considered. The results of conducted experiments indicate that the performance of MTS is considerably lower than that of AGVs and ALVs. This is attributed to the lower handling rate of cranes for MTS due to the batch-type processing and related travelling distances of cranes, which is not compensated by the higher carrying capacity of MTS in the model. Further, the authors conclude that robotized ITT (AGVs and ALVs) achieves an acceptable degree of non-performance, which is expressed by the number of delayed ITT containers, at lowest costs. The number of required ALVs is less than half the number of AGVs as ALVs can load and unload containers independently thus providing higher utilization rates. In this regard, the implications of robotized ITT, such as the need for dedicated roads, needs to be carefully assessed. Specifically, the individual infrastructure and environment of ports play an important role in assessing the performance of ITT systems and may also lead to different decisions regarding the modal split. In some ports, the concept of robotized ITT over dedicated roads may not be feasible, especially in ports where the distance between different port areas and terminals is high. Moreover, the study demonstrates the effects of peak demands on vehicle and handling equipment occupation, which shows that more research on peak demand leveling techniques and concepts to better share and utilize port resources become increasingly important. Note that the outcomes of this study are further presented in Ottjes et al. (1996) and Duinkerken et al. (2006).

Ottjes et al. (2006) present a generic SM and simulation results concerning existing and future terminals in the PoR MV and its structural expansion referred to as MV2. The work complements a preliminary study presented in Ottjes et al. (2002). The simulation study focusses on an ITT system which is built upon AGVs. Generally, the simulation study complements existing studies by exploring different types of terminal infrastructure endowment: a compact configuration where terminals are equipped with all facilities to handle ITT and hinterland transports, a dedicated configuration separating terminals from dedicated facilities (e.g., empty depots, logistics service areas) and dedicated terminals (truck, barge, rail) for handling hinterland transportation that are connected with each other through ITT, and a combined configuration where both compact terminals and dedicated terminals are included. Moreover, the proposed SM considers different dwell times of containers, customs regulations, and supply-chain related influences. Moreover, various ship types with different call sizes, required/allowed cranes, stacks, and crane handling rates are taken into account. A separate generator model is used to provide input data on arrival patterns of deep-sea ships, modal split statistics, and dwell time distributions. Thus, the SM is more detailed compared to the previous approaches and thus provides more realistic results. Comparing the compact and the dedicated configuration, the simulation results show that the dedicated configuration requires three times as many AGVs. In contrast, the stack capacities do not differ significantly. In both configurations, the quay length does not represent a bottleneck. The simulations further indicate that extra security-related transports (e.g., container scans) have a considerable share within ITT. This also reflects the growing importance of ITT in ports. The study further provides novel insights into ITT traffic patterns demonstrating the impact of peak demands. To fully assess the different infrastructure configurations, however, the SM needs to be extended by other transport links and transport modalities. The transport capacity of AGVs may lead to a low productivity and high emissions per container compared to intermodal transports with rail or barges, especially if the distance between terminals and facilities is high. In the latter case, the operators may aim to reduce the number of transports without reducing the number of transported containers. An example could be the Port of Shanghai, where containers need to be transported between terminal and facilities of different port zones (e.g., between the Yangshan deep water port area and the Waigaoqiao port area that is around 90 km linear distance). In this context, the configuration of intermodal transportation aligned with certain multi-terminal configurations could be studied aiming at assessing the ITT modal split for certain terminal configurations and traffic conditions.

Schroër et al. (2014) presents an SM to evaluate the performance of different vehicle configurations and infrastructure endowment types with different transport demand, terminal capacity scenarios, and traffic volumes at the PoR MV1+2 for the year 2030. The transport demand scenarios for the ITT system are used from Gerritse (2014). For generating the ITT streams between container terminals including destination distributions, the SM incorporates traffic modeling. Thus, it is the first SM that considers the effects of traffic on ITT. Moreover, stochastic impacts are modeled by using an exponential distribution for the interarrival times of the arrivals of ships, trains, and trucks as well as for loading/unloading and handling times for containers. The SM predefines vehicle configurations for different demand scenarios by using the optimization approach and road network configuration proposed in Nieuwkoop et al. (2014) (see Sect. 3.4). A queuing approach is used to model traffic at intersections implementing a first-come-first-serve strategy combined with a priority algorithm, as also suggested in Evers and Koppers (1996) (see Sect. 3.4). The simulation results indicate that ALVs have the lowest non-performance and lowest delay for each of the three demand scenarios as they are not fully dependent on stacking cranes. Further, it is shown that the performance of vehicles with a large capacity is often low because of longer waiting times to be fully loaded or due to underutilization or speed limitations. Dedicated terminals or combined terminal configurations, as proposed in Ottjes et al. (2006), may help to enhance the performance of vehicles with higher capacities as well as the combination of demands, as proposed by Evers (2006), to reduce empty trips. Furthermore, priority-based mechanisms are not only important at intersections, but also for selecting the transport mode and starting time. Containers with a low priority (e.g., due to a sufficient time buffer) could be aggregated in barge or rail areas in order to better utilize those large-scale resources and thus reduce transport costs and emissions per container. This requires not only a certain degree of coordination between competing terminals, but also integrated scheduling and vehicle routing algorithms for decision support.

