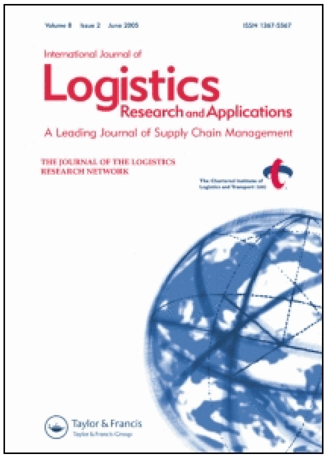

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Evaluating road-rail intermodal transport services - a heuristic approach

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Evaluating road–rail intermodal transport services – a heuristic approach

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The aim of this paper is to develop an approach for evaluating intermodal transport solutions based on a road–rail interconnection that incorporates mathematical and heuristic procedures and with regard to data collection challenges and difficulties. The approach is dedicated to the design of a road–rail intermodal transport system taking into consideration goods flow opportunities and requirements. The approach incorporates a model that focuses on evaluating road–rail intermodal transport services that maximises the attraction of goods flows within a particular frame of restrictions. As a result, it can help identify potential relations and routes for road–rail intermodal transport services by evaluating the potential outcome of alternative solutions. Empirical research shows that there are substantial savings to be made by designing road–rail intermodal transport solutions in a systematic way with regard to opportunities and requirements by shippers and the structure of goods flows.

Keywords: intermodal transport; scheduling and routing; transport system; transport system design; train shuttle; transport modelling

1. Introduction

Trends such as globalisation, production patterns (Das and Handfield 1997, Búrca 1997, O'Donnel 1997) and urbanisation (Scott and Storper 2003) have driven structural and geographical changes and constitute great logistics challenges. This is especially true at the regional level, where business activities in many peripheral regions have decreased (Barry 1997, Kotler *et al.* 1999). Parallel to decreased business activities, goods flows decrease, challenging the transportation system and the logistics effectiveness and competitiveness of firms in the region (McKinnon 1997). The efficiency of a transportation system is dependent on a number of factors related to the nature and structure of goods flows, *e.g.* size, type, balance and variation over time. The status of factors greatly affects the opportunities of different transport services, for example a well-balanced flow of goods facilitates high utilisation of transport resources, *e.g.* a train shuttle with a fixed number of wagons. To enable development of effective transport solutions, approaches for efficient evaluation of alternative solutions are vital. This creates a demand for decision support tools or approaches

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that can collect and manage data of goods flows effectively to achieve quick and valid analyses of transport solutions. Such an approach would be valuable to determine the outcome of different logistics strategies, *e.g.* choice of transport modes, design of transport service, timetable, etc. This paper deals with the development of an approach for evaluating intermodal transport solutions based on road–rail transport services that are practically useful for shippers, operators and policy-makers. Road–rail intermodal transport service in this paper, refers to a door-to-door transport solution of an intermodal load unit, with combined road and rail transport.

When evaluating both the competitiveness of possible transport solutions and the development of transport models, especially for intermodal transport design, complexity is often a problem. Approaches for evaluating transport solutions often require extensive and comprehensive data, which is difficult to access and collect efficiently. There are a number of systematic approaches for the evaluation of road–rail intermodal transport systems (*e.g.* Jensen 1990, Jensen *et al.* 2001, Jensen 2004, Jensen *et al.* 2006, Nozick and Morlok 1997, Crainic 1998, Assad 1977). The approaches are often based on large entities of a transport system. They are often useful from a visionary perspective and are sometimes necessary to envision the possibilities and opportunities from a macro perspective, such as the outcome of different policy measures. An approach that enables flexible evaluations of relations between origins and destinations would be of greater value for individual actors at the regional (micro/meso) level if it were founded on relevant data provided by regional actors. Seen from the perspective of an intermodal transport operator and/or a public actor with an interest in intermodal transport development, it is of value that an evaluation approach includes the steps from practical data collection to the final evaluation of possible solutions. This imposes a demand for practical use for the target actors, such as shippers, operators, etc. The aim in this paper is to construct a practical approach, where the core is a model for scheduling and routing based on heuristics procedures.

2. Research problem and research aim

This paper derives from a project and a problem of locating a road–rail intermodal transport terminal for improving logistics in a region. The approach presented here evaluates alternative solutions for road–rail intermodal transportation to and from a region. It is based upon a common platform of system boundaries and characteristics. The point of departure is a goods-flow relation. It is assumed that goods flows originate at nodes, *i.e.* terminals in a hub-and-spoke system. In the hub-and-spoke system, one terminal is selected as a hub for a functional logistics geographical area, referred to as a region in this paper. The hub is where the majority of goods flows to and from workplaces in the region passed through (Woxenius 1998). The developed approach focuses on the transport connection between nodes. The common situation is that the transport to and from the terminal as well as between terminals is operated by road transport, *i.e.* direct road traffic. The approach developed here evaluates an alternative traffic solution, where the transport between terminals is operated by train, and the transport to and from terminals is operated in the same way as in the case of direct road traffic, *i.e.* an intermodal traffic solution as illustrated in the spatial model in Figure 1.

In reality, a functional logistics area can have many terminals operated by different logistics service providers. For the sake of validity, only the connections between nodes are compared. If the present system has more than one terminal, it is assumed that the present system is operated by only one hub and with the same location as the road–rail intermodal terminal. Since the studied regions did not have road–rail intermodal terminals, the most favourable hub-and-spoke location was chosen in connection with costs and intra-regional lead-times. Since both the direct system and the road–rail transport system serve the same functional logistics area, this location

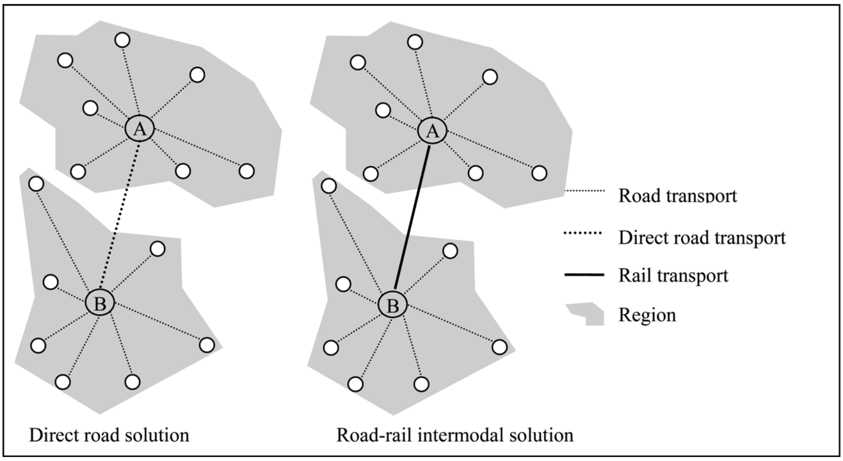


Figure 1. Different traffic solutions for transport.

is a shared optimal location in terms of costs, environmental impact and intra-regional lead-times.

