Capacity Analysis of Freight Transport on the Danish and Southern Swedish Railway.

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EAST WEST
TRANSPORT CORRIDOR II

Baltic Sea Region
Programme 2007–2013

Part-financed by the European Union
(European Regional Development Fund
and European Neighbourhood and
Partnership Instrument)

Abstract

The East West Transport Corridor project (EWTC) studies possible freight transport by train from western China to their destinations in Europe through Northern Germany, Denmark and Sweden. When planning new transport corridors with an increased amount of cargo it is important to ensure that there is capacity in the corridor for the expected increase of freight transport. Using hydro and wind power the electrified railway is an environmentally friendly mode of transport and therefore often preferred to other modes. A capacity analysis of the railways in Denmark and Southern Sweden, based on time of day and day of week, is presented here. The analysis is based on forecasts of the transportation flow in 2030. The forecasts for 2030 are separated into 2 sets; one based on a baseline scenario and another based on a green scenario. The model for the analysis is an integer multi commodity flow model which uses a time space network to route the trains on the available tracks. From the output of this model we can find which track segments have available time slots and when the available time slots occur. Using this model we show that the **Femern** connection is not only necessary for satisfying the freight transports but is also going to be the more attractive connection for most transports by train connecting to the region. Moreover the results show that with a slight increase in the capacity on the connection between **Malmø** and **Vigerslev** the huge increase in freight volumes can still be satisfied. The study is part of the East West Transport Corridor II (EWTC-II) project supported by EU.

1 Introduction

Trains that run on electricity are a green form of transportation when hydro and wind energy sources are used. Using trains for containerized freight is an environmentally friendly competitor to truck and vessels. This concept is exploited in the East West Transport Corridor (EWTC) where the transportation of freight on train from western China destinations in Europe is analyzed with focus on the freight going through Northern Germany, Denmark and Sweden.

The modeling of rail transportation can be regarded as a network where the nodes are stations and the links are lines of track. An early survey by Assad [2] from 1980 on rail transport modeling includes aspects concerning yard queueing and simulation of passenger transports. However these aspects are not considered here. A more recent extensive review was published in 1998 by Cordeau et al. [6] shows that since 1980 the research in the area of train transportation increased significantly and several details and aspects of the routing and scheduling problem of rail transport were considered.

Caprara et al. in [5] investigated the design of trains and their routes on a railway corridor. This was done in connection with the European Union REORIENT project (2004-2007) where a railway corridor connecting southern and northern Europe through eastern Europe is analyzed. In [5] the capacity in the form of the number of trains is predetermined on the route and the assignment of demand to trains is optimized with respect to the demand travel time and travel cost.

In this project in the EWTCII the goal is to find routes for the generated trains so that the forecasted demand is satisfied with respect to a arrival and departure time window while minimizing cost. The cost includes a fixed track charge, an infrastructure tax per kilometer and a delay cost. This is similar to the problem and model presented by Borndörfer et al. [4] for the track allocation problem. A general forecast based on market knowledge is used to set a departure time window and an arrival time window. These time windows are soft with a penalty connected for breaking them. However, a hard time window encapsulates these soft time windows. The hard time window does not allow for delays exceeding a given threshold.

The problem solved is an integer multi-commodity flow problem. The integer multi-commodity flow problem is known to be NP-hard on a directed graph, as shown by Even [7]. Therefore several decomposition methods have been developed for the problem (see [3] and [1]). Even though Barnhart et al. [3] show Cplex (3.0) to be inferior to their branch-cut-and-price algorithm, Alvelos and Carvalho [1] showed that in 2003 Cplex 7.5 was already competitive with several Branch-and-price algorithms for small instances. One of the main problems with both the polynomially solvable splittable multicommodity flow problem and the unsplittable multicommodity flow problem is the number of variables in the formulation as shall be discussed later.

The aim of this project

The aim of this project is to develop a method and model for analyzing the capacity of the links of the network over the duration of a week. When evaluating the network without considering time and cost the capacity of the network may appear as sufficient although a more detailed analysis will show that some time periods are saturated. If there is no need for trains between 2:00 and 5:00 then the capacity available at that time cannot be used to satisfy the demand at other time windows. This is very relevant when it comes to passenger trains; however, with freight trains the time of transport is less important. Even though freight trains do not have as extensive time restrictions, there are some constraints to the delivery. The constraints can be working hours for loading and unloading at the departure and the arrival terminal, the cost of operating a train and the working hours of the operators.