## 3.2 Optimization approaches

Kurstjens et al. (1996) propose an IP formulation and an algorithm for minimizing the number of (empty) ITT movements with MTS. Empty movements occur when a vehicle first needs to drive from one area to another area in the port to load and transport containers. This might also happen if the vehicle is forced to go back to a certain service station (i.e., depot). Attempts to reduce the number of empty and non-empty trips, such as by fully utilizing vehicles, are essential for reducing costs and emissions. As the computational time for solving the formulation is considerably large, the authors present a heuristic and apply it in the SM proposed in Duinkerken et al. (1996) (see Sect. 3.1). The heuristic describes a planning process that comprises simple decision rules to assign load to MTS, balance the number of MTS among terminals, and to increase the utilization of MTS. The simulation results indicate that the algorithm reduces the number of empty trips and increases the occupancy of MTS. In general, the approach requires either collaboration and vehicle sharing among competing terminals or a dedicated third-party service that coordinates ITT demands of the different terminals and service areas. As related empty flow and vehicle routing problems have been considered for several decades (see, e.g., Dejax and Crainic 1987; Golden et al. 2008), however, it is important to further assess the application of existing approaches for solving ITT-related planning problems.

Evers (2006) points to the importance of real-time information for supporting an optimal coordination of ITT vehicle deployments enabling mutual peak demand leveling and empty trip reductions. Taking into account the autonomy of terminal operators, the author proposes to establish a third-party ITT service. In this regard, the study extends the concept of Kurstjens et al. (1996) by exploring the coordination between different terminals and service areas by a third-party. The third-party ITT operator maintains a fleet of vehicles that can be used by terminal operators for requesting ITT or intra-terminal transports on an ad-hoc basis. By achieving economies of scale, the main objective of ITT operators is to reduce empty trips and to satisfy the varying demand for ITT. To make the service valuable, operational costs for terminal operators must be minimized by bundling requests and allocating vehicle capacity efficiently. The author outlines an LP model for deriving a feasible minimal cost vehicle deployment plan. The multi-period model considers vehicle conservation conditions, capacity constraints of equipment, parking places, and roads as well as lower and upper bounds on the vehicle demand. The simulation results show that the fraction of unproductive vehicles can be reduced by applying the proposed optimization method. Simulations on more realistic applications, however, are needed to fully evaluate the performance of the proposed methods. For further research, the author suggests to develop software for supporting the interaction between terminal managers and the ITT operator as well as the development of business models including methods to determine ITT tariffs such as based on the available vehicle capacity.

Hendriks et al. (2007a) extend the single-terminal BAP to incorporate a cluster of interrelated container terminals in order to reduce costs for ITT flows by adopting the terminal allocation of cyclically approaching vessels in a discrete time setting. The objectives are to minimize ITT and to balance the QC workload over the terminals and over time. Thus, it can be considered as the first approach aiming at reducing ITT. To investigate the benefits of terminal allocation modification, the authors formulate the static multi-terminal BAP as a two-step optimization problem. In the first step, the MILP formulation of the cyclic multi-terminal BAP proposed in Hendriks et al. (2007b) is adapted by allowing bounded flexibility in arrival and departure times by constructing Pareto frontiers of the number of required cranes versus the ITT costs in order to trade-off the conflicting objectives. This allows to allocate a terminal, a berthing interval, and a variable quay crane capacity to each vessel on an 8-h time slot guaranteeing that the quay crane capacity and quay length of the terminal are not exceeded. In the second step, the allocation is refined to a 1-h time slot based on a similar MILP formulation presented in the paper. Two experiments are conducted to test the hypotheses. In the first experiment, a given terminal allocation is modified by allowing a bounded time flexibility and different terminal allocations for a couple of vessels by considering the number of required quay cranes versus the ITT costs for varying arrival times based on the Pareto frontiers. In the second experiment, terminal allocation modifications are possible for all vessels given a fixed time allocation. Both experiments suggest that already a small modification of allocations may lead to significant ITT cost reductions. The work is extended in Hendriks et al. (2012) where the authors demonstrate possible cost savings in a case study with three interacting terminals of PSA Antwerp in the PoA. The results show that the occupation of QCs is subject to huge fluctuations leading to a considerable number of ITT between terminals. By applying the proposed optimization method, the authors demonstrate that the number of required QCs and ITT can be reduced significantly. However, the approach assumes a high degree of planning flexibility both on the side of terminal operators and the shipping lines. In addition, the willingness to cooperate and share information must exist to apply the method for reducing ITT between competing terminals.

