

## Decision support in intermodal transport: A new research agenda

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### ABSTRACT

This paper proposes new research themes concerning decision support in intermodal transport. Decision support models have been constructed for private stakeholders (e.g. network operators, drayage operators, terminal operators or intermodal operators) as well as for public actors such as policy makers and port authorities. Intermodal research topics include policy support, terminal network design, intermodal service network design, intermodal routing, drayage operations and ICT innovations. For each research topic, the current state of the art and gaps in existing models are identified. Current trends in intermodal decision support models include the introduction of environmental concerns, the development of dynamic models and the growth in innovative applications of Operations Research techniques. Limited data availability and problem size (network scale) and related computational considerations are issues which increase the complexity of decision support in intermodal transport.

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### 1. Introduction

Macharis and Bontekoning [1] define intermodal transport as the combination of at least two modes of transport in a single transport chain, without a change of container for the goods, with most of the route travelled by rail, inland waterway or ocean-going vessel and with the shortest possible initial and final journeys by road. This paper aims to shed light on new research themes concerning decision support in intermodal transport. By its nature, intermodal transport demonstrates an increased complexity due to the use of multiple modes of transportation and the involvement of multiple decision makers. The term intermodal transport further implies integration between different operators in the transport chain. The different transport modes should not only be optimized separately, but they should also be attuned to one another. A new transport mode arises when the transport chain is fully integrated. An increased level of coordination is necessary to organize the intermodal transport flow. Decision-making support tools may assist the actors and stakeholders involved in intermodal operations.

Previous work [1,2] provided an overview of planning problems at the strategic, tactical and operational decision level in intermodal transport. In this paper we focus on recent develop-

ments in quantitative models constructed to assist a variety of decision makers in intermodal transport. As a criterion to identify recent developments, only papers which appeared after the literature review of Caris et al. [2] are considered. For earlier work the reader is referred to this literature review. For example literature on terminal design is discussed in Caris et al. [2], but no new developments are found on this topic. For each research topic discussed in the following sections, earlier work is cited but not discussed in detail to provide some background. A computerized search strategy was performed, starting with a search in a multiple research databases. Next, electronic journals concerning transportation were searched separately. In addition, we included research we already knew about from informal contacts with other researchers, as well as our own research. Finally, studies were retrieved by tracking the research cited in literature obtained earlier (ancestry approach).

Decision support models have been constructed for private stakeholders (e.g. network operators, drayage operators, terminal operators or intermodal operators) as well as for public actors such as policy makers and port authorities. An insight will be given into the underlying methodology and objective of each decision support model. In particular, opportunities for applying these decision support models and their practical relevance will be pointed out.

The following sections describe a research agenda of topics for which intermodal decision support models have recently been developed. For each research topic, the current state of the art and gaps in existing models will be identified. Section 2 discusses models for supporting decisions made by public policy makers.

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**Table 1**

Overview of recent developments and related models.

Research topic	Relevant references
Policy support	Crainic et al. [8], Loureiro [9], Jourquin et al. [10], Southworth and Peterson [11], Tan et al. [12], Macharis [14], Floden [19], Tsamboulas et al. [20], Zhang et al. [21], Macharis and Pekin [13], Yamada et al. [22], Macharis et al. [15], Macharis et al. [16], Caris et al. [17], Iannone [23], Pekin et al. [18], Maia and Couto [24]
Terminal network design	Rahimi et al. [25], Limbourg and Jourquin [27], Carrillo Murillo [32], Ishfaq and Sox [28], Vidović et al. [26], Ishfaq and Sox [29], Sørensen et al. [30], Sørensen and Vanovermeire [31], Zhang et al. [33]
Intermodal service network design	Crainic and Rousseau [36], Kim [37], Newman and Yano [38], Kreutzberger [73–75], Andersen et al. [40], Kreutzberger [39], Bauer et al. [41], Caris et al. [45,46], Braeckers et al. [47], Woxenius et al. [42]
Intermodal routing	Min [55], Barnhart and Ratliff [49], Boardman et al. [50], Ziliaskopoulos and Wardell [51], Erera et al. [53], Grasman [54], Chang et al. [52], Chang [48], Bock [59], Gromicho et al. [60], Yang et al. [56], Cho et al. [57], Verma et al. [58]
Drayage operations	Wang and Regan [62], Francis et al. [63], Imai et al. [64], Caris and Janssens [65], Caris and Janssens [66], Escudero et al. [67], Braeckers et al. [69], Escudero et al. [68]
ICT Innovations	Dullaert et al. [70], Dotoli et al. [71]