The approach presented in this paper focuses on evaluating the connection between nodes. It incorporates heuristic procedures and regards data collection challenges and difficulties. To enable a valid evaluation, the approach needs to contain estimations of decisive goal variables related to transportation activities. Many variables constitute the performance of a transport activity. In this paper, three dimensions are regarded superior: costs, environmental impact and lead-time. With regard to quality aspects of time, *i.e.* time restrictions on lead-times, the approach evaluates variables of cost efficiency and environmental impact. Cost efficiency is measured in terms of 'cost of running the service' and the difference in cost efficiency between services is measured as a difference in total cost of running the service, given the same output of transported units. Environmental impact is measured in terms of energy consumption (kWh) and emission: CO_2, HC, SO, Nox, CO, PM. According to Newman and Yano (2000), few models have the aim of optimising the transport service in terms of cost efficiency, environmental impact in connection with the combination of capacity and timetabling. Since timetabling strongly affects the performance in costs and environmental impact of road–rail intermodal transports, it is a central part of the research aim: to develop an approach for evaluating cost efficiency and environmental impact of road–rail intermodal transport services based on a heuristic model for scheduling and routing.

The aim is explored given a set of variables and restrictions. The input variables are: origins, destinations, goods flows of workplaces, speed limits and time restrictions of shippers. The model is allowed to construct any alternative solution with regard to time restrictions set by shippers. The alternative solutions must be able to deliver the goods at the receiving terminal at the same time as the direct road solution does. However, the road–rail intermodal solution may arrive in the morning, if the direct road solution arrives during the night. This exception is based upon the assumption that goods arriving at night are not distributed to the end customer until the morning. Both traffic solutions follow the specific speed restriction set by the infrastructure and the capacity in terms of speed and loading of the transport vehicle. Besides, they comply with the same set of restrictions and boundaries.

The research aim was explored for two regional transportation systems, *i.e.* Skaraborg and Sjuhärad located in western Sweden (see Figure 2 below). The approach is applied to and tested on the above-mentioned regions.

Figure 2. Map of Sweden.

The ambition was to consider as many of the important logistics prerequisites and preferences affecting a road–rail intermodal transport service as possible. The main challenges of the case study of Skaraborg and Sjuhärad were the trade-offs between the level and amount of data, and the accuracy of the analysis. The approach was developed with regard to a pragmatic balance between data collection opportunities and competent analyses. To get a better understanding of the complexity of a transportation system, the next section deals with the structure and nature of transportation systems.

3. Methodological aspects

There are numerous conceptual models of transportation systems (Manheim 1979, OECD 1992, Sjöstedt 1994, Jensen 1990, Coyle *et al.* 2000) defining different but much of the same levels, layers and components. Similarly to OECD (1992) conceptual model of the transportation system, this paper focuses on three components (cf. Wandel and Ruijgrok 1993, Hansen 2001), *i.e.* material flows, resources (infrastructure and transport resources) and transport operations. The common denominator is that shippers create a demand for movements: a material flow. Resources such as vehicles and infrastructure fulfil necessary prerequisites for movement: a supply. Movements, *i.e.* the interconnection between material flow and resource, are conducted at the components of operations. In sum, demand arises, supply exists and interconnection is created. The supply and demand components of the transportation system constitute fixed entities, whereas the modelling approach focuses on the interconnection between supply and demand. The analogy is illustrated in Figure 3 below.

This structure facilitates transferability of the transportation system into the modelling phase. Material flows and resources are treated as inputs to the model, operations concern behaviour and system-dynamics that are transferable to heuristics in the model. When transferred into a model, analyses in goal variables are possible, in this paper: cost estimates and environmental impact. Furthermore, the solutions produced by the model should comply with the same restrictions as in the case of direct road service. Goods transported with a train shuttle service should arrive at the destination at the same time of day (a.m. 08–12, p.m. 12–18) as a direct road service would besides the exception when the direct road service arrives in the night time (18–08), then the train shuttle service may arrive as late as 8.00 a.m.

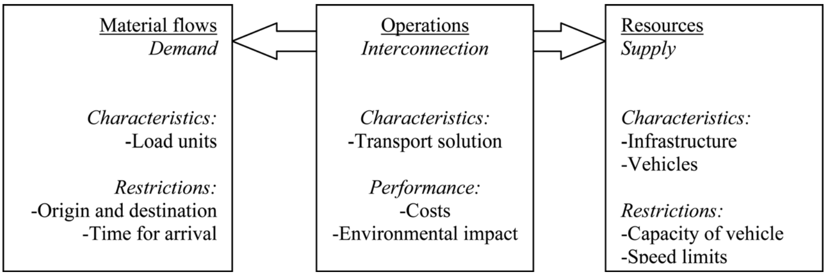


Figure 3. Three-component model of the logistics system.

Produced solutions are believed to have the best environmental design when as many goods as possible are transferred from direct road haulage to intermodal road–rail transport (*i.e.* max. volume) or when the utilisation of train resources is maximised (*i.e.* maximum volume balance). Volume is defined as the sum of flows in both directions, *i.e.* to and from a region. The transportation system costs are believed to be minimised for designs where either the utilisation of train resources is maximised (maximum volume balance) or when the designs attract the most goods volumes (maximum volumes). The use of 'volume' and 'volume of balance' as goal variables for determining and evaluating train schedules of road–rail intermodal transport services is believed to be suitable based on the following assumptions:

1. The volume of goods flows affects the cost efficiency of a road–rail intermodal transport service. Apart from that, increased goods flows have a positive influence on the profitability of the road–rail intermodal transport service, *i.e.* the marginal revenue generally exceeds the marginal costs.
2. The nature of goods affects the handling operations by its requirements on equipments and procedures. Goods that can be transported in load units, such as ISO-containers, can be effectively handled and transported by train. A high density of bulky, temperature sensitive, dangerous and fragile goods is negatively associated with the handling efficiency of intermodal road–rail transport.
3. The balance of goods flow in relation to its size in volume affects cost efficiency. Relations with goods flows that are relatively balanced generally have a positive influence on the cost efficiency of the road–rail intermodal transport service.
4. Variation over time affects the cost efficiency of the intermodal road–rail service. The smaller the variation over time the greater the opportunity for cost efficiency of the intermodal road–rail service. This assumption is increasingly relevant when the time-schedule and the capacity of a transport service are fixed over a longer period of time.

The heuristics developed in this paper are based upon these assumptions. When contemplating these assumptions, it is obvious that they are limitations to the approach. The logic formulated in the assumptions is based upon a situation where a road–rail intermodal transport service is supposed to compete with a direct road service. If road–rail intermodal transport services already exist on the studied relations, the formulated logic is distorted and the developed approach invalid. However, this paper concerns regions where the existence of competing road–rail intermodal services on the same relations is unlikely, since the volume of goods flows is hardly sufficient for more than one cost efficient road–rail intermodal service, if any. For the regions of Skaraborg and Sjuhärad, there are no road–rail intermodal transport services.

The effect of the formulated assumptions is that the model can construct timetables that are robust against cost estimated parameters that are otherwise required when calculating timetables as part of a cost-minimising objective function. This is especially valuable from a practical perspective, since external factors, although they affect the profitability of the solution, do not change the structure of the solution, *i.e.* the timetable.

3.1. *Transport modelling techniques*

This section discusses assumptions and model heuristics in relation to models developed for similar purposes. Models of transport systems can differ greatly in structure and technique. There are many approaches for goods transport modelling not only in isolation but also in combination (cf. D'Este 2001). Previous models developed within transportation research can be categorised according to the techniques of optimisation, simulation and network modelling. Freight transportation has been an interesting area for operations research for a long time (*e.g.* Crainic 1998, Crainic and Laporte 1997, Joborn 2001, Magnanti and Wong 1984, Ball *et al.* 1995). Transportation systems are complex and can easily include hundreds of variables. Therefore, models often include both optimisation techniques and heuristics methods and principles to make them solvable (*e.g.* Gualda and Murgel 2000, Assad 1977), one drawback is, of course, that the models cannot guarantee optimal solutions. Heuristics uses rules of thumb to produce 'smart guesses'. Not all alternatives and solutions are examined. However, it is assumed with this method, using rules of thumb, that certain solutions and alternatives are not relevant to examine further. Heuristics does not guarantee an optimal solution, but it can find near optimums and in turn gain a lot in computational cost, since heuristic solutions are normally relatively fast (Reeves 1993, Flodén 2005). One very common example of heuristics in freight transport is the travelling salesman problem.