In this project the cost is only relevant for prioritizing the paths, to minimizing delay when selecting departure times and in cases where trains must be canceled. In the model presented it is assumed that it is always more profitable to route a train than to cancel. This means that only capacity limitations can result in canceled trains however the canceled trains will by the model be selected so that the most expensive train on the capacity exceeded link is canceled. Therefore only simple costs are included and socio-economic costs covered in [11] are not considered. Trains can only be canceled due to lack of capacity in the acceptable time period.

These constraints are used in this project to give a more precise model of the capacity. A desired time window for the departure and the arrival of the train is also included in the model. Moreover, it is required that the train can travel through the network without waiting at intermediate stations because of capacity issues, and the trains between a given origin and destination must have a somewhat even distribution during the week. Using these requirements it is possible to evaluate the density of the network at different times.

Overview

This paper is organized as follows. In the following section we discuss the forecast transportation demands and how these demands are converted to train schedules with specific time demands. Section 3 describes the train network of Denmark and Southern Sweden and discusses future expansions of the network. In Section 4 the train network is modeled as a time expanded graph, and a mathematical model using this representation is developed in Section A. Finally, Section 6 presents the optimal results for routing the trains through the network based on various scenarios. The paper is concluded in Section 7 with a short summary of the found results.

2 The freight demands on the network

The present flow analysis is based on transportation forecasts provided by Tetraplan [9] as part of the EWTC II project workproject 6B. These forecasts were generated using the program Trans-Tools [8].

The forecasts contain the freight in tons per year between 47 different zones in Europe in the three scenarios: 2010, 2030 base scenario and a 2030 green scenario. This was provided in an origin destination (O-D) matrix as well as maps showing the cargo flow transported through the Danish and Southern Swedish region. For each zone a terminal is selected and all cargo with origin or destination in a given zone starts and ends at the selected terminal. Figure 1 shows a map of the zones in Europe.

From this we were able to extract the start and end terminals (S-E pair) in the region for the flow through the region and also the amount of freight from each O-D pair going through the region. It should be noted that transport between an O-D pair may not go through the region. Moreover for an O-D pair some percentage of the cargo may be transported through the region while the rest may not, or the cargo may be split so that some enters the region at one point and some at another even though the origin and destination is the same.

The O-D matrix provided by Tetraplan [9] represents the volume in terms of tons. This is in our project converted into volume in terms of trains. For each O-D S-E pair the number of trains needed to transport the forecast amount of tons of cargo was calculated. It is assumed that the trains operate on a weekly schedule since the capacity of the tracks is scheduled with a weekly cycle. We have been informed by the Danish traffic authority [10] that a single weekly departure of a full train can transport between 22000 and 37000 tons freight per year. If less than 15000 tons is to be transported on an O-D S-E pair, then it would be better to relocate the cargo to other modes of transport or distribute it on existing trains instead of allocating a train for the small amount of freight.