Sections 3 and 4 give an overview of network design models which assist individual decision makers such as network operators. Section 3 focuses on the design of the terminal network, whereas in Section 4 decision support models for designing service networks are studied. Recently, research attention has been given to intermodal routing decisions, as described in Section 5. Decision models concerning drayage operations in the first and final part of the intermodal transport chain are presented in Section 6. A last trend in decision support models for intermodal transport analyses the impact of ICT innovations (Section 7). Section 8 draws general conclusions on trends and issues that recur in multiple topics described in the previous sections. Table 1 presents an overview of models discussed in the following sections.

## 2. Policy support

Policy makers have a clear interest in intermodal transport. A further market share for intermodal transport would mean a shift towards more environmental friendly transport modes, less congestion and a better accessibility and opening-up of the seaports. The European Commission expressed in several of their policy papers a wish to have a further stimulation of intermodal transport [3,4]. Also on the national and regional levels several policies are implemented to stimulate intermodal transport further [5,6]. Not many research models exist to analyze different policy measures in the intermodal transport sector [7]. The spatial price equilibrium models and network models developed in the past were not directed towards intermodal transport. Crainic et al. [8], Loureiro [9], Jourquin et al. [10], Southworth and Peterson [11] and Tan et al. [12] were the first to develop network models which are capable of dealing with intermodal flows, which implies that freight can be transferred from one mode to another in the model via transfer points. This section discusses recent developments in network models that support public policy makers. A discussion of earlier models may be found in Caris et al. [2]. All models presented in Section 2 are able to perform scenario analyses to assess the impact of policy measures or new capital investments on future freight flows, whereas Section 3 focuses on network design models for individual stakeholders such as network operators. Several models may be applied by policy makers as well as private stakeholders. We have categorized them in the section on their main application area or according to the application described in the paper.

Macharis and Pekin [13] present the assessment of policy options such as the introduction of new terminals and the effect of subsidies. The authors demonstrate the possibilities of a geographic information system (GIS)-based location analysis model, entitled the LAMBIT model, which was previously developed by

Macharis [14]. The LAMBIT model uses the Dijkstra algorithm to find the shortest path and the attached transport costs from the port of Antwerp to each Belgian municipality via intermodal terminals. For each destination, total transport costs for unimodal road, inland waterways/road and rail/road transport are compared. The authors conclude that different policy measures to stimulate intermodal barge and rail transport should be integrated in a coherent vision, in order to avoid a modal shift between the different intermodal transport options. In Macharis et al. [15] the LAMBIT model is applied to estimate the impact of fuel price increases and the internalization of external cost on the market area of intermodal terminals. Within Macharis et al. [16], the LAMBIT model is combined with the NODUS model [10] and a discrete event simulation model for inland waterways, creating a decision support framework which covers all aspects for intermodal transport policy analysis. This framework enables policy makers to estimate the impact of policy measures on all related transport modes and at multiple aggregation levels. The NODUS model is a virtual network representing successive operations involved in intermodal transport and includes a detailed analysis of all costs. Generalized costs are minimized according to the shortest path algorithm. A detailed description of this discrete event simulation model for intermodal barge transport (SIMBA model) is presented in Caris et al. [17]. In this special issue Pekin et al. [18] further improve the LAMBIT model by integrating next to the market price, the value of time. Taking this value of time into account shows that the types of goods in the containers have an important impact on the competitiveness of intermodal transport. Next, other factors influencing the cost structure are integrated in the LAMBIT model, such as the possibility to use the terminal as an empty depot and the role of pre- and post-haulage in the multimodal chain.