In a simulation model, the structure is based on appropriate causal links. The model is intended to imitate the structure and behaviour of a real-world system (Banks 1998, Flodén 2005). As the model behaves similarly to reality, it is possible to conduct experiments that otherwise would be costly, or in some cases even impossible, to examine in a real-world situation (Pegden *et al.* 1995). Thus, simulation models are suitable for answering 'what-if' questions.

Network models structure the transportation system based on a set of nodes, *e.g.* terminals connected by links, *e.g.* road and rail infrastructure. Links are associated with a number of allowed transfer links that contain restrictions on the allowed mode of transport, vehicle type, etc. The link has certain characteristics such as costs, delay functions, distance, etc. An objective function combined with restrictions on the network enables an optimisation of the objective function. Network models are often used for strategic planning of transportation systems (c.f. Guélat *et al.* 1990, Nozick and Morlok 1997, Jourquin and Beuthe 1996, Bergqvist and Tornberg 2005, Crainic 1998).

To cope with the aim of this paper, the modelling techniques used are simulation and heuristics based optimisation. The approach developed is best described as heuristic and here simulation plays an important role as visualisation tool and for introducing random variation. Figure 4 illustrates the steps included in the approach.

The simulation technique is used for introducing randomness in the model, *i.e.* stochastic simulation (Gordon 1969). Simulation is also used for testing and evaluating the solution suggested by the heuristics approach (*i.e.* scheduling and routing). The approach developed focuses on the problem of scheduling and routing. There are several models and approaches developed for such problems, *e.g.* Dall'Orto *et al.* (2006), Equi *et al.* (1996) Haghani (1989), Crainic *et al.* (1984) and Keaton (1992). However, none of the models are meant to produce a detailed schedule of the railroad, they produce only train frequencies for a representative day, which provides a rough framework for creating a schedule (Gorman 1998). Caprara *et al.* (2006) give one example of a timetabling algorithm based on an exogenous timetable demand from transport operators' requests for paths on given railway lines. Train paths are given priority, and ideal timetable, with ideal

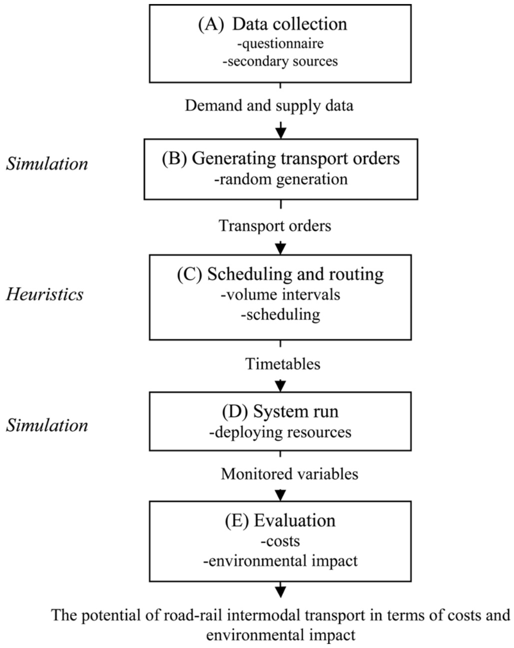


Figure 4. The main steps incorporated into the approach.

departures and arrival times, and tolerances within which they can be ‘moved’. The optimal allocation is found by maximising the difference between the scheduled trains and a cost penalty function that considers deviations from the ideal timetable under certain constrains on, *e.g.* line and station capacity, signalling and maintenance operations. However, the algorithm requires that the operator specifies ‘ideal’ timetables and estimates tolerances within which they can be ‘moved’ Caprara *et al.* (2006) assume that train operators know their ideal timetable, hence, that the timetable demand is given exogenously. It is common that the configuration of the network train schedule is regarded as exogenously given (c.f. Nozick and Morlok 1997). Nozick and Morlok (1997) state that many, if not most, of intermodal freight trains are scheduled, considering needs of major customers. Furthermore, major changes must consider interactions with other (non-intermodal) trains (Nozick and Morlok 1997). This paper concerns train shuttle services that have routes with just a few stops. The services are constructed to work in isolation from other services, hence, the arguments stated by Nozick and Morlok (1997) are not applicable and it is of value to identify train schedules that are favourable, *i.e.* timetable demand is not exogenous.

Few models have the aim of optimising the design of the service in terms of capacity combined with specific timetabling by means of optimising goods volumes or goods flow balance of the train services (Newman and Yano 2000).

4. Creating interconnection between supply and demand

4.1. *Data collection*

4.1.1. *Demand Data*

The prerequisite for evaluating transport solutions is access to necessary data. The method for collecting data was a questionnaire with the purpose of describing the regional logistics system.

It contained 57 questions covering outgoing and incoming goods flows that describe the logistics prerequisites of the workplace, *e.g.* volume of goods flows, destinations, variation over time, type of goods, present use of intermodal transport, etc. The questionnaire was distributed to actors in the regions that were believed to have substantial goods flows that could be coordinated and consolidated with other goods. The reason for this was that a road–rail intermodal solution would benefit from large quantities that were possible to co-load and thus coordinate (assumption 1).

The target population consisted of persons responsible for logistics in workplaces with five or more employees in industries with the SNI-code (branch code) 15–37 (manufacturers) and 51 (wholesaling); since these industries are believed to have the largest goods flows of interest for road–rail intermodal transport solutions. The industries were chosen in such a manner that duplicates of goods flows are minimised. If, for example, retailers would be included, there would be a risk of goods flow duplets between retailers and wholesalers. The choice between wholesalers and retailers was depended on the fact that the sample of wholesalers is smaller in numbers and that wholesalers often take care of the interregional flows for retailers.

The response-rate for the population in Skaraborg was 22% and 24.1% for Sjuhärad. Interestingly, the coverage in terms of goods flow volumes was 70% and 70.3%, respectively. This analysis was mainly possible due to the construction of regression models for the response sector, where the dependent variable was annual goods flow and the independent variable was number of employees. A random sampling analysis of non-responding workplaces (sample of 20) showed that there was no divergent relationship between the dependent and the independent variable for the missing workplace population. One very probable reason for the results obtained by the regression models is that large workplaces have more insight into their logistics situation and that they are more willing to participate by filling out and returning a questionnaire. As a comparison, it is worth mentioning that the response rate for workplaces with 100–199 employees was 36.7% in Skaraborg and 40.0% in Sjuhärad, whereas the response rate for workplaces with 5–9 employees was 17.4% in Skaraborg and 13.9% in Sjuhärad.

To ensure good reliability in relation to the response-rate (about 70%) in terms of goods flow coverage, the developed evaluation and design approach was only tested for workplaces that participated in the 'mapping' questionnaire. With data being as complete, comprehensive and representative as possible, an approach for evaluating and designing road–rail intermodal transport solution could be applied.