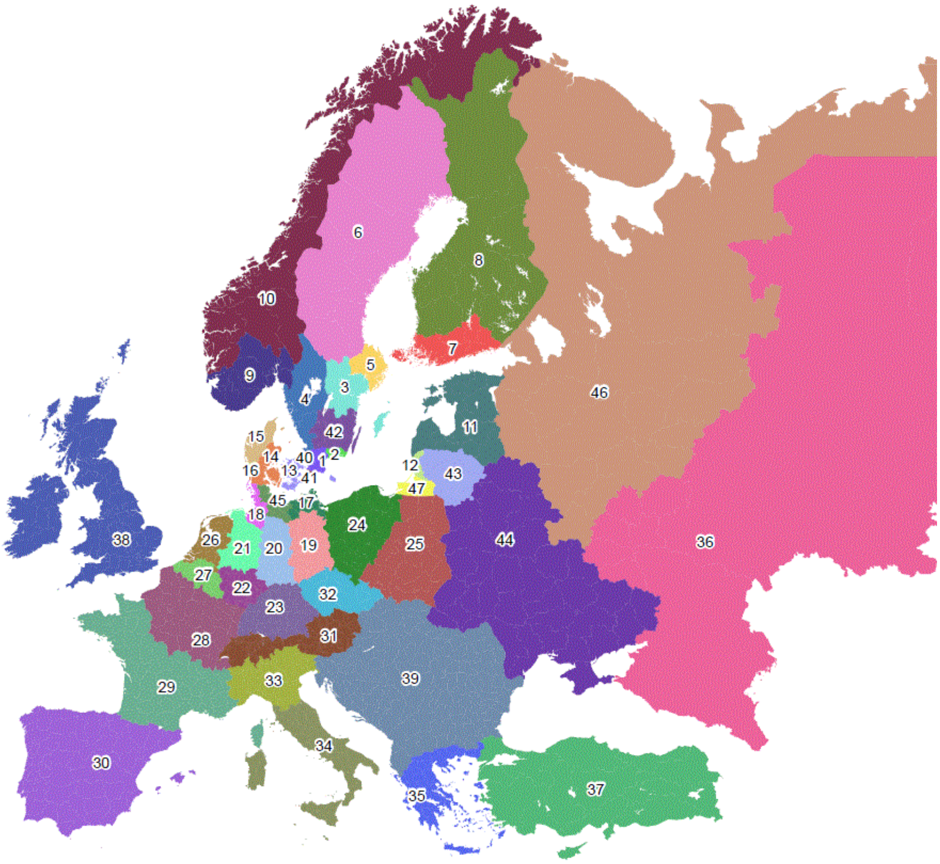

Figure 1: The zones in Europe used for the O-D matrix.

Let σ be the forecast freight in tons for an O-D pair with a specific S-E pair, then the weekly number of train departures ϕ between O-D entering and leaving the Danish and Southern Swedish region at the terminals S-E is calculated as follows:

$$\phi = \left\lfloor \frac{\sigma}{22000} \right\rfloor + \left(\left\lfloor \frac{\sigma - \lfloor \frac{\sigma}{22000} \rfloor}{15000} \right\rfloor \right)$$

Clearly we do not know which days and times trains are scheduled for in 2030 therefore we have in our model used a distribution which estimates how the weekly departures are distributed. It is assumed for business purposes that a single train departure for an O-D S-E pair will depart on a Wednesday and so on as it is assumed that O-D S-E connection is desired to be spread evenly as to minimize the time goods is stored at origin or destination. The trains are distributed somewhat evenly during the week according to a distribution pattern shown in Table 1 obtained from the Danish traffic authority [10]. The and the pattern will continue as shown for a higher number of weekly departures. Note that freight trains are not scheduled for departure during the weekends. Trains may travel during the weekends but are not scheduled for departure as the terminals are often partly shutdown for operations during the weekends.

Usually the freight is loaded on the train during the afternoon and therefore the operators desire a departure for the train in the evening between 8 pm and 2 am. Moreover, since the freight is

Number of needed trains	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
1			1				
2		1		1			
3	1		1		1		
4		1	1	1	1		
5	1	1	1	1	1		
6	1	1	2	1	1		
7	1	2	1	2	1		
8	2	1	2	1	2		
9	1	2	2	2	2		
10	2	2	2	2	2		
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Table 1: Distribution of train departures during a week. For instance if 3 trains are needed per week, then one train is scheduled for Monday, Wednesday and Friday.

unloaded at the destinations during the morning hours it is desired that the train arrives between 10 pm and 6 am. For the departure it would be a problem if the train was scheduled to depart at 2 pm as it may not be possible to load the freight before departure. The same is the case for an arrival after 6 am as it may not be possible to unload the goods so they can arrive to the customers in due time. Therefore a penalty is associated for departing early and for arriving late. However, it is not possible to arrive more than 24 hours past the end time of the arrival time window as this would generate an unacceptable distribution of departures for the operators. This may result in the cancelation of trains even though there is available capacity on the links. A table with distances in time from the terminals of the zones to the entry points was provided by the Danish traffic authority [10]. These times are shown in Table 2.

