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Opportunities for OR in intermodal freight transport research: A review

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Abstract

Intermodal transport reflects 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 traveled by rail, inland waterway or ocean-going vessel, and with the shortest possible initial and final journeys by road. Operational Research has focused mostly on transport problems of uni-modal transport modes. We argue that intermodal freight transportation research is emerging as a new transportation research application field, that it still is in a pre-paradigmatic phase, and that it needs a different type of models than those applicated to uni-modal transport. In this paper a review is given of the operational research models that are currently used in this emerging field and the modelling problems, which need to be addressed.

Keywords: Operational research; Intermodal transport; Transportation

1. Introduction

Intermodal freight transport has developed into a significant sector of the transport industry in its own right. This development has been followed by an increase in intermodal freight transportation research. Intermodal freight transport is the term used to describe the movement of goods in one and the same loading unit or vehicle which uses successive, various modes of transport (road, rail, water) without any handling of the goods themselves during transfers between modes (European Conference of Ministers of Transport, 1993). In this paper we focus on inland intermodal freight transport, rail–truck and barge–truck transport. Comparable research involving ocean shipping is not taken into account in this paper.

Fig. 1 provides a simple depiction of road–rail intermodal freight transport. A shipment that needs to be transported from a shipper to a receiver is first transported by truck to a terminal. There it is transhipped from truck to it's second mode, in this instance a train. The train takes care of the terminal to terminal transport. At the other end of the transport chain the shipment is

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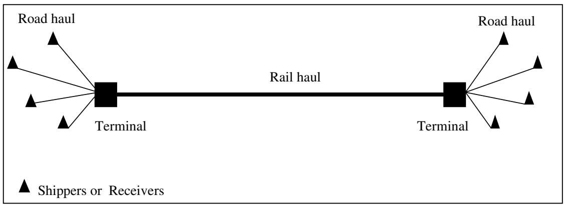

Fig. 1. A typical representation of road–rail intermodal freight transport.

transhipped from train to truck and delivered by truck to the receiver. The trucking part of the transport chain is called drayage, pre- and end-haulage or pick-up and delivery. Instead of rail transport between the terminals transport by barge also is possible. The transport between two terminals is called the long haul. For a comprehensive description of intermodal freight transport see Muller (1999).

Intermodal freight transport is only just starting to be researched seriously. Since 1990 a substantial number of analytical publications specifically addressing intermodal transport issues have appeared (see Bontekoning et al., in press). Various intermodal freight transport decision problems demand models to help in the application of operation research techniques. However, the use of OR in intermodal transport research is still limited. The intermodal transport system is more complex to model than the mono-modal one and thus more difficult to research. This gives very interesting and challenging tasks for the OR practitioners.

Our contribution attempts to provide a comprehensive overview of the use of operations research (OR) in intermodal freight research and to elaborate a research agenda for the application and development of OR techniques in intermodal freight transport research. Essentially, we want to answer the following questions:

- What makes the problems in intermodal freight transport research interesting for OR scientists?
- Which OR techniques have been applied, and for which problems?
- Have these techniques been applied appropriately? Are there alternative approaches to the same problem?
- To what extent do the specific problems of intermodal transport contribute to the overall development of OR techniques?

Section 2 describes our review procedure and the set-up of a classification of OR techniques applied in intermodal transport. In the subsequent sections (from 3 to 6) this classification is followed. For each actor in the intermodal transport system a general problem description is given, followed by the review of problems investigated and OR techniques applied in intermodal research.

2. Approach

We have performed a scientific literature review. We chose a computerised search, due to it's speed and efficiency. However, we must note that electronic sources such as databases have limited coverage. Their earliest date is 1988. Nevertheless, this relatively short period of coverage is not really a significant bias in our review, as we presume that the majority of the intermodal literature has been published in the last ten years. We used a number of channels when choosing our studies, in order to avoid bias in the coverage. As a preliminary step we searched the following databases: Transport, Dissertation Abstracts, and the (Social) Sciences Citation Index (SCI). However, the databases and SCI do not contain all journals; therefore, we performed a separate search of the electronic journals concerning transportation which were not covered by those channels. We also performed a physical search of the collection in the Delft University of Technology library, which holds the largest collection of transportation literature in the Netherlands. In addition we included research we already knew about from informal contacts with other researchers, as well as our own research. Finally, we retrieved studies by tracking the research cited in the literature that we had already obtained (ancestry approach). Most channels cover the period from 1988 to 2002, with the exception of the electronic journals, the Dissertation Abstracts database, research of informal contacts and our own research. These channels cover the period from 1995 to 2002. Appendix A provides a detailed overview of the channels we investigated.

In the first round of the research it appeared that the studies reviewed could be categorised using two criteria: (1) type of operator, and (2) time horizon of operations problem. Based on the four main activities in intermodal transport we have distinguished the following operators:

- drayage operators, who take care of the planning and scheduling of trucks between the terminal and the shippers and receivers;
- terminal operators, who take care of the transhipment operations from road to rail or barge, or from rail to rail or barge to barge;
- network operators, who take care of the infrastructure planning and the organisation of rail or barge transport;
- intermodal operators, who can be considered as users of the inter modal infrastructure and services, and take care of the route selection for a shipment through the whole intermodal network.

These operators face operational problems with different time horizons. Strategic, tactical and operational problems can be distinguished. In the strategic level, decisions are found on a very long term (10–20 years). The location of terminals, the network configurations and the design and layout of a terminal are typically decisions were a large amount of capital is fixed for a long time and that are difficult to change. The tactical levels involves a time period of months/weeks. Finally, at the operational level, day-to-day or even real-time decisions are made.