4.1.2. *Supply Data*

Supply data mainly consist of previous research and reports concerning different modes of transport and their cost-structures and environmental effects. Dual-sources data was used as much as possible to improve reliability. The main data concerning costs and cost related factors was retrieved from SIKA (2005), Enarsson (1998), Mariterm (2001). Cost related data consist of fuel consumption, taxes, purchase values, salaries, etc. Environmental effects are sources from operators, manufacturers and updated information from environmental networks such as NTM, *i.e.* The Network for Transport and Environment (www.ntm.a.se). Emissions and energy consumption constitute the environmental impact on which evaluations are made.

4.1.3. *Output*

The main output is the information concerning goods flows retrieved from the questionnaire. Based on assumption (2), goods flows that are dangerous, bulky and sensitive to variations or travelling by air are not included in the information and used in the next step in the approach. Goods-flow information from the questionnaire is structured according to origin and destination, size and variation over time (intervals of day, week and year). In the questionnaire, goods flows are divided into intervals of 'time of day'; 00–06, 06–10, 10–14, 14–18, 18–24. The weekly distribution of goods flows is in units of days of the week, *i.e.* Monday, Tuesday, etc. The yearly distribution is divided into months, *i.e.* January, February, etc. Hence, information is structured according to origin/destination, time variations and in number of load units (preferably TEU). Since the demand component concerns both outgoing and incoming goods flows to the region, data concerning incoming goods must be transferred, so it will have the same structure as the outgoing goods flows. The time related information available concerning incoming goods flows refers to arrival of the goods. This information has to be transformed in order to know the latest departure of the transport in order to fulfil time restrictions, *i.e.* time of arrival must be translated into latest time of departure. This was done by calculating at what time the departure of the train service was at the latest to meet the time restrictions. Consequently, outgoing goods flow requirements on time had to be transformed into train service departure requirements, since the goods flows currently used direct road service. The logic applied was that the train had to arrive no later than a direct road service would, with one exception. If the direct road service would arrive later than 18.00, then the train service was allowed to arrive early the next morning, *i.e.* 8 a.m. This was based on the assumption that goods transported by direct road service are usually not distributed to the end customer until the morning, even if it arrives at the terminal during the night. Now, goods flows are based upon the time restrictions set by the respondents and the mode of transport. The final output is structured as goods volume distributions over time for outgoing and incoming goods to and from the region given a specific inter-regional transport relation. The flowchart below (Figure 5) illustrates the logical sequence of the *Data collection* step.

4.2. *Generating transport orders*

Besides defining the route to travel, this step also decomposes data into transport orders, *i.e.* number of load units, with specific arrival and latest departure time based on the goods volumes over time distributions from the previous step. However, in order for the model to construct robust solutions, it is necessary to subject the data to variation. Hence, the transport orders are randomly picked based on goods volume over time distributions, provided by the previous step. After its generation, the transport order time interval is adjusted to suit the transport- and handling times. Transport times are calculated based on speed limits. The transport orders are generated in the software package *Planimate*™. Figure 6 illustrates the transport orders for outgoing goods volumes in TEU from Skaraborg to Port of Göteborg during one year.

4.2.1. *Output*

This step creates random transport orders that are based on the data retrieved by the respondents in the region. Thus, the data transferred into the next step is realistic, but also unpredictable, since it is subjected to randomness, an important prerequisite for the verification of the design

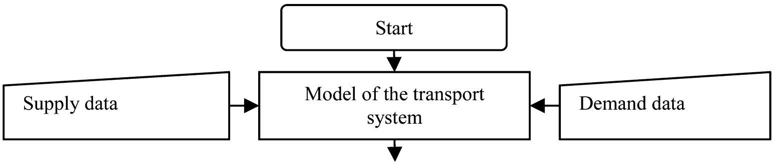


Figure 5. Flowchart of the *Data Collection step.*

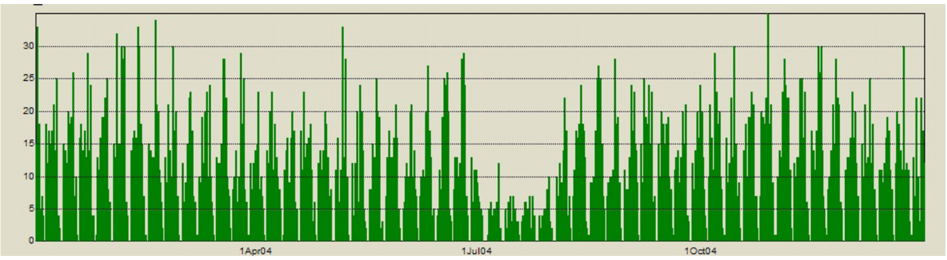


Figure 6. Transport orders from Skaraborg to Port of Göteborg.

solution and to ensure robustness. The flowchart below (Figure 7) illustrates the logical sequence of *Generating transport orders.*

4.3. *Scheduling and routing*

This step of the approach aims at constructing solutions that produce large amounts of goods flows on the train shuttle service with a defined route, and at the same time achieving a good balance of goods flows. Based on the four assumptions defined in the methodological section, at least one of the produced solutions should be near optimum, given certain prerequisites. The prerequisites are:

1. Initially, only one train set and departure per day.
2. Departure times must be the same every specific day of the week during a year, *e.g.* Mondays. (The reason is that the service should be easy to use and plan to)
3. The shuttle train needs to be back before the next departure
4. The train set is fixed, *i.e.* number of wagons.

The volume over time distributions consists of many aggregated transport orders. Every transport order has an interval with a given arrival and departure time. Since every relation has many transport orders, it is likely that transport order intervals have time overlaps. The model cannot manage overlapping intervals without some modifications to the transport order intervals. If there

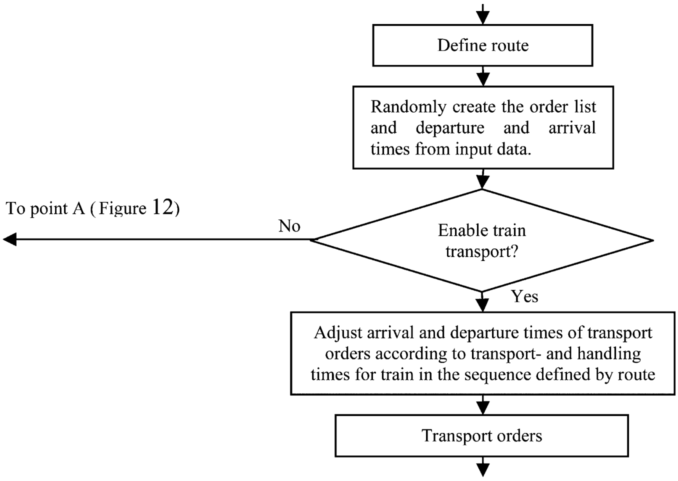


Figure 7. Flowchart of the *Generating transport orders* step.