If an O-D pair has more than one departure on a day the second departure is scheduled for departure between 10am and 4 pm and arrival between noon and 10 pm and a third departure would be scheduled with a desired departure between 6 am and noon and arrival between 8 am and 2 pm. For the 4th or more departure on a day for the same O-D S-E pair the departure time window is the entire day and the arrival time window is the entire day of estimated arrival.

Since rolling material return to their origin with or without freight, the number of trains from O to D is be the same as the number trains from D to O.

3 The train network of Denmark and Southern Sweden

In the present project we study the rail network of Denmark and Southern Sweden. Two different networks are studied: One representing the rails in 2010 and one representing the rails in 2030. These two networks are shown in Figure 2 and 3. The network in Figure 2 represents the network as it is today. The network in Figure 3 incorporates all projected expansions of the rail network. The new links are show in red in Figure 3. The projected expansion of capacity (extra tracks) on existing links are not shown in Figure 3 but will be discussed later. The cargo starts and ends at the nodes defined as Terminals. The freight train may have an origin and destination outside the network and enter or leave the network at a terminal.

The fixed link between **Helsingør** and **Helsingborg** was discussed when modeling the network. The Danish traffic authority [10] determined that it would have to include a new connection from **Helsingør** to **Ringsted**, which is probably not realistic to finish before 2030. However we have

Origin	Destination	Hours
Hallsberg	Älmhult	4.7
Stockholm	Älmhult	5.4
Sundvall	Älmhult	13.1
Turku	Älmhult	15.0
Finland	Älmhult	20.0
Petersburg	Älmhult	22.0
Oslo	Halmstad	8.5
Trondheim	Halmstad	18.6
Kleipeda	Karlshamn	14.2
Volgograd	Karlshamn	25.0
Aalborg	Taulov	4.7
Bremen	Hamburg	1.6
Hannover	Hamburg	2.1
Duisburg	Hamburg	5.5
Frankfurt	Hamburg	7.9
Munchen	Hamburg	12.7
Munchen	Trelleborg	19.5
Rotterdam	Hamburg	8.1
Paris	Hamburg	16.0
Lyon	Hamburg	23.2
Innsbruck	Hamburg	16.2
Innsbruck	Trelleborg	22.3
Milano	Hamburg	24.0
Prag	Hamburg	12.0
Prag	Trelleborg	16.6
Dresden	Hamburg	8.0
Budapest	Hamburg	22.0
Rostock	Trelleborg	6.5
Dresden	Trelleborg	12.7
Athen	Trelleborg	64.3
Budapest	Trelleborg	26.2
Hamburg	Trelleborg	9.6
Gdansk	Trelleborg	15.5
Warszawa	Trelleborg	18.9
Istanbul	Trelleborg	65.0

Table 2: Time between the terminals in relevant zones and the entrypoints into the modeled network.

included a connection between **Helsingborg** and **Ringsted** in some of the tests of the 2030 network so that this alternative can be considered.

The links have travel times and costs associated with them. The travel times are received from the Danish traffic authority [10]. The cost of traversing a link contains several costs. In this model only very elementary costs are included as the cost is used for the selection of path and departure time. The costs included in the model was provided by the Danish traffic authority [10]. The costs are a capacity and bridge cost which is a fixed cost imposed on some links. This cost is shown in Table 3. Moreover infrastructure, locomotive and carriage charges are included in the cost of the links. These costs are provided in Table 4. All other costs are ignored as these are not very important for the model.

These costs are given as parameters to the solver, and can easily be changed. For each link the capacity is given in the form of the number of freight trains that can pass per hour in each direction. These capacities are described in Section 6.