Lee et al. (2012) propose an IP model for the TYAP in a large port with multiple terminals. The model integrates decisions on terminal allocation for vessels as well as yard allocation for container movements within a terminal and between terminals. The objective is to minimize intra- and inter-terminal handling costs by first finding a good terminal allocation plan and then minimizing the reallocation of containers between yards within a terminal and between terminals. Consequently, the model represents another approach to reduce ITT. A 2-level heuristic algorithm is developed to solve the problem efficiently. In a first step, a neighborhood search is conducted in the neighborhood of a randomly generated initial terminal allocation plan. That is, neighborhood solutions are generated in each searching loop by employing pair-wise interchange (random interchange of the terminal allocation of two vessels) and flipping patterns (random change of the terminal allocation of one vessel). As the remaining yard allocation problem needs to be solved to obtain the total handling costs and evaluate the fitness of neighborhood solutions, the authors apply an LP relaxation by relaxing the integer constraints of the yard allocation decision variables. To evaluate the fitness of those neighborhood solutions in terms of handling costs, the remaining yard allocation problem is approximately solved by relaxing the integer constraints of the yard allocation decision variables. Given a terminal allocation plan, the remaining problem is to determine the container flows and find a good loading sequence in terms of handling costs. The authors propose a TS-based greedy heuristic to find a good solution for the reallocations and respective handling costs. In general, the 2-level heuristic provides high quality solutions within a short computational time (average gap between the heuristic-based solutions and optimal solutions is less than 5 %). Compared to a simple planning method, the proposed algorithm implies a significant improvement of handling costs (about 20 %), in particular for larger problem instances. The main difference to the works of Hendriks et al. (2007a) is the consideration of storage yard allocation for transshipment flows. Especially for terminals with limited storage yards this is an important aspect to be considered allowing the compensation of storage space constraints. Both the work of Hendriks et al. (2007a) and the work of Lee et al. (2012) demonstrate the effects of limited capacity of handling equipment and infrastructure, respectively. Taking into account the balancing objective, another research problem could be the balancing of containers among empty container depots or repair stations by considering both the transport cost from a terminal to an empty depot and vice versa to another terminal or service station (e.g., for packing).

Mishra et al. (2013) propose a stochastic model for mainly analyzing the ITT container throughput time and vehicle utilization for different types of ITT vehicles. The problem is modeled using a SOQN where the vehicles can have different container carrying capacities. Moreover, the authors consider exponential travel times between terminals and exponential handling times for loading and unloading activities within the terminal. The ITT demand is modeled for each origin-destination pair using a Poisson process with a fixed rate. Based on these foundations, the authors develop an SM using a path mover system. Experiments are conducted for single stream uni-directional container flows (simple transfer from terminal A to terminal B) and multiple streams of container flows considering uni-directional and bi-directional flows as well as balanced and unbalanced ITT demand rates. The results indicate that the vehicle utilization does not significantly change with varying vehicle carrying capacities. With data from PoR MV1+2, the authors further demonstrate the effects of different depot locations. The reduction of empty trips as discussed in Evers and Koppers (1996), however, has not been addressed in this study; vehicles are forced to return empty to a central depot after transporting a container from one terminal to another. Other than that, the authors propose the first stochastic model for modeling ITT and thus allow to consider events that are unpredictable or difficult to predict such as with respect to the traffic situation or equipment breakdowns in ports. Moreover, the approach supports fleet management decisions of third-party ITT operators and may help to determine the location of such service. In a way it thus complements the approach of Evers and Koppers (1996).

He et al. (2013) investigate the sharing of internal trucks among adjacent container terminals in order to reduce vehicle bottlenecks between QCs and storage yard areas. To address the problem, the authors propose an IP model that aims to minimize overflowed workloads and total transferring costs in every time-period by employing a rolling-horizon approach for considering the immediate scheduling. Although the approach focuses on intra-terminal container transports and thus is not directly related to ITT, the concept of sharing vehicles can be easily applied to ITT. In fact, the objectives are similar to the ones regarded in Evers (2006). The main difference is that vehicles are provided in a decentralized way and that transport demands of different terminals are not bundled. To coordinate activities of different terminals, however, a mechanism to match demand and supply of different terminal operators is needed. Regarding the sharing of vehicles, an integrated problem formulation considering both intra- and inter-terminal activities may lead to further enhancements regarding the utilization of vehicles leading to cost savings and emission reductions.