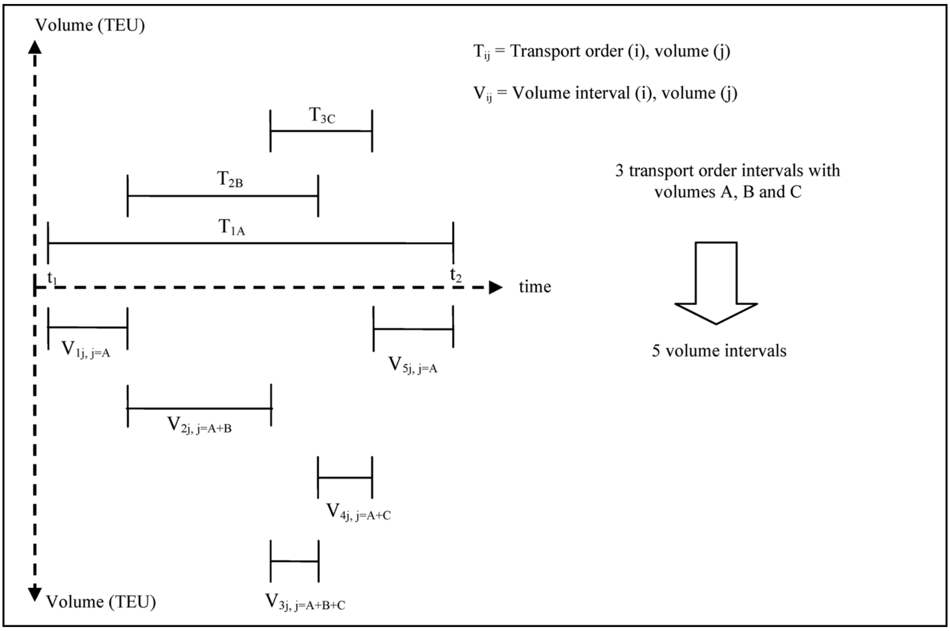


Figure 8. Transforming transport order intervals into volume intervals.

are overlapping transport order intervals, the model constructs new intervals with a fixed volume (number of TEUs), so that all intervals have a given volume during its duration. The new intervals constructed based on this transformation are termed ‘volume intervals’. The transformation process is illustrated in Figure 8.

A transport order (*e.g.* T_{1A}) has one direction and contains a certain volume in terms of TEU (A) and the limits of the interval are determined by the time that the order arrives at the terminal (t_1) and the latest necessary departure time (t_2) from terminal for the train shuttle service to obtain the same service in terms of time restrictions as a direct road service.

Since the defined route can contain many origins and destinations, volume intervals have to be adjusted according to waiting times. Transport- and handling times have been considered earlier in the process in the generation of transport orders. Waiting times are, however, central in this step. Waiting time is the time when the train is idle at a terminal. The model allows the user to examine the outcome of different waiting times at different terminals on the defined route. More importantly, the model can suggest waiting times that improve the schedule of the train shuttle service, either to increase goods flows or achieve a better balance of goods flows.

The algorithm in the model does not optimise, it uses heuristics to reach a near optimum solution, one reason being that a simulation technique like ‘Monte Carlo’ would have to consider vast amounts of possible solutions and would be very inefficient and require a large computer capacity. The possibility of adjusting volume intervals by inserting waiting times at each terminal makes the number of possible solutions for the train shuttle service vast.[1]

The algorithm tries to minimise the number of possible solutions that have to be evaluated. This is done by evaluating solutions based upon the volume intervals of each link in the defined route. For the defined route 1–2–3–4–3–2–1, there are 12 links, *e.g.* 1–2, 1–4, etc. Each link represents a goods relation with associated volume intervals. For volume intervals of different links, *e.g.* 1–4, to be comparative, they are ‘moved’ backwards in accordance with the required transport time of that link, *i.e.* the time to travel 1–2–3–4. After this adjustment, an initial solution A is identified based on the aggregated volume of each link in the defined route and without any necessary waiting times. After the initial solution, the search for alternative solutions begins by looking for

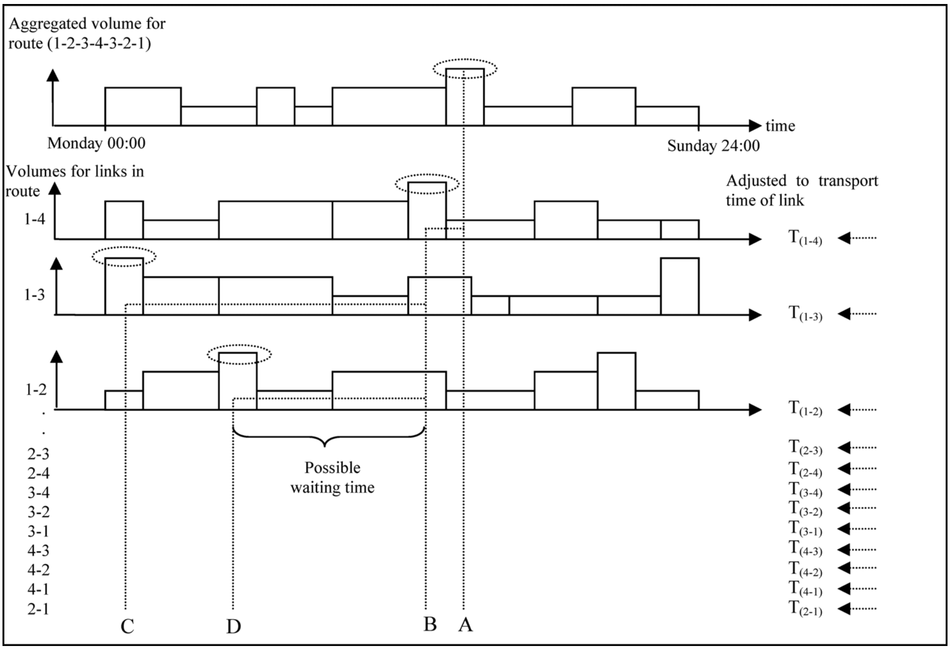


Figure 9. Illustration of scheduling logic.

the highest peak at the first individual link (in this case, the link from terminal 1 to terminal 4). The search is stepwise and introduces waiting times in a time-ascending order, *i.e.* A to B to D to C as illustrated in Figure 9. Each solution A, B, C and D represents a timetable for the train shuttle service.

The figure above shows possible departures for the train shuttle service (*i.e.* A, B, C, and D). The situation A is based on the total amount of goods with adjustment to the corresponding transport times at each link (*e.g.* 1–4, 1–2, etc.). Solutions B, C and D incorporate waiting times along the defined route, whereas A is a solution going between 1–2–3–4–3–2–1, waiting only for the handling of goods. The method is similar to that of 'Tabu search', where a search starts with a feasible solution and attempts to improve the solution in a stepwise manner, where previously visited solutions are regarded as 'tabu' (cf. Glover 1990, Glover 1986).

The analogy in the model is to find alternative departure times, *i.e.* that the departure times are scheduled earlier but fulfil the time requirements of arrival. The condition for this is that waiting times are introduced into the defined route. The model examines possible waiting times between different volume intervals if the terminal of origin of the superior volume interval is later in the sequence of the defined route than the destination terminal of the subordinate volume interval, see Figure 10.

If this condition of waiting time is not fulfilled, the intervals will not close in on each other when waiting times are introduced. The volume intervals will only move in either solidarity or the volume intervals themselves will shrink without closing in on each other as a consequence of changed time restrictions on first and latest departure time. This discussion is the reason for the formulated condition 'Is superior volume interval origin terminal later in the order of route sequence than the destination node for the subordinate order?' in Figure 11.