The combination of these two categories provides a classification matrix with twelve categories of intermodal operations problems (see Table 1). The classification is not exhaustive and some decision problems can be faced by several decision makers and can be relevant for the same decision maker at the different time horizons. However, the decision problems have been placed in the classification matrix of Table 1 were they were most prominent. The studies reviewed have been assigned to one of the categories, which provides a structured overview of the type of OR problems in intermodal transport. The number of studies that require decisions from more than one operator and/or more time horizons are very limited. This is already an important conclusion of the survey. Intermodal transport, by definition, involves many decision makers who all need to work in collaboration in order for the system to run smoothly. If intermodal transport is to be developed it will require more decision-making support tools to assist the many actors and stakeholders involved in the operation. A very good attempt at outlining these tools can be found in the paper of Van Duin and Van Ham (2001) where a three-level modelling approach is followed in order to take account of the different goals of the different stakeholders.

Table 1 is used to structure the review of the papers in the following sections. Each section starts with a general problem statement, which provides a description of the intermodal operations related to the type of decision maker and decision problems involved. In each section the individual contribution to the general problem statement of the paper reviewed is discussed. Here, the categorisation along the time horizon is used.

3. Drayage operator: OR problems and applications

3.1. General problem statement

Drayage operations involve the provision of an empty trailer or container to the shipper and the subsequent transportation of a full trailer or container to the terminal. The empty container may be picked up either at the terminal, at an empty depot or at a receiver. Delivery operations involve the distribution of a full container or trailer from the terminal to a receiver, followed by the collection of the empty container/trailer and its transportation to the terminal, an empty depot, or a shipper. The possibility of separation of tractor and trailer allows two procedures: "stay-with" and "drop-and-pick". In the stay-with procedure, the tractor and driver stay with the trailer/container during loading and/or unloading. In the drop-and-pick procedure, a full or empty trailer/container is dropped off at the shipper/receiver. During loading/unloading,

Table 1
Overview of publications reviewed—by research category

Decision maker	Time horizon		
	Strategic	Tactical	Operational
Drayage operator	*Co-operation between drayage companies* Spasovic (1990) Walker (1992) Morlok and Spasovic (1994) Morlok et al. (1995)	*Allocation of shippers and receiver locations to a terminal* Taylor et al. (2002)	*Redistribution of trailer chassis and load units* Justice (1996)
	Truck and chassis fleet size –	*Pricing strategies* Spasovic and Morlok (1993)	*Scheduling of truck trips* Wang and Regan (2002)
Terminal operator	*Terminal design* Ferreira and Sigut (1995) Meyer (1998) Van Duin and Van Ham (2001)	*Capacity levels of equipment and labour* Kemper and Fischer (2000) Bostel and Dejax (1998)	*Allocation of capacity to jobs* –
		Redesign of operational routines and layout structures Voges et al. (1994)	*Scheduling of jobs* –
Network operator	*Infrastructure network configuration* Crainic et al. (1990) Loureiro (1994) Jourquin et al. (1999) Southworth and Peterson (2000)	*Configuration consolidation network* Jourquin et al. (1999) Janič et al. (1999) Newman and Yano (2000a) Newman and Yano (2000b)	*Load order of trains* Feo and González-Velarde (1995) Powell and Carvalho (1998)
	Location of terminals Rutten (1995) Meinert et al. (1998) Van Duin and Van Ham (2001) Arnold and Thomas (1999) Groothedde and Tavasszy (1999) Macharis and Verbeke (1999)	*Type of production model* Nozick and Morlok (1997) *Pricing strategy* Yan et al. (1995) Tsai et al. (1994)	*Redistribution of railcars, barges and load units* Chih and van Dyke (1987) Chih et al. (1990) Bostel and Dejax (1998)
Intermodal operator	n.a.	n.a.	*Selection of routing and service* Barnhart and Ratliff (1993) Boardman et al. (1997)

Source: own setup.

the tractor and driver are free to carry out other activities.

An intermodal terminal may be used by a large number of drayage companies (a dozen or even more). Each drayage company faces a trip scheduling problem with trips between shippers, receivers and one or more terminals meeting several requirements, such as customer's pre-specified pick-up and delivery times (time-windows), on-road travel times, and realistic limits on the length of the working day. Most shipments are known about in advance. Only a fraction of loads in a given are short notice. However, loads must sometimes be reassigned due to traffic, dock and intermodal terminal delays. In addition, time must be allocated for local trailer chassis distribution. Drayage companies carry out trips from and to several nearby terminals in an area. For example, in North-America trailer chassis are pooled over several terminals in a region. At each terminal sufficient chassis should be available. Due to imbalances in flows, empty chassis need to be redistributed from terminals with abundant chassis to terminals with a shortage.

The general problem of drayage operations is its cost effectiveness. Despite the relatively short distance of the truck movement compared to the rail or barge haul, drayage accounts for a large percentage (between 25% and 40%) of origin to destination expenses. High drayage costs seriously affect the profitability of an intermodal service, and also limit the markets in which it can compete with road transport (see Spasovic and Morlok, 1993; Morlok and Spasovic, 1994; Morlok et al., 1995). Consequently, alternative, less costly operations need to be designed.

3.2. OR applications for strategic problems

Spasovic (1990), Morlok and Spasovic (1994) and Morlok et al. (1995) investigate whether central planning of all pick-up and delivery trips of several drayage companies in one terminal-service area can reduce drayage costs. They examine the impact of a centralised planning on the total fleet size and utilisation. The objective being to minimise total cost of tractor and tractor-trailer activities subject to several time and service constraints. The model has been constructed as a large-scale integer linear program with time windows and service constraints. The tractor-trailer delivery, repositioning and pick-up operation is considered as a time-space network consisting of nodes connected by links. The nodes represent the terminals and the shippers/consignees, the links the tractor and tractor-trailer activities. Integer problems of this size are very difficult to solve. Several redundant and definable constraints have been introduced in order to push the model closer to becoming a general network. The model is dynamic as it considers the temporal variations in demands for trailer load movements. The model has been applied to a data set with 330 trailer movements for an 8-day period, including trailer origins and destinations and requested times for pick-up and delivery. Due to imbalances in trade the set includes 215 movements from terminal to receiver and 115 from shipper to terminal.