4 Time expanded network

The capacity is given in trains per hour, thus we have chosen to represent the network as a time expanded network with a node per terminal or connection point representing each hour. Since we are looking at a time period of one week there will for each station be $24 * 7 = 168$ vertices in the time expanded graph. A connection in the original network between two nodes i and j will

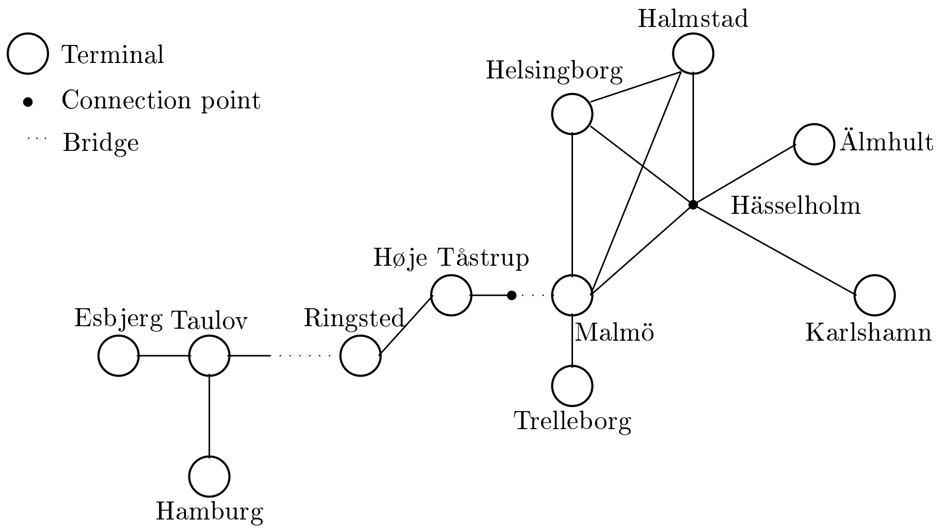

Figure 2: Considered network year 2010

Capacity toll	DKK per train
Vojens-Vamdrup	844
Hvidovre fjern-Høje Tåstrup	1056
Kastrup-Kalvebod	317
Bridge toll	
Storebælt	5373
Øresund	2198
Helsingborg-Helsingør	2198
Femeren	5373

Table 3: Capacity and bridge cost on links.

in the time expanded network be represented by an edge for each time expanded node of station i to the corresponding time expanded node of station j representing a direct connection. The corresponding time expanded node of station j is the first node which is larger than or equal to the time of the time expanded node at i plus the travel time needed to reach j. It should be noted that due to the fact that it is not desirable to allow the trains to stand and wait at intermediate stations on their journey, only time wise direct connections are represented in the time expanded network. Therefore a time expanded node i_t has the same number of incoming edges and outgoing edges as the station i in the original network.

5 Modeling the problem

In this section we will describe the model applied to the problem.

In the model each demand corresponds to a train between a specific origin and destination and with a specified time window. The goal is to maximize the number of trains scheduled and to

	DKK per hour	DKK per km
Locomotive	1.225	26,35
Carriage	0	3,80
infrastructure charge Denmark/Sweden	0	1,87
infrastructure charge Germany	0	15,00

Table 4: Infrastructure, locomotive and carriage charges.

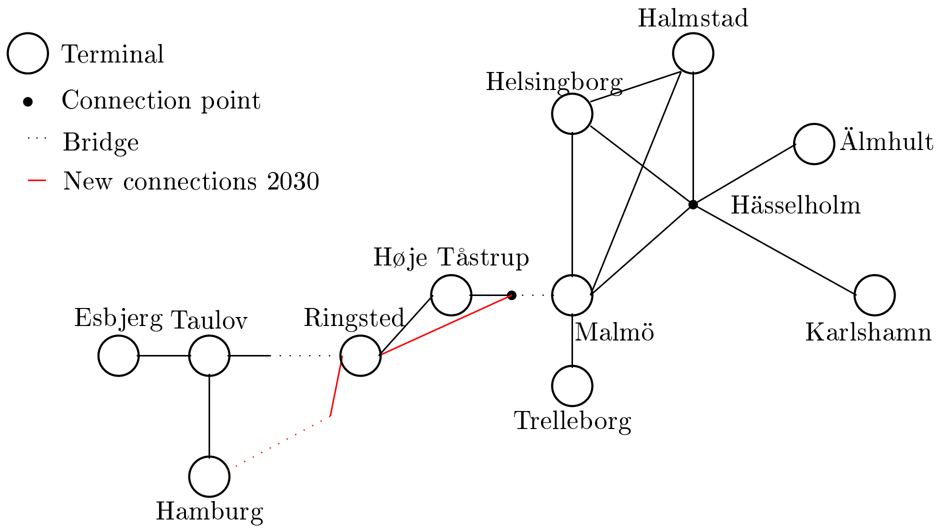

Figure 3: Considered network year 2030

minimize the total delay.