The models developed by Gorman (1998) and Newman and Yano (2000) have a similar analogy. However, they do not consider the possibility of introducing voluntary waiting times. The approach developed by Canadian Pacific Railway and MultiModal Applied Systems (Ireland *et al.* 2004)

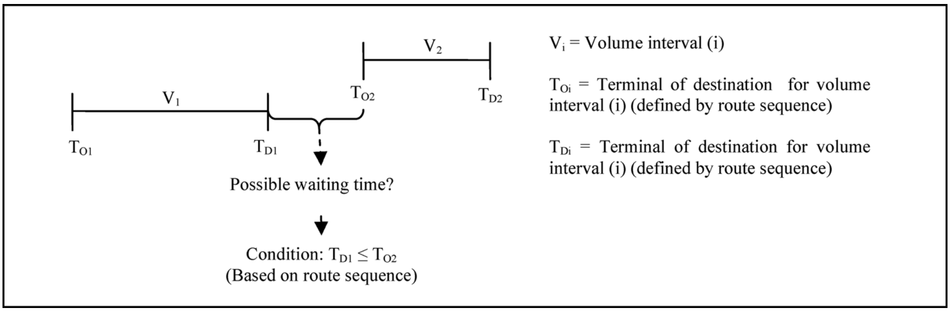


Figure 10. Illustration of waiting time condition.

considers time adjustments to be made to the timetable. However, the adjustments require manual judgements.

The heuristics used for the model developed here produces waiting time in terms of intervals of minimum and maximum waiting times that enable a combination of different volume intervals. The model calculates a number of such solutions, (given by the user), going backwards in time, based on volume intervals as illustrated in the figure above. The numbers of calculations are, thus, determined by the desired number of suggested solutions that the user wants the model to produce. Three types of solutions (S_i) exist with associated volumes (V_i) and balance of goods (B_i):

1. S_1: When the volume (V_1) of the goods flows is maximized (1st rule of timetabling)
2. S_2: When the balance of goods (B_2) is maximized (2nd rule of timetabling)
3. S_j: Intermediate combinations (3rd rule of timetabling), all solutions were $V_j \geq V_2$ and $B_j \geq B_1$.

Besides possible optimal solutions when goods flow volumes are maximised (1st rule of timetabling) or when the goods volume balance is maximised (2nd rule of timetabling), there might be optimal solutions that produce neither largest volume nor best balance. To cope with such problems, the heuristics also examines solutions according to intermediate combinations (3rd rule of timetabling). Intermediate solutions (S_j) must have a volume (V_j) that is greater than or equal to the volume (V_2) for the solution (S_2) based on the 2nd rule of timetabling and also a balanced volume (B_j) greater than or equal to the balanced volume (B_1) for the solution (S_1) based on the 1st rule of timetabling. S_j fulfils the following conditions: $V_j \geq V_2$ for S_2 and $B_j \geq B_1$ for S_1. Hence, the smaller difference in volume between S_1 and S_2 the smaller the possibility of optimal intermediate solutions. The difference between S_1 and S_2 is, thus, a good indication of the total amount of solutions that should be evaluated to ensure that a near optimum is located. This rule ensures that all possible optimal solutions are examined. However, empirical results from the simulations made in the regions of Skaraborg and Sjuhärad were always solutions that maximised volume or balance or both. To illustrate this, four scatter plots of possible solutions for different train shuttles services (A: Sjuhärad – Göteborg, B: Skaraborg – Malmö and C: Skaraborg – Stockholm, D: Göteborg – Sjuhärad – Småland – Blekinge), given a defined route and a given departure day, *e.g.* Monday, are displayed in Table 1. Solutions based on the first and second rules of timetabling are labeled S_1 and S_2, respectively.

One possible explanation why there were no optimal intermediate solutions in the case of Skaraborg and Sjuhärad is that volume intervals are, in fact, aggregated material flows of workplaces of a large transportation system, *i.e.* a region. Since many of the workplaces have similar variations over time in their goods flows, peak periods are amplified and optimal solutions are likely to consist of either maximum goods flow volumes (1st rule of timetabling) or maximised balanced goods volume (2nd rule of timetabling). Since the heuristics seeks solutions that combine

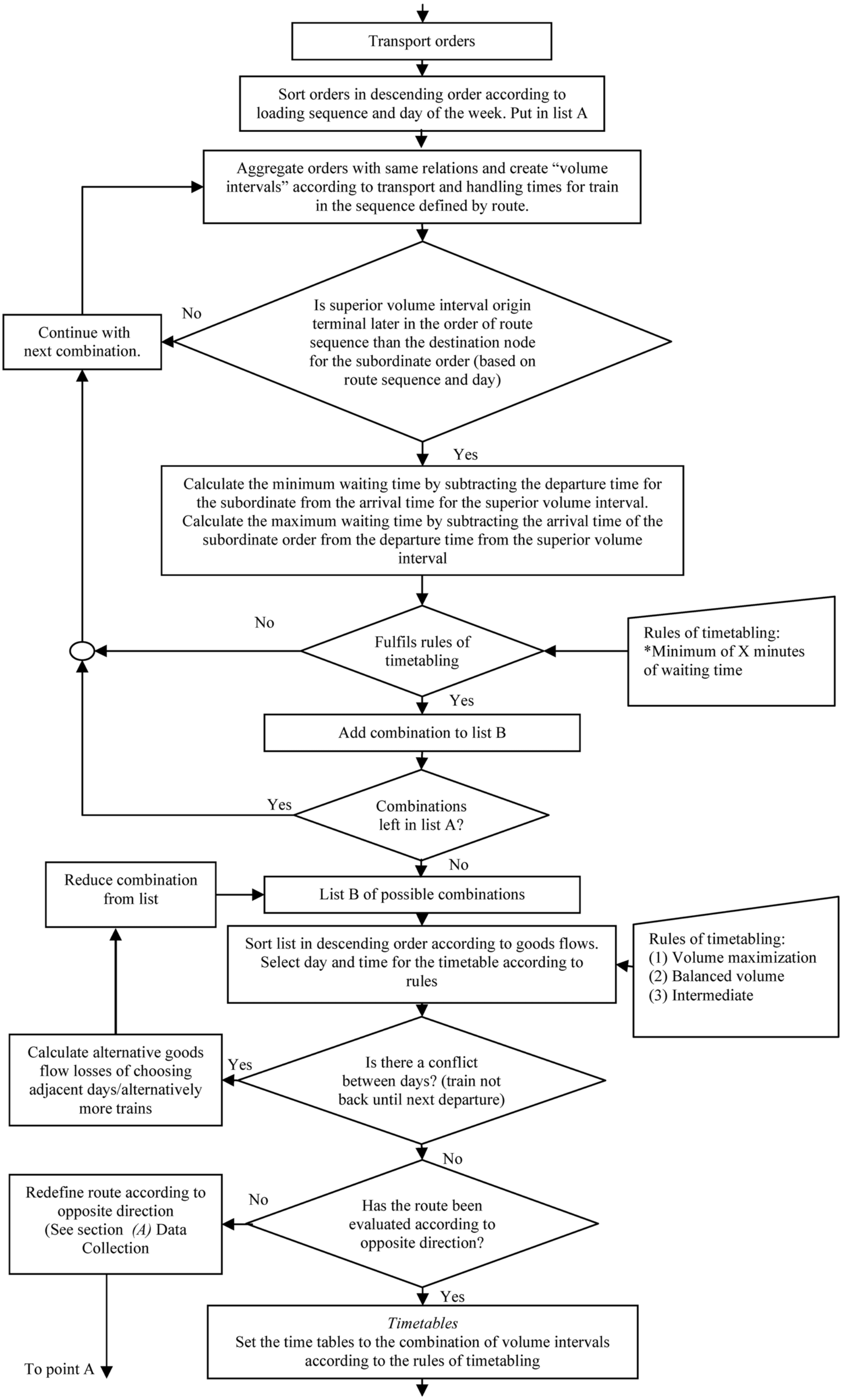
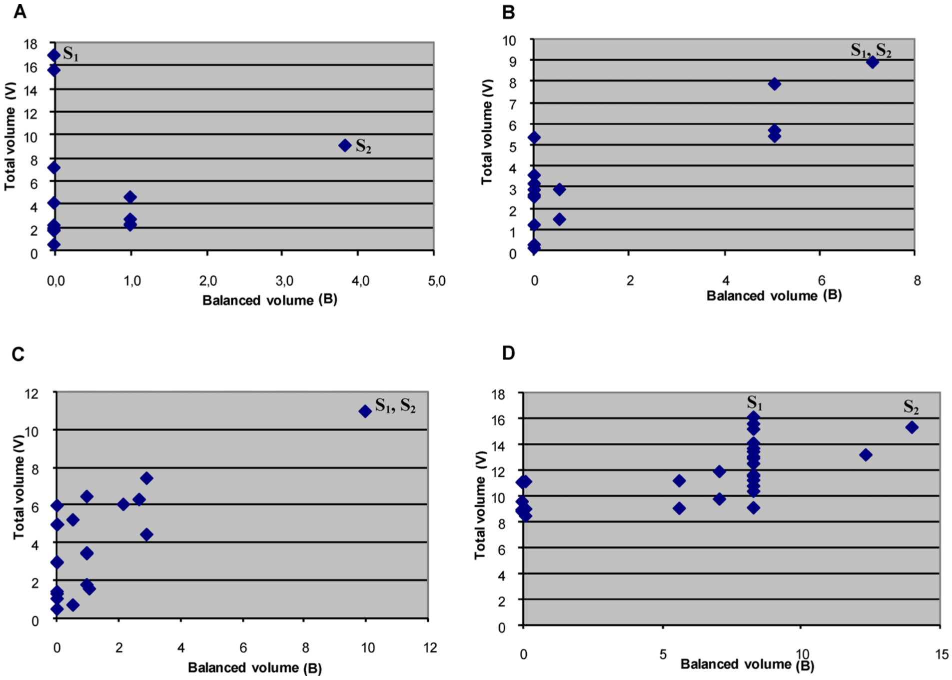