In addition, the model is used to evaluate the efficiency of drayage rates charged by truckers in the current operation as well as rates used in a proposed operation with centralise planning of tractor and trailer movements (see Spasovic and Morlok, 1993). The marginal costs generated by the integer linear program are used for this purpose. These are then evaluated by considering the change in total cost resulting from moving an additional load.

Walker (1992) addresses the similar problem of central planning as indicated above. His objective being to develop an efficient set of driver tours consistent with the shippers' pick-up and delivery times, on-road travel times, and realistic limits on the length of the working day, using a cost-minimising vehicle-scheduling algorithm. This is accomplished by constructing a computerised network, containing arcs representing all trailer movements and all feasible bobtail connections between trailer movements. The simulation is of a Monte-Carlo assignment and observes the trailer movements using a set of hypothetical trucking firms with a given size distribution. Trailers are randomly distributed to a given number of firms of equal size. The work hours and number of drivers required to service the schedule are then tabulated by company and for all trailer movements. The algorithm is then applied to a data set with 300 trailer movements distributed among 47 individual drayage companies and 150 drivers. Factors such as repositioning and redistribution of empty trailers and the delivery of empty trailers to be loaded are not taken into account in this example. Only specific pick-up and delivery assignment of full trailers from A to B are included.

3.3. OR applications for tactical problems

Taylor et al. (2002) deal with the assignment of shipper locations to terminal service areas. Their objective is to develop two alternative heuristics for intermodal terminal selection and determine their robustness with respect to alternate terminal location assumptions and other pertinent parameters, with respect to minimisation of total non-productive (empty) miles associated with circuitous (off-route miles) and empty travel (in between two successive assignments). After the mathematical formulation of the problem, software has been written to analyse 40 scenarios for the two alternatives:

1. Circuit only: assignment of freight to terminal pairs where load circuitry is the sole criterion.
2. Total miles: assignment of freight to terminal pairs based on the sum of total circuitry, empty miles associated with the geographical separation of pick-ups and deliveries, and the empty miles associated with terminal imbalances.

The 40 scenarios to account for all combinations of assignment heuristic (two alternatives), allowable circuits per load (five possible values) and allowable dray length (four possible values). The heuristics have been applied to 44,546 shipments and 43 terminals.

3.4. OR applications for operational problems

Justice (1996) deals with the problem of a drayage company ensuring sufficient chassis available at terminals in order to meet demand. Trailer chassis are pooled over a set of terminals on both sides of a long haul corridor. Reallocation can take place by truck within a region or by train between regions. The objective is to determine when, where, how many and by what means (truck–train) chassis are redistributed and to develop a planning model with minimum cost solutions for daily decision support. The problem is mathematically formulated as a classic bi-directional time based (network) transportation problem. Own software has been developed to calculate solutions using five steps: (1) find planning horizon, (2) determine train arrivals and departures, (3) obtain chassis supply and demand; (4) obtain unit costs with each supply–demand pair; (5) optimise for minimum cost solution through simplex based iterations. The model is applied to eight interconnected terminals across the USA, three of them located in the same region. One scheduled double-stack train arrivals and departures per day at each terminal. There is a known number of supplies and demand for chassis at each terminal in a given period of time.

Wang and Regan (2002) are concerned with the problem of a single drayage company and how they can move within a local area with one or more terminals as many loads as possible at the least cost. The objective is to minimise the total cost of providing service to loads within their time constraints. Only pick-up time windows (and not delivery time windows) are considered in order to simplify the process. The fleet size is fixed. New assignments, trailer repositioning moves and reassigned moves due to traffic, dock and intermodal facility delays are added to the system as the day progresses. The problem is solved several times within the day and more information becomes available. Each loaded trip is treated as a node. In this way the problem may be viewed as an asymmetric multiple travelling salesman problem with time window constraints.

4. Terminal operator: OR problems and applications

4.1. General problem statement

Transhipment is inherent to intermodal transport. As Fig. 1 shows, load units are transhipped at least twice between truck and train or barge; once at a beginning terminal and once at an end terminal. This type of transhipment is called road–rail or road–barge exchange. A road–rail or road–barge terminal consists of:

- a road gate, where trucks enter and leave the terminal,
- a rail or barge gate, where trains or barges enter and leave the terminal,

- a storage area for longer term storage of load units (24 hours or more),
- a buffer area, for temporary storage of load units,
- lifting equipment to unload and load trains, trucks and barges,
- storage and transport equipment.

Operations at such beginning or end terminals are globally as follows. When a loaded truck arrives it joins the queue at the gate where administrative handling takes place. Trucks arrive randomly at the terminal. The truck enters the terminal and lines up either for the storage area or near the rail or barge siding for direct transhipment to a train or barge. Next, the truck lines up to deliver a second load unit or to pick-up one or two new load units from the storage, buffer or directly from the train or barge. The latter transaction also applies to an empty truck after it has passed the gate. Trains and barges arrive and depart according to a fixed timetable. They can enter the terminal when tracks or berths are empty respectively. Trains and barges are first unloaded and then reloaded. Load units are transhipped from the train or barge either to the buffer, directly to a truck, to the storage areas or onto an internal transport device that brings the load unit to a remote storage area.