Other decision support models developed with the objective to assess intermodal transport policy measures include the work of Floden [19], Tsamboulas et al. [20], Zhang et al. [21], Yamada et al. [22] and Iannone [23]. Floden [19] constructed the Heuristics Intermodal Transport model (HIT-model), intended to support decisions in a strategic setting in intermodal rail transport in Sweden. The model may be applied to determine the market area for a terminal, the need for additional intermodal transport terminals or superfluous terminals, geographical areas where intermodal transport has a strong potential and capacity bottlenecks. It is also possible to test different scenarios and parameter settings such as effects of changed taxes, increasing train speeds, allowing longer trains, congestion (i.e. reduced speed), standardization of the type of ITUs used, market entry of foreign low cost road haulers, new infrastructure investments, changes in infrastructure fees, changed cost structure (fuel prices, salaries, etc.),

changed time requirements (e.g. later deliveries allowed by intermodal transport) and effects of different cost estimations (e.g. the valuation of environmental effects). The assessment of transport policy measures in favour of intermodal transport is performed on a European scale by Tsamboulas et al. [20]. Their methodology comprises a macro-scan, a sensitivity analysis and a policy action plan. The macro-scan calculates costs and door-to-door travel times for road transport and intermodal transport by rail, inland waterway or short sea shipping between individual origin-destination pairs in Europe. Zhang et al. [21] developed a multiproduct freight network simulation-assignment model for a pan-European intermodal rail network as a policy decision support tool. The authors illustrate the application of their model by predicting the potential impact of expedited operations at international borders (e.g. by employing multivoltage locomotives or by implementing ICT solutions for a better communication) leading to decreased border crossing times and the impact of infrastructure improvements on rail services leading to an increase in rail maximum speeds. Yamada et al. [22] recently presented a strategic, discrete network design model for investment planning. Their bi-level programming model is constructed to select actions from a list of possible actions, such as improving the existing infrastructure or establishing new roads, railways, sea links and freight terminals. A genetic local search (GLS) method is suggested to find near-optimal actions, maximizing a benefit-cost ratio depending on their impact on freight and passenger flows. The model is applied to investigate how to improve the interregional freight transport network in the Philippines. Iannone [23] developed a strategic model of a port-hinterland logistic system in the Campania region of Southern Italy. The model minimizes all container-related logistic costs and may be used by shipping lines or freight forwarders, port authorities, railway companies and public actors. The model is applied to analyze the effect of introducing an extended gateway system offering rail connections to inland ports in the region. Other possible applications include the simulation of alternative scenarios in terms of infrastructure and services offered, changes in demand characteristics and both government and industrial policies. In this special issue Maia and Couto [24] present a strategic planning model for both road and rail transport and considers two different types of cargo: general cargo and intermodal cargo. The proposed model takes into account both capacity constraints and a variable perception of costs by users.

### 3. Terminal network design

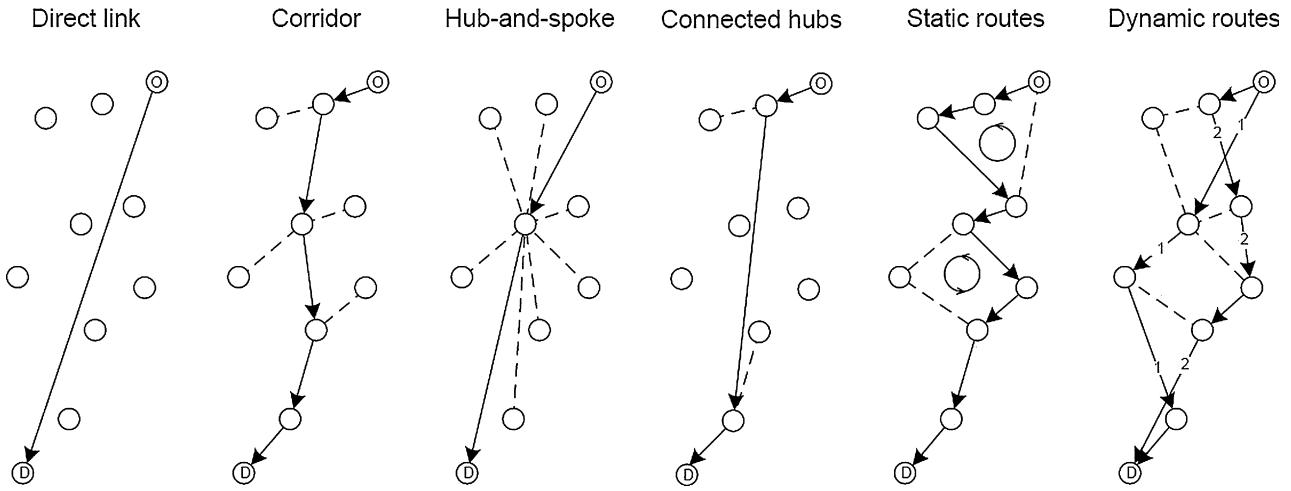
Network operators are confronted with the long-term decision on the layout of their intermodal terminal network. Recently, several network models are proposed in literature to support strategic decision making on the most appropriate locations to construct intermodal terminals. Besides supporting network operators, these models may also be applied by policy makers to gain an insight in the terminal landscape.