Tierney et al. (2014) present an IP model for analyzing the impact of new infrastructure, the placement of terminals, and ITT vehicle investments for new and expanding ports. The proposed model considers several real-world ITT aspects, such as traffic congestion, penalized late container delivery, different ITT vehicles, and port infrastructure modifications. A time-space graph is used to model traffic congestion, loading and unloading of vehicles as well as different types of infrastructure. The time-space graph consists of terminal nodes, intersection nodes and long-term nodes. The latter reflect the long term loading/unloading of containers, for instance, in case that barges are involved. Stationary arcs connect each terminal, intersection and long-term nodes in subsequent periods to allow vehicles and containers to remain in one place across time periods. Effects of traffic congestion are considered by providing each arc in the time-space graph with a maximum number of vehicles that can travel on them in a single time period. Likewise, a capacity for each node is modeled. ITT demands are represented by their origin node, destination node, amount of containers, release period, due period of demand, and a penalty function. Using the time-space graph, the IP model aims at reducing the lateness of container delivery by minimizing associated penality costs. To evaluate the proposed model, datasets of the PoR MV 1+2 and the PoH in combination with vehicle properties defined in Duinkerken et al. (2006) are used. Different sets of demands, a varying number of road vehicles, barges or no barges, and different traffic patterns including uniform traffic and rush hour traffic were generated to explore effects of the ITT system. An LP relaxation is applied where the model is unable to find optimal solutions in time limits deemed practical. In general, the results indicate that the lowest penalty can be achieved by using MTS for ITT. This is contradictory to results given in Duinkerken et al. (2006) where the impact of port and non-port traffic is not considered. The main drawback of AGVs and ALVs is their low carrying capacity. The independent and faster loading/unloading capabilities of ALVs do not compensate this. Further, traffic congestion, mainly at the intersections, leads to significant performance losses. For the MV area, the authors introduce dedicated fast-connectors that connect terminals directly to key intersections. Although more cargo can be delivered on time using fast-connectors, the fast lanes intensify the congestion at those intersections thus only showing little improvement given that a high number of containers needs to be transported. Results from the instances with rush hour traffic patterns show a marked increase in penalty for AGVs and ALVs compared with uniform traffic patterns. This does not hold for MTS which therefore seems a reliable option, in particular in port areas where port and non-port traffic are mixed. In general, the authors propose the first model that explicitly considers the limitations of road infrastructure and different transport modalities. In this regard, it provides a technique to evaluate specific ITT settings and scenarios in various environments in detail.

Nieuwkoop et al. (2014) extend the IP model proposed in Tierney et al. (2014) in order to consider costs for extra vehicles and costs of delay penalties when determining an optimal ITT vehicle configuration. Moreover, the proposed model provides several advancements to further reduce the computational time. The computational experiments investigate ITT vehicle configurations for the PoR

MV1+2 and consider three different scenarios regarding the layout and development stage of the port. The results show that MTS are the most reliable option in all three scenarios in terms of punctuality, which is consistent with results given in Tierney et al. (2014). Moreover, the study explores the required number of vehicles when using future ALVs and AGVs with higher speeds and demonstrates that the required number of vehicles can be significantly decreased thus reducing investment costs and preventing congestion problems. The model can also be used to determine the maximum ITT capacity, which is an important indicator for the overall performance of the port and thus important for strategic decisions. Further observations regarding the potential trade-off between added costs for added vehicles and costs of delays would be interesting, but are not included in the paper. Consequently, the model extensions are useful to better support strategic and operational decisions in the context of ITT. In both the work of Tierney et al. (2014) and Nieuwkoop et al. (2014), however, the aspect of greenhouse gas emissions produced by certain vehicle configurations or congestion issues is not considered. The models provide a good starting point to further investigate the environmental impact of certain ITT settings in order to find a sustainable ITT solution for individual ports.

Li et al. (2015b) recently focus on ITT seaside operations with inland vessels. The authors propose a two phase approach integrating MILP with coordination rules in order to generate rotation plans for enhancing the cooperation and coordination of inland vessel operators. After optimizing the transport plans for single vessels, a collaborative planning is conducted to solve existing conflicts in terms of terminal berth occupation in order to reduce waiting times. The authors propose a preference-based coordination rule and a utility-based coordination rule. While the former rule updates the ranking of a vessel's transport order in the rotation plan if an overlapping would lead to a higher total transport time, the latter uses a utility function instead. Experimental results indicate that the efficiency of ITT can be improved by having advanced means for coordinating the arrival and departure times of inland vessels. In this regard, the authors demonstrate that the utility-based coordination outperforms the preference-based coordination in terms of departure time of the last vessel, total time of transports, and total waiting times.

### 3.3 Information system approaches

Zhang et al. (2006) propose an ITT system that employs fully automated and unmanned trucks for the transport of containers on dedicated roads. A supervisory controller aims to efficiently synchronize automated trucks and automated cranes based on real-time information and road characteristics. The automated trucks are equipped with communication devices, differential global positioning systems (DGPS) and on-board sensors. The automated trucks travel between terminals in platoon formations consisting of five trucks at relatively high speeds. After a truck is released from a platoon, it follows the assigned traffic lane and collects/delivers the container from/to the assigned crane. The transport system is modelled and analyzed using PNs. The study demonstrates the feasibility of the proposed system based on simulations considering the road characteristics between the Pier G Mega-Terminal and the Union Pacific's ICTF (intermodal container transfer facility) at the PoLB. Although the approach is very interesting regarding current developments, further investigation of economic and technological aspects with respect to cost, reliability, performance, eco-friendliness, and safety is required. Furthermore, it should be noted that space limitations are considered as a major problem in many ports thus making it difficult to establish dedicated roads for trucks. Another problem could be the long distances between terminals in some ports leading to high investment costs for road construction. However, the coordination of ITT subprocesses as well as the reliability of ITT might be increased if all required transport information are available. Similar to Duinkerken et al. (1996), the implications of robotized ITT and dedicated roads need to be further assessed in order to proof application potentials.