Depending on the consolidation concept (see Bontekoning and Kreutzberger, 1999) applied in the rail or barge haul, additional intermediate transhipment can take place. This is called rail–rail or barge–barge exchange. The infrastructure of rail–rail or barge–barge terminals is rather similar to that of road–rail and road–barge terminals, but the layout of the terminals can differ. In addition, such terminals do not necessarily have facilities to handle trucks. Rail–rail terminals are a new concept and are still in the planning stage. Traditionally, shunting of rail-wagons is applied to rail–rail exchange. Barge–barge exchange also still solely exists on the drawing board.

Operations at a rail–rail terminal involve the exchange of load units between a group of related trains. When trains are in the terminal at the same time—this is called simultaneous exchange—cranes pick up load units from one train and drop them directly off onto another train, or onto the buffer or other transport system. In the latter two situations, the load unit is picked up by crane which puts back onto train. When trains are not at the terminal at the same time but have an exchange correlation to each other, load units are sequentially exchanged via the buffer or storage area (see Bontekoning and Kreutzberger, 1999, 2001, for detailed descriptions of infrastructure and operations of rail–rail terminals and barge–barge terminals). Containers, swap bodies, trailers or complete trucks need to be handled at a terminal. Equipment used at the terminal must suit these load units. Terminals can apply different transhipment techniques, layouts, operational strategies, dimensions, etc. The features of an optimal functioning terminal depends on demand volume and type of exchange (road–rail, road–barge, rail–rail or barge–barge, or sometimes rail–barge). Shunting is a quite different operation, which consists of the receiving of trains and an inbound inspection of rail wagons, classification (sorting) of rail wagons by pushing wagons over a shunting hill into a yard with switch and classification tracks before trains are assembled and permitted to depart.

Exchange leads to an increase in chain lead time and total transport costs. Consequently, exchange operations need to be efficient and fast. Terminal operators have to make decisions on how to meet demand requirements. One factor specific to the strategic level is the design of the terminal itself. Decisions regarding design include the type and number of equipment used and type and capacity of load unit storage facilities, the way in which operations are carried out at the terminal and how the equipment is used, and the layout of the terminal. At the tactical level a terminal operator decides on the required capacity levels of equipment and labour, and on the redesign of operational routines and layout structures. Finally, the terminal operator needs to make operational level decisions regarding capacity and scheduling. One may even add a real-time level, where relatively detailed control decisions can be made regarding automatic equipment, for example, which route to take for an AGV, or to reschedule capacity to work, based on real-time data, such as equipment brake-downs or delays.

4.2. OR applications for strategic problems

Ferreira and Sigut (1995) deal with the question "Which terminal design performs better, a conventional road–rail terminal or the RoadRailer concept?" The RoadRailer technology uses trailers with the capability of being hauled on road as well as on a rail. Although normal road trailers are also carried on rail there is a significant difference: the bi-modal trailers are not carried on rail wagons. Bi-modal trailers are connected by detachable bogies, which roll on the tracks. The two concepts are compared for one variable, the speed of operation expressed as a mean loading finish time. For both terminal concepts a discrete event simulation model has been constructed with Simview. Both types of operations have been divided into four activities. For each terminal concept the service time for each of the four activities has been determined based on 120 observations. Experiments were run for 30 RoadRailer trailers and 30 containers respectively.

Meyer (1998) faces the design problem of a rail–rail terminal in a hub-and-spoke system for the exchange of a maximum of six trains at a time. In addition, the terminal should be able to handle a limited volume of rail–road exchanges. Dynamic computer simulation (SIMPRO) with Petri-net application and animation was developed to determine required capacity for cranes and internal transport systems, and the most efficient arrival pattern of trains. Results were obtained from simulation runs with the arrival of one group of 6 trains for the time period 2:30 to 3:42 and 62 load units per train.

4.3. OR applications for tactical problems

Voges et al. (1994) analyse operating procedures for an existing terminal. They focus on three questions. How should the dispatcher at the gate and the crane drivers make their decisions on how to continue the process? If a certain crane strategy would result in favourable waiting times for trucks, are the crane drivers able to follow it without computer support? When would it be useful to abandon the strategy and to work intuitively? The value of measurement is the waiting times of trucks (mean value and standard deviation). A combination of Human Integrated Simulation (HIS) and pure computer simulation based on a Petri-net model has been applied. This combined approach takes both objective influences and human factors into account. It is a game approach: real human beings play the role of operators at the terminal. The simulation has been applied to a terminal with two cranes serving four tracks, two truck track and one storage lane.

Real data were recorded between 5 a.m. and 9 p.m. The simulation was constructed for a the time period between 5 a.m. and 2 p.m. All experiments were done with the same distribution of arrival times and other characteristics of real data.

Bostel and Dejax (1998) want to optimise the initial loading allocation of containers on trains in beginning terminals and their reloading after transhipment at a rail–rail terminal. The objective is to minimise transfers at rail–rail terminals as well as the use and volume of the handling equipment. The dimensions of the rail–rail terminal are: four tracks, seven storage lanes (42 places per row), nine bridge cranes and one device to move load unit from one bridge crane to another. The problem is considered as a minimum cost multi-commodity network flow problem with binary variables, which are hard to solve optimally. Therefore, the problem is broken down into four parts, applying heuristic methodology and linear programming:

1. the problem of optimisation of container transfers with imposed initial loading,
2. the problem of joint optimisation of the initial loading and the reloading area,
3. both of the above problems with unlimited storage capacity,
4. both of the above problems with limited storage capacity.

This approach has been applied to four different data sets with each set of 31 trains divided into nine groups of three or four trains, comprising a total of 1,000 containers.