A first group of recent research papers formulates the terminal network design problem as a hub location problem. Rahimi et al. [25] develop a location-allocation model to determine the optimal number and location of inland ports in a case study in California. The hub-and-spoke network consists of rail and road links. The model determines which transportation nodes are served by which inland ports based on the minimization of daily transportation costs and fixed terminal costs. Vidović et al. [26] combine a multiple-assignment  $p$ -hub network location model with simulation to select intermodal terminal locations in a case study in Serbia. A simulation model is constructed to evaluate solutions in terms of direct road and intermodal costs, transit times and environmental effects. Limbourg and Jourquin [27] construct an iterative procedure, based on the  $p$ -hub median problem and the

multimodal assignment problem, to select  $p$  optimal locations from a set of estimated potential locations for rail-road terminals in an international hub-and-spoke network. The objective function includes costs of pre- and end-haulage by road, transshipment costs and rail haulage costs. Transshipment costs are related to the volume handled at the terminal. Ishfaq and Sox [28] also base their mathematical model on the  $p$ -hub median problem to design an intermodal road-rail network. The objective function minimizes transportation costs and fixed costs of hub facilities. These fixed costs include modal connectivity costs, which depend on the type of modes served by the hub. The authors add service time requirements for each origin-destination pair in the network. A tabu search approach is proposed to solve data sets up to a hundred nodes in the network. Ishfaq and Sox [29] extend previous work with the introduction of a queuing system to model hub operations. The queuing system provides time estimates for shipment delays at hubs. The integration of the queuing model with a  $p$ -hub median network design model provides managerial insights into the impact of limited hub resources on total network cost, number and location of hubs, modal flows and shipment waiting times. In their recent work, Sørensen et al. [30] develop two metaheuristics to determine the optimal number and location of intermodal terminals. The authors minimize fixed and variable transportation costs. Both heuristics consist of two phases: a construction phase and an improvement phase based on local search. In this research, the number of terminals to be opened is not predefined. Furthermore, not all flows have to go through a hub, also direct transport by road between two nodes is explicitly taken into account in the mathematical model. In this special issue Sørensen and Vanovermeire [31] extend their problem formulation to the bi-objective case, in which transportation costs for users of the terminal network and locations costs for terminal operators are treated as two separate objectives. This allows decision makers to estimate the relationship between the level of investment and the shift towards intermodal transportation.

A different approach to model the terminal network design problem is proposed by Carrillo Murillo [32]. The author combines a nested logit model and the Free Economic Energy model to analyze location patterns of hinterland terminals in road-rail intermodal transport. The problem is studied from a private perspective, but may also be applied to assess policy measures such as intermodal subsidies and internalizations of external costs as well as the issuing of building permits for new inland terminals.