Heilig and Voß (2014a) focus on real-time data exchange and data-driven ITT decision support. The authors propose a service-oriented architecture (SOA) to integrate, process, and disseminate operational data based on an integration of identification, sensing, and mobile technologies. The approach utilizes the potentials of cloud computing as a basis for providing a scalable and cost-effective information platform that can be used by involved companies to share and gain information and decision support. The proposed SOA further allows to collect and process data of external systems (e.g., port community system, traffic control system) as well as to develop web applications based on extracted information in order to support certain activities in port operations. By supporting real-time data exchange and decision support, the proposed system improves planning, collaboration, information sharing, and the coordination of intra- and inter-terminal activities. In this way, the proposed information system can, for example, be used by third-party ITT operators enabling the communication with terminal operators, such as for pre-registrations or supply and demand matching as required in Konings (1996) and Evers (2006). The approach considers the actual situation within a port reflected by the current traffic situations, occurring unforeseeable events (e.g., traffic accidents, breakdowns of vehicles), and the current location of vehicles used to efficiently coordinate multiple demands of different terminals in real-time. Decision support can be realized by adopting respective models, such as proposed for avoiding ITT (e.g., Lee et al. 2012) and managing ITT (e.g., Tierney et al. 2014). To enable scalable parallel computations and integrate real-time data, those models need to be extended. Moreover, the proposed system could be used to enhance ITT demand forecasts based on historic data in order to better handle peak demands as proposed in Evers and Koppers (1996). In order to fully evaluate the proposed information system, a cloud-based prototype needs to be developed and applied for an ITT case study.

## 3.4 Other concepts and case studies

Evers and Koppers (1996) present a technique for modeling traffic control of intra- and inter-terminal AGV traffic by applying the concept of semaphores. The technique allows to model terminal nodes, transport links, and intersections. Semaphores represent those common resources by assigning a capacity and controlling the access by multiple vehicles, and together build a queuing network.

Therefore, the technique can be used to evaluate different traffic control strategies with respect to their impact on the occupancy of important port areas and road fragments. The authors suggest to use information on container priorities (e.g., earliest due time) in combination with a first-in-first-out strategy. The authors demonstrate the application of the technique for evaluating the transport network performance of different port areas using AGVs (e.g., defined by acceleration, speed, curve radius) and QCs (defined by handling time, crane productivity). To solve congestion problems in port areas, however, it is important to develop and evaluate advanced scheduling mechanisms taking into account traffic variations and the position of vehicles in the network. This may include information or predictions on traffic for the subsequent road segments. Consequently, real-time information on vehicle, equipment, and infrastructure aspects needs to be collected to handle the dynamics of traffic in a port area.

Konings (1996) emphasizes that advantages of rail and barge transport are frequently cancelled out by costs for handling and transport at the origin and destination of containers. Further, larger barge and rail transport volumes would increase the demand for more productive handling technologies and highly affect traffic within container terminals. In particular for the extension of the PoR MV, the author emphasizes that conventional transport modes and information technologies will be unable to handle the growing ITT streams of containers. Transport by trucks only would lead to severe congestion problems in and between container terminals and other related facilities. The author proposes the introduction of an internal transport system operated and maintained by a so-called integrated centre for the transshipment, storage, collection and distribution of goods. The proposed concept mainly intends to build more productive and efficient links between businesses sharing a site in the port (in a Distripark) and container terminals in order to gain qualitative improvements and transport time savings due to the physical proximity of businesses thus enhancing intermodal supply chain performance. In this respect, various factors need to be considered for selecting appropriate transport vehicles including investment and on-going costs, possible transport cost savings, performance and quality criteria (e.g., manoeuvrability, speed, flexibility/expandability), safety considerations as well as environmental conditions such as available space. The author analyses some advantages and disadvantages for AGVs, MTS, and 4TEU trucks, which are trucks with a capacity of four TEU. Other advanced transport systems such as monorail systems, chain-driven systems, and rolling roads are mentioned as alternatives. The author further indicates that advanced information systems such as for pre-registration and information exchange are required to further enhance ITT traffic flows and to reduce empty trips. Finally, they suggest that peak load-dependent congestion could be reduced by delivering containers at night. The scheduling of ITT needs to be further investigated in order to consider daily and weekly traffic patterns.