Kemper and Fischer (2000) model the transfer of containers in a rail–road terminal with a single crane. In this terminal a storage yard with a capacity of 40 containers is used to buffer containers which need to be unloaded from a truck or train, but cannot be directly reloaded for further transportation. The objective of the modelling is to determine quality of service in terms of waiting times and utilisation of resources, especially with regard to the dimensions of the waiting areas for incoming trucks. Other characteristics of the problem are: trucks carry two load units or none; trains supply and pick up 20 containers in each instance; and the arrival process of trucks is a Poisson process. Stochastic Petri-nets are used as modelling language and results are obtained numerically by computation of the steady state distribution of an associated Markov chain.

5. OR problems facing network operators

5.1. General problem statement

The network operator faces decision problems concerning infrastructure planning (strategic level), service schedules and pricing of services (tactical level) and daily operations of the services (operational level). The majority of the studies related to intermodal infrastructure decisions deal with the interconnectivity of modes in order to achieve intermodal transport chains and the location of intermodal terminals. In order to achieve decision support models for these kinds of problems the former uni-modal (road/rail/inland waterway) network models have to be connected to each other and a transfer of freight has to be made possible at the nodes (terminals). We see a difference in the type of stakeholder that is involved in these type of decisions between the European and North American papers, especially with respect to railway infrastructure. In Europe, it is often the government dealing with railway infrastructure and terminal location decisions, while in North America it is the railway operator's responsibility. However, both European and North American governments are mostly concerned with questions regarding the interconnectivity of the modes, the impact of a capacity increase and the effects of price/cost increases/decreases on the use of the different infrastructure networks. The search for optimal locations is often done by the private sector although the government may also be interested to know which kind of investment to support.

At the tactical level the network operator has to determine which services he will offer. Unlike traditional rail and barge, fixed schedules are used in intermodal transport rail and barge systems. In traditional rail haul networks, trains run only when full and excessive classification at intermediate nodes takes place. In traditional (bulk) barge transport barges travel on demand. Hence, the network operator has to fix a service schedule for several months to a year in advance. This suggests two things.

Firstly, he has to decide which consolidation network (point-to-point, line, hub-and-spoke or collection–distribution) to use. This must take into account how to consolidate flows (Fig. 2), the routing of the trains or barges through the network and which nodes to serve. Point-to-point consolidation of flows is the easiest way to organise services and it has appeared to be feasible. Therefore network operators most often apply this system. In a point-to-point consolidation network, trains or barges respectively travel between two terminals, without intermediate stops. However, this method of consolidation requires large volumes in order to offer a daily service. Still little is known about the feasibility of other consolidation

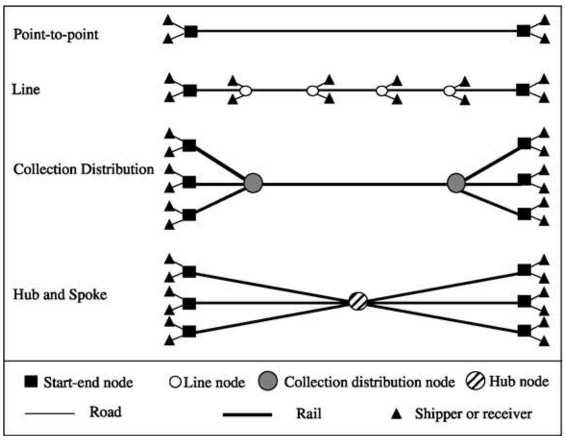

Fig. 2. Four basic consolidation networks (*Source:* Adjusted from Bontekoning and Kreutzberger, 1999).

forms such as line, hub-and-spoke and collection–distribution models. A few researchers started to investigate the relationships between consolidation model, frequency, train length and costs.

Secondly, the network operator has to decide which production model to use, i.e. how to operate the trains or barges. It involves decisions about frequency of service, train length, allocation of equipment to routes and capacity planning of equipment. Publications show that only intermodal rail transport has been investigated with respect to network operator decisions at the tactical level. The intermodal rail system to be modelled is a fairly complicated one, and is quite distinct from the traditional rail carload service which has been the subject of much modelling in the last decade or so (see e.g. Assad, 1980). A substantial difference is the interaction between a large variety of both trailers/containers and railcars, and the multiple level of service classes which must be considered. In addition, pricing strategy decisions have to be considered at the tactical planning level. Pricing the intermodal transport product is a complicated issue. The intermodal tariff is based on several tariffs determined by several actors related to the various parts of the intermodal transport chain. Intermodal agents, railroad, terminal and drayage managers must each have their own tariff (pricing) strategy. Tariff determination itself can be very complicated. It requires an accurate cost calculation and insight in the market situation. To estimate his negotiating power, each actor must be aware of his market position and the cost structure of other actors. The review shows a few studies that estimate costs for individual parts of the intermodal chain. In Section 5.3 we discuss pricing of the rail haul part in the intermodal chain and in Section 3.3 pricing of drayage has been discussed.

The operational level involves the day-to-day management decisions about the load order of trains and barges, redistribution of railcars or push barges, and load units (fleet management). A typical management problem in intermodal rail/road transport is the assignment of a set of trailers and containers to the available flatcars that can move this equipment. In the European context the problem focuses on assign containers and swap-bodies to the different flatcars. The problem is quite complex as different types of flatcars exist, and there are many types of trailers and containers.

5.2. OR applications for strategic problems

The network operator faces making decisions about the development of the intermodal network, which includes decisions regarding investment in links and nodes (terminals). In the past, spatial price equilibrium models and network models have been developed for network infrastructure planning. The network approach stems from mathematical graph theory and practical experience which was gained from analysing urban road traffic and transit systems. The equilibrium approach stems from the study of spatially separated markets and the concepts of spatial and economic equilibrium. Most models, however, have been developed for one mode only, and cannot deal with intermodal flows. Crainic et al. (1990), Loureiro (1994), Jourquin et al. (1999), and Southworth and Peterson (2000) have developed 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.