Figure 11. Flowchart of the *Scheduling and routing step.*

Table 1. Scatter plots or possible solutions.



peak periods, the solutions that combine peaks that either maximise goods volume or balanced goods volume are likely to be the optimal solutions, since there are few other peak periods in that specific time period, *e.g.* during a day. Since the model focuses on timetabling one day at the time, the number of peak periods is limited.

Altogether, this means that the number of solutions examined by the model is much smaller than in the case of the Monte Carlo simulation.

Summarised, the number of solutions to be evaluated is limited and manageable. However, if the problem would increase and there is a demand for limiting the number of solutions to be evaluated, and decrease the computing hardware requirements and/or speed up computing times, a restriction on the algorithms seeking in time could be introduced. One way of restricting seeking is to limit the maximal waiting time allowed at a given point. Furthermore, maximal total transport time for the defined route cycle and number of departures per week are other methods to restrict seeking and reduce the number of solutions to be evaluated.

4.3.1. *Redefining routes*

If the model suggests negative waiting times, this is an indication that the defined route can be redefined in a favourable way. The defined route can be either redefined, so that it will run in the opposite direction, but it can also be an indication that it would be favourable to include waiting times that would have the effect of an overnight (next day) shift of orders. An 'until the following day' waiting time would enable the train to pick up more goods from the following day's orders, if possible according to time restriction. However, this possibility is closed in the model for three reasons: (1) The algorithm would automatically 'jump' to the next peak if no restrictions were to be put on maximum waiting time. This could lead to a situation where the first constructed departure would take large volumes into account, whereas the following departures would be much smaller in volumes, hence, an unbalanced solution would arise that would lead to a demand for an unnecessarily large capacity in the train design. (2) From an operator's perspective, there is an advantage of having the train returned as quickly as possible to enable better flexibility and robustness of the system, given that the origin of the defined route is the market in which the operator has his platform for operations. (3) There is a possibility that the total waiting time would be very long and incompatible with the ambition to keep waiting times within reasonable limits, maybe due to work conditions, etc.

4.3.2. *Output*

The output from the scheduling step is a timetable for the train shuttle service including departures, stops and waiting times. The next step, *i.e.* system run, is based upon the timetable defined here. The flowchart in Figure 11 illustrates the logical sequence of *Scheduling and routing*.

4.4. ***System run***

The purpose of the system run is to simulate the train shuttle service according to the timetable and the list of orders. The train shuttle service is set based upon some restrictions:

- Capacity (when goods volume exceeds train capacity it is transported by direct road service from terminal to terminal)
- FIFO (First In First Out: the goods that arrive at the terminal first is also transhipped to the train first, and unloaded at the final destination first).

Other rules that could be useful to apply are heuristics on the trade-off between volume of goods and train capacity, if the volume is greater than the train capacity. Another possible rule would be that goods with the largest travelling distance are chosen before goods with short distances. However, the model presented here does not consider these aspects. Hence, no order related judgements are made concerning priority of transport orders, except the order in which they are loaded, *i.e.* FIFO.

4.4.1. *Output*

After the system run, the model monitored a number of variables related to the resources required that later are input into the step for evaluating cost efficiency of the design solutions, quality performance and environmental impact. The monitored variables are:

1. Direct road service:
   - Number of transported units by direct road service
   - Number of cycles (definition: origin-destination-origin) made by direct road service
   - Number of load units handled at every stop by direct road service
   - Average lead-time for the direct road service
   - Average utilisation rate for the direct road service
2. Train shuttle service
   - Number of transported units by train shuttle service
   - Number of cycles made by train shuttle service
   - Number of load units handled at every stop by train shuttle service
   - Average lead-time for the train shuttle service
   - Average utilisation rate for the train shuttle service

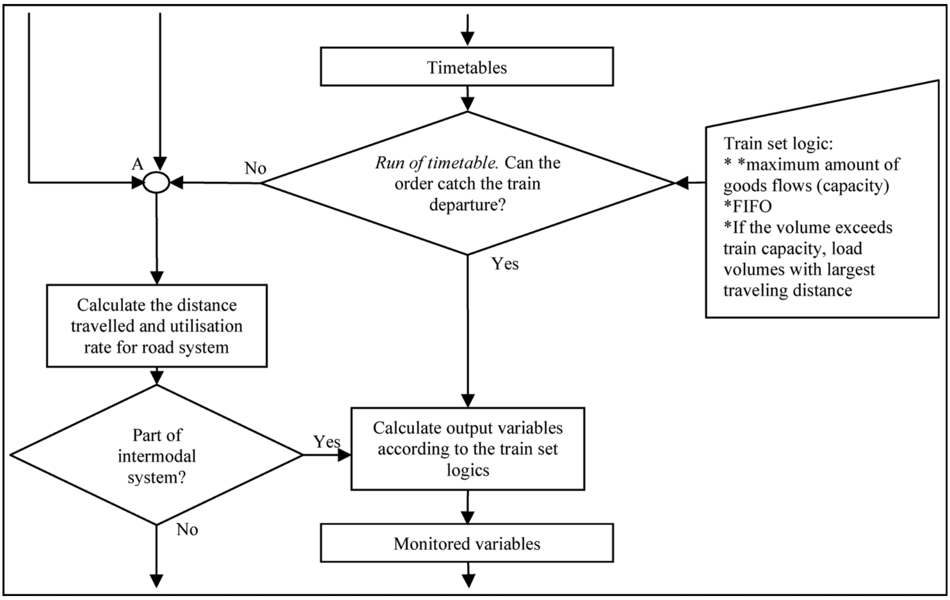


Figure 12. Flowchart of the *system run* step.