As argued by Zhang et al. [33], important challenges in the design of terminal networks are still to be tackled. According to Zhang et al. [33], few researchers take economies of scale in terminal handling costs into account, which play a critical role in the efficiency of intermodal transport. Furthermore, no linkages are made between the design of terminal infrastructure networks and intermodal service networks, which are discussed in Section 4. When applying network design models to real world applications, often a validated demand model is lacking and long computation times are incurred. Within Zhang et al. [33] economies of scale are considered in their bi-level programming model. The authors apply a monotonic decreasing function to describe the relationship between terminal scale and unit handling costs. The lower level consists of a multicommodity flow assignment model. The flow assignment is constrained by the terminal accessibilities defined at the upper level. The upper level model searches for the optimal combination of terminal network configuration and CO<sub>2</sub> price in order to achieve minimal system cost. A genetic algorithm is proposed to solve the optimization problem at the upper level. The model is implemented in a GIS application as a user-friendly interface for decision makers. Besides supporting network operators, an important aim of the model is to assist policy



**Fig. 1.** Service network design typology [35].

makers in analyzing the effect of varying CO<sub>2</sub> prices on terminal network solutions.

#### 4. Intermodal service network design

Service network design involves the selection of routes on which services are offered and the determination of characteristics of each service, particularly their frequency [34]. At the tactical decision level a network operator has to decide which consolidation network to use. Woxenius [35] presents a service network design typology for intermodal transport, as depicted in Fig. 1. Network designs for transportation systems are classified in six different types. The proposed generic terminology will be used in this overview of decision support models for intermodal service network design. Relatively few research has been performed on the design of the intermodal service network and in particular the determination of an optimal consolidation strategy.

A first intermodal formulation is given by Crainic and Rousseau [36]. The authors propose a solution algorithm based on decomposition and column generation techniques. Kim [37] presents a large scale transportation service network design model, applied to the express package delivery industry. Packages may either pass through a hub-and-spoke network or be delivered through a direct connection. An application of service network design in intermodal rail transport can be found in Newman and Yano [38]. The authors compare a variety of decentralized planning approaches with a centralized approach for scheduling trains in an intermodal network consisting of a hub-and-spoke structure combined with direct connections. Extensive research has been done by Kreutzberger [73–75] on service network design in intermodal rail freight networks. In recent work [39] the author analyses in which transport landscape do which bundling network types ensure the lowest operational cost and which of the lowest cost bundling networks may be competitive with unimodal road transport. Andersen et al. [40] formulate a service network design model to study the impact of an increased level of synchronization in intermodal rail transport on the rail efficiency and interoperability across borders. A general network structure is proposed in which multiple rail services are combined in a network of connected hubs. Bauer et al. [41] incorporate environmental costs in a service network design formulation for intermodal rail transport with connected hubs. Their aim is to minimize greenhouse gas emissions of transportation activities instead of minimizing internal transportation costs. Results are compared with the time-value minimizing objective function of Andersen

et al. [40] on a case study described by the same authors. Bauer et al. [41] conclude that minimizing time implies running more services on the network as compared to minimizing emissions. Consequently, the utilization of service capacity is higher when minimizing CO<sub>2</sub> emissions. In this special issue Woxenius et al. [42] identify, characterize and evaluate existing measures for increasing the space utilization for intermodal trains operating in a corridor network. Possible measures include adapting the train's capacity, changing departure times, altering train routes and sending trucks to different terminals as well as replacing rail transport with trucks. The authors assess to what these degree measures are likely to fulfil the users' demands for service quality and how the measures are likely to support the providers' profitability.

Service network design studies in intermodal barge transport are the following. Groothedde [43] and Groothedde et al. [44] discuss the design of an inland intermodal service network with connected hubs for transporting palletized fast moving consumer goods. Caris et al. [45,46] study bundling strategies for intermodal barge transport in the hinterland network of a major port in Western Europe. One potential network concept is the uncoupling of the hub-and-spoke services in the port area from the trunk haul services with direct connections to the hinterland. Four alternative hub-and-spoke scenarios for bundling in the port area are compared by means of discrete event simulation [45]. In a second study, Caris et al. [46] analyze the organization of intermodal barge transport in a corridor network. Inland terminals may cooperate to achieve economies of scale and bundle freight to and from the same sea terminals in the port area. A service network design formulation is proposed to identify interesting cooperation scenarios. Next, selected cooperation scenarios are simulated and compared with their previous work on bundling in the port area. In this special issue Braekers et al. [47] present a decision support tool for service network design in intermodal barge transport. Barge operators, logistic service providers or shipping lines that want to offer regular roundtrip barge services between a number of ports located along the same waterway may use this model to determine vessel capacity and frequency of these roundtrips. For each service type (capacity and frequency) the model determines optimal shipping routes and number of containers to be transported in a corridor network. The decision maker may use this information, together with information on other factors like customer preferences, to evaluate all possible types of service and choose the best among them.