Hansen (2004) presents an innovative ITT system invention with track-guided self-driven container wagons that transport containers between container yards and shared rail marshalling yards where the container wagons are uncoupled or coupled for ITT or rail-driven hinterland transport, respectively. The EU-patented container wagon (Hansen 1999) is driven by a long-stator linear motor incorporated as a stator winding in a dedicated ITT track bed between container and rail terminal thus replacing locomotive-driven container trains by self-driven wagons. Such systems have been applied in public transport systems (see, e.g., Skytrain and Transrapid systems). The self-driven wagons can be coupled to conventional locomotive-hauled freight trains so that handling activities for loading are not necessary, and vice versa. Although the investment costs for establishing long-stator traffic lanes are higher in comparison with other systems, the advantage of a long-stator system is that the wagons only need to be equipped with a reaction rail under the bogie which limits the financial and technical effort for the conversion or construction of wagons. To further reduce horizontal moves, the author proposes to build (turnout/crossover) tracks directly behind the stack or even under quay cranes to some extent. For the PoR MV, the study explores the use of self-driven container wagons by comparing process times of conventional systems and estimate a lead-time reduction of about 30 % achieved by reduced efforts for shunting, loading and unloading of container wagons. Finally, higher productivity and lower operating costs in comparison with conventional systems, often operated by expensive personnel, may outweigh high investment costs. The evaluation of innovative ITT systems becomes increasingly important due to the growing container volumes und traffic issues. However, the comparison of different ITT system options need to be made in the context of the individual port in order to consider specific conditions.

### 3.5 Summary

The annotated bibliography in this section shows that most of the research works concentrate on modeling and evaluating different ITT concepts and configurations by providing optimization and simulation approaches, or both. We see that all of these approaches are heavily dependent on data inputs when it comes to the application in practice. First approaches that consider information systems in the area of ITT have been proposed. Furthermore, innovative technologies and alternative ITT systems, also with an engineering focus, have been investigated with the aim of solving future challenges. This demonstrates the need for interdisciplinary research to address ITT challenges. Furthermore, we see that a lot of studies focus on the PoR MV. Empirical studies considering different port areas would be necessary to further evaluate the proposed approaches. Also, the requirements of involved actors (e.g., port authority, terminal operators, forwarders, etc.) need to be included more explicitly.

In general, the annotated bibliography also reveals important research topics that need to be addressed to extend the current body of knowledge. We should note in passing that ITT has become a somewhat busy research topic at universities which can be reflected, for instance, by the following selection of theses on different levels: De Vries (2013), Jansen (2013), Liu (2013), Van den Berg (2013), Gerritse (2014).[1]

[1] De Vries (2013) proposes an ontology for defining ITT ecosystems and further discusses physical, functional, and non-functional requirements. Jansen (2013) investigates cost effects of collaboration compared to self transportation by proposing a SM for evaluating different ITT configurations in this respect. The author points out that a large container flow stems from the transport of empty containers to

In the following section, we point out different focus areas resulting from this overview in order to provide a research agenda. Table 2 summarizes the main findings of the annotated bibliography.

## 4 Research agenda

Given the current and future importance of ITT for seaports and the comprehensive review of the current body of ITT literature, several research gaps have been identified. This section extends the suggestions on future directions for specific works provided in the previous section by proposing a more general categorization of aforementioned research topics and some additional ideas of how to address them. By this, our aim is not to point out all research opportunities, but to stimulate interest in related disciplines in addressing important aspects that require more attention according to recent discussions in the literature. Overall, approaches in the proposed directions may lead to a more integrated decision support system that facilitates the planning, interaction, and collaboration among port community members to improve ITT operations with respect to economic and ecological aspects.

### 4.1 Transport scheduling

The annotated bibliography has shown that scheduling plays an important role in the context of ITT and has been considered in some queuing theory based studies (e.g., Evers and Koppers 1996; He et al. 2013). However, to further enhance the processing time and utilization of handling equipment and vehicles, integrative scheduling approaches are required in order to improve dispatching of multiple resources for handling ITT requests under certain constraints such as deadlines and priorities. This may further include optimization and simulation approaches to investigate and improve the coordination of intra- and inter-terminal activities.

While scheduling approaches found in the literature primarily examine subproblems, focusing on specific transport modes or handling equipment (e.g., AGV scheduling proposed in Qiu et al. 2002, crane scheduling proposed in Ng 2005), integrative approaches supporting interrelated decision problems become increasingly important for enhancing the coordination of sub-activities. In this context, Xin et al. (2014) propose a hierarchical control architecture consisting of a higher-level discrete-event scheduler determining the time and sequence of

Footnote 1 continued
and from empty container depots. Liu (2013) investigates the implications of an ITT asset-light approach by extending the IP model of Tierney et al. (2014) in order to allow adding extra vehicles at any point in time. Van den Berg (2013) proposes an asset-light solution for ITT assuming that residual capacity of visiting trucks can be flexibly used to handle ITT operations. An SM is used to determine how much extra capacity, besides the available capacity of trucks and barges, is needed to ensure that every container is delivered on time. Gerritse (2014) analyzes demand scenarios for the PoR MV1+2 in 2030 with respect to different ITT streams including import and export container streams, empty container streams, container flows from and to common logistics services and auxiliary services (e.g., customs) areas.

containers to be transported aimed at reducing the makespan integrated with lower level controllers to consider continuous-time dynamics of certain types of container handling equipment aimed at reducing the energy consumption.