In order to adapt the traditional network models, more importance is given to the nodes, connecting two or three networks. Crainic et al. (1990) extended uni-modal network models by adding links connecting the various modes in order to derive an intermodal network model. The development of geographic information system (GIS) technology yields new possibilities for the modelling of large multi-modal freight networks as Jourquin et al. (1999) and Southworth and Peterson (2000) show. GIS is in their work based on the concept of the 'virtual network', that, in a systematic way, breaks down all the successive operations involved in multi-modal transport and includes a detailed analysis of all costs. The generalised costs are minimised according to the shortest path algorithm. By simulation with different parameter values the software can provide indicators such as tons per km, total distance, total cost, duration and capacity utilisation of nodes and links.

Loureiro (1994) presents a multi-commodity multi-modal network model to be used as a planning tool for determining investment priorities for intercity freight networks. The model is designed to select the best set of investment options for a multi-modal regional network, given a limited investment budget. The main component of the model incorporates the solution of a non-linear bi-level multi-modal network design problem formulated to choose investments. It's main aim is to minimise the transportation costs incurred by users (shippers) and the environmental impacts caused by the use of less efficient modes of transportation for moving freight. Investment options to be considered by the model may involve the addition of new physical links to the network, the improvement of existing links (i.e. an increase of capacity), and the location of intermodal transfer facilities at specified nodes of the network.

Also for the location of terminals multi-modal networks were developed. These network models are used in combination with origin/destination matrices, wherein the existing and/or the future transportation flows are given. The traffic flows are assigned to the network by a generalised cost function. The possible routes/modes through which the freight will pass are determined by the costs (in terms of price, time, congestion phenomena or other performance criteria) that are assigned to the routes/modes. The intersections of the networks are seen as possible locations for the intermodal terminals. Using this method the problem is reduced to a discrete (although sometimes large) set of possible locations. A general problem when searching for an optimal location is the choice of which objectives to optimise. Examples of these objectives are: minimising transportation costs on the links, maximising terminal profitability, maximising modal shift from road to intermodal means, minimising total transport costs and minimising drayage distance and costs.

Network models for terminal location decisions have been applied by Rutten (1995), Arnold and Thomas (1999), Groothedde and Tavasszy (1999), Van Duin and Van Ham (2001). Rutten's (1995) objective was to find terminal locations that will attract sufficient freight to run daily trains to and from the terminal. He studies the effect of adding terminals to the network on the performance of existing terminals and of the overall intermodal network. Van Duin and Van Ham (2001) identify optimal locations while incorporating the perspectives and objectives of shippers, terminal operators, agents, consignees and carriers. For each level, an appropriate model is developed. At the strategic level, a linear programming model searches the optimal locations for intermodal terminals. This model takes account of the existing terminals in the Netherlands and can then be used in order to find some new prospective sites (or areas). In the next level a definite location in the prospective area is found by means of a financial analysis. Here the location of large potential customers is one of the most decisive factors. On the lowest level or operational level a discrete event simulation model of the terminal gives the possibility to simulate the working of the terminal. This model can be used to make decisions on the amount of cranes, amount of employees, etc. Arnold and Thomas (1999) minimise total transport costs in order to find the optimal location for intermodal rail/road terminals in Belgium with the use of a linear programming model. Groothedde and Tavasszy (1999) minimise generalised and external costs in order to find the optimal location of intermodal rail/road terminals. They used the simulated annealing technique. In order to find the optimal locations of terminals, terminals are added to the network randomly and, for each changed network configuration, the total generalised (from a user viewpoint) and external costs (from a systems viewpoint) are calculated in order to find the optimal locations.

Meinert et al. (1998) investigate the location of a new rail terminal in a specific region in which three rail terminals are already located. They specifically consider the impact of the location of the new terminal on drayage length and time. In order to accomplish this, they developed a discrete event simulation tool which provides the ability to address individual rail terminal design considerations such as handling capacity required, regional design considerations related to terminal location and trucking distances, and demand distribution over time. A significant feature of this simulator is that, rather than modelling only the operation of the terminal, it also models the drayage to and from regional destinations.

Another kind of location analysis exists when a number of definite location sites are found but have to be evaluated in order to select the most optimal site. Such location analysis allows more criteria, as more specific information becomes available. Macharis and Verbeke (1999) examined four potential sites for new barge terminals in Belgium. They followed a multi-criteria analysis approach, wherefore a hierarchy of criteria was built. These criteria represent the aims of the actors who are involved, namely the users of the terminal, the operators/investors and the community as a whole. The evaluation of the terminal projects was executed by the PROMETHEE-method (Preference Ranking Organization METHod for Enrichment Evaluations), a multi-criteria analysis method developed by Brans (1982) and extended for group decisions by Macharis et al. (1998).

5.3. OR applications for tactical problems

Janič et al. (1999), Jourquin et al. (1999), and Newman and Yano (2000a,b) compare different consolidation networks with each other. Janič et al. (1999) evaluates 23 state-of-the-art complex consolidation networks in Europe by means of a multi-criteria analysis in order to assess the most promising layouts. The simple additive weighting (SAW) method is used here. A set of evaluation criteria for network performances has been defined and quantified for the selected cases. Jourquin et al. (1999) show how a network model and GIS can be used to model different consolidation networks and their impact on the distribution of flows over the available infrastructure and modalities (see also Section 5.2). Newman and Yano (2000a,b) developed a model for determining a train schedule with both direct and indirect (i.e. via a hub) trains and the allocation of containers to any of these trains for a one to two week time horizon. Given container demands differentiated by origin, destination, arrival date at origin, and due date, the objective is to determine a train schedule and container shipment plan to minimise the total cost while meeting delivery punctuality requirements and adhering to train capacity restrictions. The problem is formulated as an integer program with a new decomposition procedure to find near-optimal solutions. Thirty problems with one hub, three to six origins and destinations, and with different container demand patterns and cost structures have been generated. Newman and Yano succeeded in obtaining optimal solutions for problems with three or four origins and destinations using their decomposition procedure. However, larger problems could not be solved.