## 5. Intermodal routing

Intermodal routing involves the selection of routes for shipments through an intermodal network. Intermodal transport may be competitive with unimodal road transport due to economies of scale on the main haulage. Multiple objectives may be defined, such as the minimization of route cost or route time and the maximization of economies of scale. Economies of scale are often modelled with a piecewise linear concave cost function. The complexity increases due to the incorporation of multiple transport modes. Additional schedules may have to be included for certain transport modes. These schedules may be treated as time window constraints [48]. Although intermodal transport is seen as the way to go for freight transport in Europe, still few research papers exist on intermodal routing.

A number of routing methods have been developed, each taking some but often not all characteristics of intermodal transport into account. Barnhart and Ratliff [49] discuss methods for determining minimum cost intermodal routings to help shippers minimize total transportation costs. Their models are focused on rail/road combinations compared to uni-modal road transport. Optimal routings are determined with a shortest path procedure or with a matching algorithm and a b-matching algorithm. A decision support system is constructed by Boardman et al. [50] to assist shippers in selecting the least cost combination of transportation modes (truck, rail, air and barge) between a given origin and a corresponding destination. Ziliaskopoulos and Wardell [51] introduce the concept of time dependency of optimal paths in their intermodal routing model. Also delays at switching points, fixed time schedules of transport modes and movement delays or movement prohibitions are taken into account. An extension of this work is presented by Chang et al. [52], who calculate time-dependent intermodal minimum cost paths. Cost rather than time is optimized, based on time-dependent and fixed travel and transfer costs. The algorithm is adapted to solve the problem of intermodal routing of hazardous materials, taking into account both travel risk and travel cost. Erera et al. [53] propose a model for the joint routing of loaded tank containers and repositioning of empty tank containers in an intermodal network. Grasman [54] presents dynamic programming formulations for the optimal routing of freight in an intermodal network.

Multiple researchers focus on the multi-objective nature of the modal choice decision. In Min [55] a chance-constrained goal programming model is constructed to choose the most effective intermodal route, taking into account costs, market coverage, average length of haul, equipment capacity, speed, availability, reliability and damage risk. A multi-objective intermodal routing problem is also proposed by Yang et al. [56], who minimize transportation cost, transit time and transit time variability. A goal programming approach is tested in a case study of alternative routings between China and four destinations in the Indian Ocean. Cho et al. [57] suggest a dynamic programming algorithm for a bi-objective international intermodal routing problem, minimizing transportation cost and time. The problem is formulated as a weighted constrained shortest path model. A label setting algorithm is combined with additional pruning rules to generate Pareto optimal solutions. Verma et al. [58] develop a bi-objective framework for routing hazardous materials in a rail-truck transportation network. Intermodal railroad companies which offer door-to-door services for hazmat, aim to minimize transport cost and transport risk. The authors take customer specified delivery times into account and describe a tabu search solution methodology. The model allows railway managers to gain insight into the risk-cost tradeoff in routing hazmat and into the captive areas for intermodal rail terminals. Chang [48] formulates the international intermodal routing problem as a multiobjective

multimodal multicommodity flow problem with time windows and concave costs. The objective function minimizes the weighted sum of total flow cost and total travel time. The cost associated with each link in the network is assumed to be a continuous non-convex piecewise linear function of the total flow along the link, representing economies of scale in intermodal freight transport. Each piecewise linear segment represents a fixed and variable transportation cost. Chang [48] takes three essential characteristics of intermodal routing into account. Chang [48] states it is important to include (1) multiple objectives, (2) transportation mode schedules and demanded delivery times and (3) economies of scale. Research efforts are still needed into the further development of solution methods and the comparison of proposed techniques, taking all three characteristics into account.