Constraints to be considered

- A train must be routed continuously through the links.
- The arrival and departure may create a penalty if a time window is violated
- Capacity on the links must be satisfied
- For each train going from O to D there must be a train going from D to O. This is to ensure the return of the trains.

An edge based model is presented in Appendix A.1. In the edge based model the number of variables corresponds to the number of combinations of trains and edges. Since the problems contain between 900 and 2500 trains and the number of edges in the time expanded graph corresponds to 168 time expanded links for each link in the original graph, the number of variables in our network will be several million. This many variables can be a problem for even commercial solvers. Moreover this model may construct routes which are unacceptable for the operators. Such routes could be routes which travel for parts in the opposite direction of the destination to ensure arrival at links when capacity is available.

Therefore we have chosen to use a path based model presented in Appendix A.2 where each origin destination pair has a set of possible paths. The acceptable paths for the trains through the network are normally provided by the operators and for these paths time-dependent paths are generated in the program. Using this method we ensure that only acceptable paths are generated; however, we also limit our selves to the operator's knowledge of paths. The number of time-dependent paths corresponds to the number of variables in the IP problem. For the scenarios provided this results in 70 000 to 500 000 variables, which is a much more reasonable number. As explained in the Section 6, the running time is mostly spent setting up the model while only a few seconds were used on solving the model. Therefore, the model is likely to scale well for even larger problems.

6 Tests and results

In this section we will describe the input given to the model and the results of running the model on this input. It should be noted that the test results of the model are based on forecast data provided by Tetraplan [9] and hence are subject to the same uncertainty as the underlying data.

6.1 Capacity Analysis test scenarios

From Tetraplan three scenarios were delivered representing an estimate of the past situation in 2010 and two forecasts for 2030 with a baseline scenario and a green scenario. For each scenario an O-D matrix with the tons of cargo transported between the O-D pairs was developed by Tetraplan with the use of Trans-Tools [8]. This matrix is the basis for our calculations. For each scenario, maps showing flow through a few selected arcs was delivered. Together with the Danish traffic authority [10] the specific flow through the network was estimated by combining the knowledge provided by the maps and the information in the O-D matrix. This resulted in an O-D S-E table from which a set of trains is created, as described in Section 2 by converting the tonnage to trains. On the three data sets, one for each scenario, the capacity of the network is analyzed using the different capacity settings described later in this section.

2010: From the transportation given in tons in this scenario, 926 trains were created.

2030 Baseline: From the transportation given in tons in this scenario, 2246 trains were created.

2030 Green: From the transportation given in tons in this scenario, 2354 trains were created.

2030 Baseline SK: Is the 2030 Baseline where all freight with origin **Sundsvall** and destination **Karlshamn** is removed assuming a direct link **Älmhult Karlshamn**.

2030 Green SK: Is the 2030 Green where all freight with origin **Sundsvall** and destination **Karlshamn** is removed assuming a direct link **Älmhult Karlshamn**.

The last two data sets were developed to account for the possibility of transport between **Sundsvall** and **Karlshamn** using a track not represented in the model of the network. This track may be a future project.

A set of capacities are used on the connections. The capacities are given per hour which allows the edges to be distributed in the time expanded graph with one hour intervals. The capacities provided by the Danish and Swedish traffic authorities [10], [12] are shown in Table 5. These capacities are also denoted **cap1**.

The model was used on the scenarios using the capacities from Table 5. From analyzing the results of these instances, variations on the capacities were generated. These variations are described below using **cap1** (Table 5) as the basis.