Nozick and Morlok (1997) developed a model to plan different rail haul operations simultaneously: incorporating such variables as train length, motive power allocations, fleet allocations to various traffic lanes, distribution of empty rail cars and trailers, routing policies of traffic, work allocation and estimation for terminals; but not including train schedules and consolidation networks (point-to-point) as variables. In their study they use fixed examples of these factors. The model aims at a planning period from one week to a month. The complexity of the models is due to the fact that it encompasses all elements of the rail haul operations. Integer linear program is used, which is computationally difficult to solve. Therefore, a heuristic procedure was developed which provides near-optimal solutions, to within 1% of the known optimal solution to the 'relaxed' (non-integer) problem.

Yan et al. (1995) focus on cost calculations regarding cost-related pricing strategies for the rail haul. They notice that the usual cost calculations are taking an average empty movement cost to determine the system incremental costs. In doing this, they ignore the opportunity costs of using the conveyances on movements and on the availability of train capacity on a daily basis. A mathematical program was written to address this problem incorporating an efficient algorithm for approximating reduced cost. The algorithm combines the use of Langrangian Relaxation with a minimum cost flow algorithm and a shortest path algorithm.

Tsai (1994) constructed two models to determine optimal price and level of service for intermodal transport in competition with truck transport. The models consider the whole intermodal chain, contrary to Yan et al who only considered the rail haul. This problem has a number of features which distinguishes it from typical pricing problems in other industries and services, because of the special technology and economies of transportation interconnection with headhauls and backhauls (usually unbalanced flows). The models take into account not only carriers' pricing behaviour (supply side) but also shippers' mode choice behaviour (demand side). Solutions to find equilibrium are pursued by a mathematical programming approach. The objective of the models is to optimise intermodal profit within some constraints, which include shippers' mode choice behaviour, non-negativity of carrier price and cargo amounts and intermodal volume constraints.

5.4. OR applications for operational problems

Feo and González-Velarde (1995) are using an optimisation procedure to tackle the problem of assigning highway trailers to railcar hitches ('piggyback' transport). The problem is treated as a set-covering problem. The idea is to "cover" all of the trailers with a set of railcars at minimum cost. With the use of an integer-linear programming model, solved by a branch and bound code, a solution can be found within a reasonable timescale. Additionally, a heuristic for the Trailer Assignment Problem is developed. In the greedy randomised adaptive search procedure (GRASP) a feasible assignment is contrived. This incorporates a selection of the most difficult to use railcars available together with the most difficult to assign trailers. In doing this, the least compatible and most problematic equipment is considered first.

Powell and Carvalho (1998) take this a step further. The previous model ignores the importance the choice of destination has in the aim to fully utilise the equipment. For example, if the container is going to a destination that pools a large number of trailers, flatcars are favoured that can carry trailers. Network information such as this can influence the decisions made by the local terminal. In the paper of Powell and Carvalho, the model is set up to aid a local terminal manager to determine how to assign several trailers and containers to a flatcar, governed by complex assignment rules. The problem, in this case, is formulated as a logistics queuing problem, being a new formulation of the dynamic fleet management problem. Furthermore, the problem of deciding how to move flatcars is typically coupled with the problem of planning the repositioning of empty boxes owned by the railroad (ROE). The management of ROE is a classic dynamic fleet management problem. The object is to maximise returns. This is assessed by calculating the proportion of fulfilled requests (i.e. placing empty boxes where they are needed) against the costs of achieving this. For a review on dynamic models for fleet management see Powell et al. (1995) and Dejax and Crainic (1987) where special attention is given to the management of empty flows. In order to solve the coupled problems, two dynamic assignment models were developed: one assigns trailers to customer requests and the other assigns flatcars to boxes. A linear programming formulation is used. The LQN approach can be used in a real-time setting.

In Chih et al. (1990) a decision support system called RAILS is set up to optimally manage intermodal double-stack trains. This assignment problem is even more complex than the mono-problem as there are also height constraints and choices between different modes have to be made. The system is to be used on a daily basis to ensure the correct size of each train and to generate rail car repositioning instructions. The planning horizon is two weeks and takes the local and global system needs into consideration. The problem is formulated as a non-linear multi-commodity integer network flow problem. As the problem is NP hard, a heuristic method had to be developed in order to be able to solve the network optimisation problem within a reasonable time (13 minutes). The heuristic breaks the solution procedures into several components and uses well developed traffic assignment and capacitated network transhipment optimisation algorithms to solve the problem. In Chih and van Dyke (1987) a similar approach is followed for the distribution of the fleet's empty trailers and/or containers.

6. OR problems facing intermodal operators

6.1. General problem statement

Intermodal operators organise the transportation of shipments on behalf of shippers. Intermodal operators buy the services offered by drayage, terminal and network operators. Decisions made by intermodal operators deal with route and service choices in existing intermodal networks. This type of decision, by its nature, is an operational one, because it concerns the assignment of shipments to routes and carriers. Intermodal routing is rather more complex than the routing problems of road haulage. In road haulage, the minimum cost path algorithm was most commonly used in order to find the route most suited to meeting the objective of the company, for example, the least costly or less time consuming route. A large variety of combinations of transportation modes is possible. In this case the routing decision is a mere modal choice problem for specific trajectories between beginning and end points, taking into account specific freight volumes and, possibly, specific time constraints. The three papers that will be discussed are concerned with the route choice for one shipment (container/flatcar/trailer). Any cost reduction for groups of shipments has not been taken into account. The cost functions are quite comprehensive. Also time/service constraints have been considered.