From these variables it is possible to estimate cost efficiency and environmental impact in the next step. The flowchart in Figure 12 illustrates the logical sequence of *System run*.

4.5. *Evaluation*

The flow chart displays the case in which, at the end, the potentials in costs and external effects are estimated. Cost calculations are made in *Excel*™ based on the data retrieved for the *supply component* of the *data collection* step (see Figure 5).

Costs may be an impossible platform for comparison if the transportation system currently in use utilises transport modes and solutions besides direct road. The limitation of the model is that it is best suited for comparing road–rail intermodal transport solutions with a current system that is based on a direct road service. In the situation of many different transport modes, an aggregated comparison for, *e.g.* a region in terms of market shares of transport modes may be useful as a measurement and estimation of the 'potential'. This requires implementing the assumption that an increase in market share for specific modes is positively associated with environmental impact and/or costs.

4.5.1. *Output*

The results are displayed in terms of possible cost savings and decrease of environmental impact compared with a system based entirely on direct road service. The results are presented in the following variables for each service (direct road service and road–rail intermodal transport service): Cost of service, Energy use (kWh), CO_2, HC, SO, Nox, CO and PM emissions. When comparing the two systems, the variables indicate a potential, in terms of cost savings and decreased environmental impact, associated with the implementation of the designed road–rail transport solution. The flowchart in Figure 13 illustrates the logical sequence of *Evaluation*.

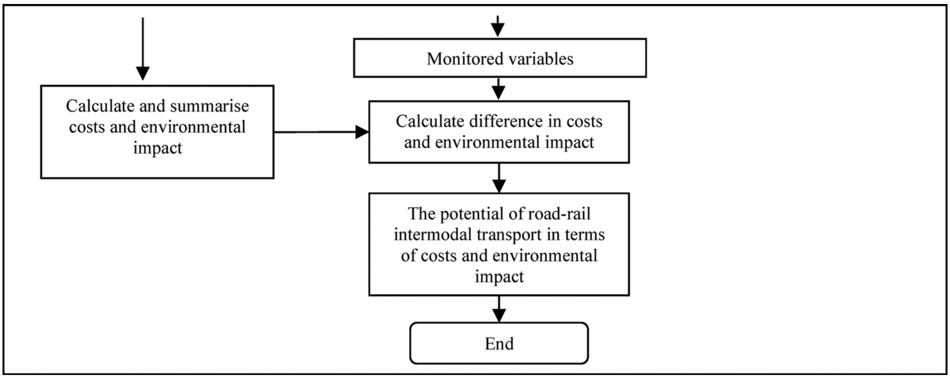


Figure 13. Flowchart of the *Evaluation* step.

5. Empirical findings

To test and validate the approach, two case studies have been conducted, *i.e.* Skaraborg and Sjuhärad. The region of Skaraborg showed the largest potential (in the Sjuhärad case, no individual train shuttle service showed cost efficiency compared with direct road) and the results from that case study will be presented here, in short. For Skaraborg, three potential train shuttle services were identified: one dedicated service transporting goods between Port of Göteborg and Skaraborg, the other two services were based on connecting wagons onto already existing train shuttle services passing through the region (a realistic situation for Skaraborg, since it is located on a main national railway link).

The relation Skaraborg – Port of Göteborg had annual goods volumes of 22,418 TEU and a goods flow balance of 86.6%. The distance between the two destinations is a mere 135 km. The two main questions to answer were:

- How many of the annual 22,418 TEU could be transported with a train shuttle service by implementing a volume maximising timetable, according to the approach?
- What would be the cost savings and environmental savings of a service that maximises volume and a service that maximises balance?

Results indicated that, when maximising goods volumes, the best possible solution produce by the approach could transport 7810 of the 22,418 TEU, annually. Furthermore, such a solution could achieve annual cost savings on that relation of about 3.2 million SEK, a substantial annual decrease in environmental impact (see Table 2) with about the same energy consumption. Calculations of environmental impacts have been made in NTMCalc^{TM}.

Besides the decrease in emissions, the road–rail intermodal solution also results in a better use of renewable energy. In the case of road–rail intermodal transport, renewable energy constitutes more than 99% of the total energy consumption based on the purchased energy mix by the Swedish rail administration Banverket.

Table 2. Decrease in emissions for the 7810 TEU road–rail intermodal solution compared to direct road solution.

CO_2	Nox	HC	PM	CO	SO_2	
519676066.7	3410133.7	877748.3	59824.8	535004.2	130786.1	g
519676.1	3410.1	877.7	59.8	535.0	130.8	kg
519.676	3.410	0.878	0.060	0.535	0.131	tonne

The balance maximising service was able to transport 6487 TEU, annually. That solution, however, produces an annual cost saving of about 3.3 million SEK and a slightly less decrease in environmental impact than the goods volume maximising solution, since the goods volume transferred from road is about 1323 TEU less per year. Which solution to select in the end is determined by the choice of either minimising costs or minimising environmental impact.

To test the importance of producing good timetable, some randomly generated timetables were analysed. Compared with the produced solutions by the approach, randomly constructed solutions showed volume losses of 20–75%. As an example, a fixed timetable with departure from Skaraborg at 19.03 p.m. and departure from Port of Göteborg at 20.44 p.m. would be able to transport 2583 TEU per year. The span of results is large, but combined, they illustrate the importance of having a well designed timetable that complies with shippers' requirements. This is especially important during the start-up phase of a train shuttle service when you are trying to attract goods flows from direct road services. Given a timetable complying with the time restrictions of goods flows, transferring goods flows to train departures becomes easier.

6. Conclusions

Empirical results emphasise the importance of a good timetable design train shuttle services in order to produce and offer an attractive service. Furthermore, the case of Skaraborg shows that a train shuttle service can be cost efficient on short distances, *e.g.* 135 km, and with relatively small amounts of goods, *e.g.* 6487, as long as the timetable is set in an optimising manner.

It is the author's belief that the approach developed in this paper introduces an efficient way of evaluating and designing road–rail intermodal transport solutions. It was designed to be holistic and to comply with demands by both potential private and public users. This approach can evaluate road–rail intermodal transport services on single relations or on more complex routes. In both cases, it aims at producing designs that are realistic for shippers and operators. Altogether, the approach can help identify potential relations and routes for road–rail intermodal transport services, suggest suitable train set designs and estimate the potential outcome of implementing the design. However, the approach does not consider how the process of designing the solutions should be carried out and what aspects are important to consider when implementing road–rail intermodal transport services – this is an interesting subject for further research. Another issue related to the implementation of potential services is the challenge of coordinating and collaborating different actors, *e.g.* the dynamics between shippers, operators and policy-makers. This constitutes an interesting area for further research.

Note

1. Assume that we have number of stops (n) equalling 4, which are connected in the route 1–2–3–4–3–2–1, according to the logic of train shuttle services. This gives the opportunity to adjust intervals in a number of comparisons in relation to each other, *i.e.* $n \times (n-1) = 4 \times 3 = 12$ number of comparative adjustments. If the maximum adjustment is set to 24 h for the route and we want to evaluate possible solution based on steps of 30 min, it would produce $(2 \times 24)^{12} = 1.49 \times 10^{20}$ solutions. Hence, the number of possible solutions grows exponentially to the number of stops on the route. Such an approach would be difficult to manage in situations where the route is complex.

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