Two research papers focus on the practical application of intermodal routing algorithms. Bock [59] studies an intermodal routing problem in a dynamic context. A real-time approach is developed to support freight forwarders in their daily operations. The model integrates multiple transport modes and multiple transshipments, partial or total outsourcing of transportation services and dynamic disturbances such as vehicle breakdowns, traffic congestion and street blockages. The dynamic problem is modelled as a rolling horizon scheme and a local search improvement procedure is applied with a variable neighbourhood structure. Gromicho et al. [60] propose a k-shortest path algorithm, which may be used in practice by logistic service providers to identify a number of alternatives for routing freight in an intermodal network in a short computation time. The algorithm minimizes route costs, while considering customer time restrictions and timetables of transportation modes. The practical use of intermodal routing algorithms still offers research challenges as computation time grows with the size of the network and dynamic events may occur in real-time.

## 6. Drayage operations

The initial and final part of the intermodal transport chain is often performed by road. Drayage operations constitute an important factor in total intermodal transport costs. Konings [61] argues that the geographical scale for profitable intermodal services is strongly determined by the performance of pre- and end-haulage by road. The distribution of containers by truck may be considered as a pickup and delivery problem, which is a special case of the vehicle routing problem. Full containers need to be picked up at their origin and brought to the terminal or delivered from an intermodal terminal to their destination. Few research has been conducted on intermodal drayage operations.

Wang and Regan [62] propose a hybrid approach to solve a pickup and delivery problem containing one or more intermodal facilities. Only pickup time windows are considered and the number of vehicles is fixed. The authors apply time window discretization in combination with a branch and bound method. Francis et al. [63] model intermodal drayage operations as a multi-resource routing problem in which two resources (tractors and trailers) perform tasks to ship loaded and empty equipment. The authors introduce the concept of flexible tasks for which the origin or destination is not defined. A randomized solution method, called the Greedy Randomized Procedure, is proposed to solve the resulting problem. Imai et al. [64] present a heuristic based on Lagrangian relaxation for the drayage problem of intermodal container terminals. In the pre- and end-haulage of intermodal containers substantial cost and time savings may be realized by merging pickup and delivery customers in a single trip. The heuristic procedure combines customers' sites into pairs in a first stage and assigns trucks to these merged trips in a second stage. Caris and Janssens [65] model the drayage of containers in the

service area of an intermodal terminal as a full truckload pickup and delivery problem with time windows. Hard time windows are imposed at customer locations. The authors propose a local search heuristic [65] and a deterministic annealing algorithm [66] to find near optimal solutions. Escudero et al. [67,68] adapt the work of Caris and Janssens [65] to the dynamic case with real-time knowledge of the position of vehicles. A geographic positioning system by satellite provides the vehicle positions. Each time an event takes place, the algorithm is run again with the updated data for the remaining tasks. Braekers et al. [69] incorporate empty container movements in the planning process of intermodal drayage operations. Either the origin or the destination of an empty container transport is not predefined. The problem is formulated as an asymmetric multiple vehicle travelling salesman problem with time windows. The authors compare a sequential and an integrated solution approach based on deterministic annealing. Results show that the integrated approach, in which container allocation and vehicle routing decisions are made simultaneously, clearly outperforms the sequential one.

## 7. ICT innovations

Intermodal transport, by definition, involves several decision makers who need to work in collaboration in order for the transport system to run smoothly. Information and Communication Technologies (ICT) may particularly play an important role at the operational planning level of intermodal transport systems. During daily operations, decisions need to be made in real-time. ICT innovations increase the flow of data, improve the timeliness and quality of information and offer the possibility to control and coordinate operations in real-time (Crainic and Kim [72]). Research is required to incorporate ICT solutions and real-time information in intermodal planning problems. The following research papers have emerged in this very young research field in intermodal transport. The selected papers in this section present ICT solutions which facilitate the intermodal transport chain and increase the efficiency of intermodal transport.