ITT processes involve several sub-activities performed by different independent actors (e.g., terminal operators, drayage operators, intermodal operators, etc.), which must be efficiently coordinated to avoid delays, such as by taking into account real-time data on containers, vehicles, and equipment. This may include the optimization related to gate appointment systems (e.g., discussed in Guan and Liu 2009) and/or the introduction of ticketing systems in order to enforce schedules during operations. In general, integrated scheduling approaches in the context of ITT will help to increase customer satisfaction, while increasing the utilization of resources implying cost reductions and energy efficiency. So far, only a few studies have proposed algorithms for scheduling integrated operations (see, e.g., Chen et al. 2007; Lau and Zhao 2008; Cao et al. 2010). The results of transport scheduling approaches can provide the basis for a more effective vehicle routing.

### 4.2 Vehicle routing

Given the results from transport scheduling approaches, such as a list of appointments for a number of trucks, a cost-effective route needs to be planned to pickup and deliver containers in multiple origin and destination locations in time, respectively. Although vehicle routing plays an essential role in coordinating ITT flows, as discussed in several works, the adaption of well-known vehicle routing problems as well as related solution approaches have not been considered in recent research approaches. The lack of studies is surprising as vehicle routing in the context of ITT offers many opportunities to reduce operational costs, improve customer satisfaction, and reduce environmental impact such as by finding minimal energy paths. As seen in the annotated bibliography, different transport modalities with different characteristics are used to handle ITT in a transport network connecting various port terminals and facilities. To increase the utilization of vehicles and decrease empty trips in ITT networks, the optimization of routes combined with scheduling approaches provides important decision support for terminal operators and/or dedicated third-party ITT operators.

Assuming that we have a third-party ITT operator with one or multiple depots, the goal is to find optimal routes for a fleet of heterogeneous vehicles. Consequently, we can model the problem as a pickup and delivery problem where containers/goods need to be transported between pickup and delivery locations (i.e., terminals and facilities). Existing problem formulations include the vehicle routing problem with pickups and deliveries where pickup and delivery locations are paired, which means that each transportation request is associated with an origin and destination (Parragh et al. 2008; Steenken et al. 1993). To optimize routes in ITT networks, we have to consider further requirements such as deadlines and time windows. In addition, not all vehicles can use all paths (e.g., road, rail and sea connections) through the network, thus implying that not all routes are feasible. Intermodal transportation is also possible, or even necessary, which means that containers must be swapped between transport vehicles. Given technology advancements enabling real-time tracking and communication with vehicles, vehicle routes should further be designed in an online fashion so that vehicles can be dynamically dispatched for serving new ITT requests (arriving online during operations) as soon as they become idle (Pillac et al. 2013). This would build the basis for mobile applications used by vehicle drivers to instantly retrieve information on new jobs.

The literature contains a large amount of works to tackle variations of vehicle routing problems (for a specific survey of vehicle routing problems at container terminals the reader is referred to, e.g., Stahlbock and Voß 2008). Variants of dynamic vehicle routing problems can be applied to enable redefining vehicle routes in an ongoing fashion. Variants of stochastic vehicle routing problems can be studied when considering ITT demands, travel times, and handling times as stochastic elements. There are also several studies on stochastic and dynamic vehicle routing problems, such as with time windows and customer impatience (Pavone et al. 2009).

### 4.3 Collaborative planning and resource sharing

To face the increasing competition among ports, competing terminal operators are, at least to some extent, forced to collaborate. In particular efficient ITT operations are dependent on well-coordinated activities carried out by multiple organizations. Consequently, the vehicle routing and scheduling plans of different vehicles and equipment of one organization need to be coordinated with the plans of other organizations. This requires some degree of collaborative planning, where a bilateral information flow between organizations must be established.

The annotated bibliography shows that research related to collaborative planning in the direction of ITT is scarce, but becomes increasingly important for coordinating ITT flows (see, e.g., Li et al. 2015b; Nabais et al. 2013). Further, there is a lack of approaches considering collaborative planning of intra- and inter-terminal activities within and between ITT origins/destinations, respectively. However, we have seen approaches that consider the sharing of vehicles, which also requires collaborative planning or at least an information platform to match supply and demand. Irrespective of whether the partner of the terminal operator is a third-party ITT operator or another terminal operator, collaborative planning activities intend to achieve performance improvements in terms of transport cost, transport time, and resource utilization. In the context of ITT, collaborative planning could be further used to negotiate, bundle demand, and reduce empty trips between terminals and facilities (e.g., as shown in Evers 2006). This also includes resource sharing approaches to limit the impact of space and capital limitations. Combined with innovative information system solutions, it further builds the basis for an efficient scheduling and routing of ITT requests. Existing studies on supply chain integration and supply chain collaboration may help to direct research (see, e.g., Gunasekaran and Ngai 2004; Dudek and Stadtler 2005).