6.2. OR applications for operational problems

Boardman et al. (1997) built a decision support system in order to assist the user in selecting the least cost combination of transportation modes (truck, rail, air, barge) between a given origin and a corresponding destination. GIS software assists in visualising the region to be analysed. Using a K-shortest path algorithm model, both cost and time are minimised. As an indicator of cost the average transportation rates for each transportation mode is used. This is a simplification of reality as there would normally be a cost difference between long haul truck and short haul drayage costs. Also the cost of the inventory is not taken into account.

Barnhart and Ratliff (1993) pay special attention to these types of costs. Their models are focused on the rail/road combinations compared to uni-modal road transport. For a 'piggyback' service the minimum cost routing for each shipment is sought taking into consideration the total transportation cost (the sum of the drayage costs and the line rail haul costs) and the inventory costs (the sum of the in-transit inventory costs and the cost of additional stock resulting from the transit time). Two types of decision settings are identified depending on who owns the equipment and who is providing the service. In the first group the railroad charges the shipper on a 'per trailer' basis and, in the second, the shipper is charged on a 'per flatcar' basis. In the first case, the minimum cost routings are achieved with a shortest path finding procedure. In the second case, the optimal routings are determined with a matching or b-matching algorithm. These latter models are also able to incorporate non-monetary constraints such as schedule requirements and flatcar configuration. Indeed, many more modal choice variables have to be taken into account.

A very good example of this is given in the paper of Min (1991). This study focuses on the multi-objective nature of the modal choice decision. A chance-constrained goal programming (GP) model is constructed that best combines different modes of transportation and best maintains a continuous flow of products during intermodal transfer. The GP model is a multiple objective technique for determining solutions. This technique satisfies multiple goals and their associated risks and uncertainties. The comparison between the transportation modes is based on the costs, market coverage, average length of haul, equipment capacity, speed, availability, reliability and damage risk. The most service-cost-effective transportation mode is sought for each segment in the international distribution channel.

7. Conclusions

Intermodal transport research is an emerging research field. It is still in a pre-paradigmatic phase, but is evolving and will soon be regarded as a legitimate branch of scientific research. For several reasons modelling intermodal freight transport is more complex than modelling uni-modal systems. Firstly, it involves at least two modes which have their own specific characteristics with respect to infrastructure and transport units. Secondly, the control of the system has to be organised by a set of actors all of whom responsible for only a part of the whole. Thirdly, complexity of assignment problems is increased due to the large variety of load units (type and size), rail wagons and trailer chassis.

A review has been executed in order to investigate how and which operational research techniques have been applied to support the specific decisions that have to be made by the different decision makers in the intermodal transport system. From the review we can conclude the following:

- Operations research has been used for various strategic, tactical and operational problems of the network operator, the terminal operator, the drayage operator and the intermodal operator. Almost all types of intermodal problems are covered, however, the number of studies in each category is still very limited.
- A large variety of operations research techniques has been applied.
- Due to the type of problems and/or size and complexity of problems, existing OR techniques have been further developed and new heuristics have emerged. However, further development of OR techniques and heuristics is needed in order to develop applications that provide good solutions to intermodal problems.
- Due to the limited number of studies, comparison of OR techniques and heuristics are still to be carried out. These are needed in order to determine which techniques or heuristics best suits which type of intermodal problem.
- Some intermodal problems have yet to be tackled by OR techniques. To mention a few: the optimal number of terminals in a network, location decisions for hub-terminals, optimal consolidation strategy, allocation of capacity to jobs and scheduling of jobs in terminals, determining truck and chassis fleet size in drayage operations.

To conclude, intermodal freight transport provides OR scientists with an interesting and challenging field of study. There is still much work to be done and much to discover on the subject.

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Appendix A. Specification of search strategy

Sources

Channels	Time period covered
Databases	
–Transport[1]	1988–2002
Social Sciences Citation Index[2]	1988–2002
Dissertation Abstracts[3]	1995–2002
Electronic Transport Journals	
–Journal of Transport Economics and Policy[4]	1997–2002
–Transport Policy[5]	1995–2002
Library of Delft University of Technology[6]	All years
Research contacts	1995–2002
Own research	1995–2002
Cited references in retrieved literature	Not applicable

[1] Transport database. Produced by: Organisation for Economic Co-operation and Development (OECD), Transportation Research Board (TRB) and European Conference of Ministers of Transport (ECMT) (information provided by International Union of Railways).

[2] Social Sciences Citation Index. Produced by: Institute for Scientific Information (ISI), Philadelphia. See http://www.isinet.com/isi/.

[3] Dissertation Abstracts. Produced by UMI/ Data Courier. See http://www.umi.com/ab-about.shtml.

[4] Journal of Transport Economics and Policy. See http://www.swetsnet.nl/link/access_db?issn = 00225258.

[5] Library of Delft University of Technology. See http://delfi.library.tudelft.nl:4505/ALEPH/-/start/tud01.

[6] Transport Policy. See http://www.sciencedirect.com [publications] [transport policy].

Search keys
Intermodal AND freight
Intermodal service
Combined transport
Drayage
Pre- and end-haulage
Rail–truck
Rail–road
Intermodal terminal
Transhipment
Hub–terminal
Hub and spoke
Barge

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