Data exchange is significantly more complex in intermodal transport compared to unimodal transport. This is amongst others due to a possible incompatibility between information systems, problems with speed, manageability and volume of the information exchanged and fear of disclosure of explicit information of the companies involved. To this end, Dullaert et al. [70] develop an agent-based, expert communication platform. The MamMoeT platform is a real-time decision support system in which operational information may be shared between multiple actors in the intermodal barge transport chain. Users of the system are represented by software agents. The communication platform serves three main purposes: to match supply and demand for barge transport, to enable tracking and tracing of shipments and to facilitate proper reactions to unexpected events. Recently, Dotoli et al. [71] investigate the impact of new ICT developments on the operational management and control of an intermodal transport chain. The authors describe a case study of an intermodal transport system in Italy. The intermodal system is modelled as a timed Petri net and a future situation with a higher degree of information exchange due to new ICT tools is simulated. The proposed methodology allows to quantify benefits of integrating ICT solutions in an intermodal transport system.

Still very few efforts have been dedicated to the modelling of ICT innovations in intermodal transport. Crainic and Kim [72] state that this largely unexplored research field offers multiple opportunities and challenges, such as the coordination of plans and operations of independent actors and the modelling of uncertainty of operations in each element of the intermodal transport chain.

## 8. Conclusions and future research

Intermodal transport is being stimulated at multiple policy levels to guarantee a sustainable freight transport system in the future. In this paper new research themes have been identified concerning the development of decision support systems in intermodal transport. Recent publications describe models for policy support, terminal network design, intermodal service network design, intermodal routing, drayage operations and ICT innovations. These research topics still offer important challenges. For example, linkages should be made between models for terminal network design and intermodal service network design. Secondly, there is a need for solution methods for intermodal routing models taking into account multiple objectives, transportation mode schedules and demanded delivery times and economies of scale. Planning algorithms for drayage operations taking into account dynamic problem aspects (such as the emergence of new transport requests or time-dependent travel times) should be developed. Finally, the development of ICT innovations to support and coordinate intermodal operations will be a key research area to stimulate the use of intermodal transport in the near future.

A number of trends may be identified which are pointed out in multiple research papers. A first trend appearing in several decision support models at multiple planning levels is the introduction of environmental concerns. The impact on the environment plays a key role in policy making for intermodal transport. However, also private decision makers are increasingly aware of the external costs of freight transport. Environmental costs have been included in decision support models for policy support [19,15,23], terminal network design [26,32,33] and intermodal service network design [41]. Secondly, intermodal planning models are being developed in a dynamic context to support decision makers in daily practice. In daily operations new information becomes available in real-time. Dynamic models are proposed for intermodal routing [59] and intermodal drayage operations [67]. ICT innovations may be important enablers to provide adequate, correct and real-time information in this context. A third trend is the growth in innovative applications of Operations Research techniques and development of decision support systems based on mathematical modelling for intermodal planning problems. The numerous recent papers mentioned in this review are all proof of this statement. An increased quantification and optimization of planning issues in intermodal transport will add to the efficiency and viability of this transport mode.

Some issues which complicate the development of decision support models for intermodal transport still remain, as stated in multiple papers. First, the limited data availability on freight flows and their aggregate static nature restrict the refinement of models to support for example policy making [13,20,21,32]. More data exchange is also required in intermodal transport compared to unimodal transport, due to the presence of multiple actors and modes. Not all required data is accessible for all actors and a risk of private data disclosure exists. A second prevailing issue is the problem size (network scale) and related computational considerations of planning models for intermodal transport systems [28,40]. Further research is needed into fast solution approaches to provide decision support in real-time for intermodal transport problems of realistic size. Third, the inclusion of all the actors in the decision support tools, is still an issue. Only looking at the problems from one point of view creates suboptimal solutions. A better understanding of all the actors that are involved and their objectives will enable to integrate them in the decision support systems. Finally, we hope that these models will be more and more relied on by the policy makers and will not be left in the scientific world.

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