### 4.4 Information technologies

The annotated bibliography indicates that the exchange and processing of data has become essential for planning, operations, and collaboration in ITT systems. The application of innovative information technologies and information systems is required to further facilitate real-time communication, data processing, planning, and decision support. An example is the use of mobile technologies and applications for supporting truck drivers in the port area, for instance, by providing means of traffic control, information and communication services, and navigational support in order to reduce port traffic and avoid traffic congestion. A central information platform is furthermore important for the implementation of resource sharing and asset-light approaches, providing web applications for announcing demand and supply of resources as well as supporting negotiation and auctioning mechanisms. Having information on the actual position of vehicles, a central route planning module can be implemented based on ITT vehicle routing approaches in order to better coordinate pickups and deliveries and thereby reduce empty trips.

In this sense, more research on innovative application designs and associated challenges is necessary. Furthermore, the integration of port community systems and external assistance systems with specific ITT applications need to be addressed in order to enhance the coordination of actors (see, e.g., Van Baalen et al. 2009; Heilig and Voß 2014b). Regarding planning systems, the sharing and coordination of certain planning results that are needed for coordinating activities between different actors, enabling collaborative planning, should be possible. In this regard, Boer et al. (2002) present a systems architecture approach that allows the exchange of planning results between multiple terminal operators. Using the planning results of the origin terminal or facility as an input, the activities at the destination could be better planned. Related research questions could further consider standards for data sharing, application development, and means to increase information sharing in a culture of limited cooperation.

## 4.5 Green logistics

Green logistics implies that the solutions are not only ecologically sustainable, but also economically reasonable. In the area of ITT-relevant research, more effort needs to be put on environmental and ecological aspects in order to better understand its implications with regard to potential benefits and challenges. Although green logistics is a related research field, it is essential to identify and evaluate eco-friendly alternatives in the context of ITT to facilitate ecologically sustainable development in seaports such as by using alternative fuels, vehicles, and/or handling equipment.

As noted in the annotated bibliography, it is important to include those aspects into optimization and simulation approaches and thus measure the environmental impact of alternative ITT solutions. This includes vehicle routing and scheduling approaches for ITT. Proposed SMs already support the integration of alternative handling equipment and vehicles. However, the effects of congestion and empty trips as well as the effect of vehicle locations have not been studied so far. Furthermore, with the deployment of robotized electric ITT vehicles, as suggested in several ITT studies, new research questions emerge such as with respect to the battery charging. In general, means to compare modalities in terms of energy consumption and cost trade-offs would help decision makers in determining best options in the context of individual ports. Consequently, the specific environmental characteristics of ports need to be taken into account.

### 4.6 Deployment models

In the current literature, the research is more focused on ITT planning and operations than on the actual deployment of ITT services in ports. To realize proposed appraoches, however, more effort must be devoted to study different deployment models with regard to stakeholders, transport economics, and transport quality.

ITT services could be offered by one or multiple third-party logistics providers or in a mixed-mode where transports are performed by both third-party logistics providers and terminal operators. The economic, ecological, and operational implications of different modes need to be studied to facilitate the adoption of ITT services. This may also include the evaluation of different business models and pricing schemes for third-party logistics providers, as suggested in Evers (2006). Moreover, extended studies regarding empty container depots, repair stations, and Distriparks are needed to better understand their impact and requirements on ITT.

### 4.7 Application areas

As seen in the annotated bibliography, most of the existing studies are applied in the PoR MV area. For further research, it would be interesting to identify major differences and similarities among various small and large seaports in order to have a broader view on the topic and to address specific issues. This may involve empirical studies and field research for capturing the current state-of-the-art and to collect requirements and data such as demands and information on the respective transport networks. Future research could also be carried out both to replicate findings and to assess the validity of the theoretical models across differing seaports in order to evaluate the generalizability of the proposed approaches. Specific application areas to be investigated include the Pearl River Delta and the Shanghai port. Moreover, recent studies are focused on containerized cargo; thus, a discussion on the implications of other forms of cargo (e.g., bulk cargo) is important to develop universal ITT systems. Moreover, we suggest to deepen the connection with existing approaches in the context of dry ports.

## 5 Conclusion

Due to several economic and environmental aspects, ITT is becoming increasingly important in contemporary seaports and thus stimulates research to better understand related issues as well as to find appropriate solutions helping to achieve competitive advantages. In this paper, we give an overview on ITT in general and propose a classification scheme to extensively explore ITT research efforts by analyzing the approach, methodology, and contribution of respective works as well as related research topics. To the best of our knowledge, this is the first survey focusing on port operations performed between multiple terminals. Thus, it extends well-recognized surveys in the area of terminal planning and operations. Furthermore, we identify research gaps and propose a research agenda to tackle those relevant problems in the future. As such, the paper provides both an entry into available literature reflecting the current state of research and possible directions for further research in this particular area, relevant for both scholars and practitioners.

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