Capacity in Trains/hour both direction (**cap1**)		
Connection	2010	2030
Malmö;Vigerslev	2	2
Malmö;Trelleborg	2	2
Malmo;Helsingborg	1	1
Helsingborg;Halmstad	1	1
Malmö;Halmstad	1	3
Halmstad;Hässleholm	1	1
Malmö;Hässleholm	4	6
Hässleholm;Älmhult	4	6
Hässleholm;Karlshamn	1	1
Vigerslev;Høje Tåstrup	2	1
Høje Tåstrup;Ringsted	2	1
Ringsted;Taulov	2	2
Taulov;Padborg	1	1
Taulov;Esbjerg	1	1
Padborg;Hamburg	2	2
Vigerslev;Ringsted	0	2
Ringsted;Putgarden	0	2
Putgarden;Hamburg	0	2
Helsingborg;Hässelholm	1	1
Helsingborg;Helsingør	0	0

Table 5: The capacities of the network. Data provided by The Danish Traffic Authority and The Swedish Traffic Authority for both 2010 and 2030.

cap1: The capacities presented in Table 5.

cap2: Cap1 where the capacity of Vigerslev Malmö link is set to 3 trains per hour in both directions

cap3: Cap1 where the capacity of Karlshamn Hässleholm link is set to 2 trains per hour in both directions

cap4: Cap1 where the capacity of Vigerslev Malmö link is set to 4 trains per hour in both directions

cap5: Cap1 where the capacity of Karlshamn Hässleholm link is set to 3 trains per hour in both directions

cap6: Cap1 where the capacity of Karlshamn Hässleholm link is set to 2 trains per in both directions and the capacity of the Vigerslev Malmö edge is set to 3 in both directions

HH: Cap1 where the capacity of Helsingborg Ringsted link over Helsingør is included with capacity of 2 trains per hour in both directions

HH2: Cap1 where the capacity of Helsingborg Ringsted link over Helsingør is included with capacity of 2 trains per hour in both directions and the connection **Hässleholm Helsingborg** is increased to 2 trains per hour in both directions.

These capacity sets are used on the Baseline and Green scenario of 2030. Especially the capacity on the **Øresunds** connection has been discussed during the EWTC II workproject 6B

scenario	Number of trains	Trains routed in the considered network and capacity scenario					
		cap1	**cap2**	**cap3**	**cap6**	**HH**	**HH2**
2010	926	926	-	-	-	-	-
2030 Baseline	2246	1808	2078	1962	2244	2078	2078
2030 Baseline SK	1814	1530	1812	1530	1812	1812	1812
2030 Green	2354	1806	2042	2064	2322	2042	2042
2030 Green SK	1922	1632	1920	1632	1920	1920	1920

Table 6: The number of routed trains using the different capacity sets. Here trains are counted in both directions thereby each demand corresponds to a train in one direction.

scenario		Trains routed in the considered network and capacity scenarios					
		cap1	**cap2**	**cap3**	**cap6**	HH	HH2
2010	Number of trains delayed	242	-	-	-	-	-
	Total minutes of delay at origin	71394	-	-	-	-	-
	Total minutes of delay at destination	83382	-	-	-	-	-
2030 Baseline	Number of trains delayed	584	903	503	997	899	885
	Total minutes of delay at origin	21750	112271	18509	104037	96617	96803
	Total minutes of delay at destination	159244	261986	140583	325119	291344	289695
2030 Green	Number of trains delayed	707	922	758	1142	897	887
	Total minutes of delay at origin	18884	84275	28200	85542	60829	61015
	Total minutes of delay at destination	178478	223979	267387	385441	265074	263610
2030 Baseline SK	Number of trains delayed	409	703	413	705	678	676
	Total minutes of delay at origin	13272	99730	13752	99430	84263	83615
	Total minutes of delay at destination	130545	250933	130065	251233	262390	261646
2030 Green SK	Number of trains delayed	445	740	454	736	671	666
	Total minutes of delay at origin	10059	94804	9328	94733	61470	61236
	Total minutes delay of at destination	133053	255171	132771	254175	212036	210807

Table 7: The number of delayed trains and the total minutes of delays in the schedule.

partner meetings and therefore it is a natural area to investigate in this setting. The rail capacity on the connection to **Karlshamn** is interesting due to the projected increase in transport from the East possibly through the **Kleipeda Karlshamn** ferry link. The bottleneck on this link is the **Karlshamn Hässleholm** link, where only one train an hour can pass.

6.2 Results

The model is tested on the three scenarios using the capacity sets described in Section 6.1. The number of trains which was accepted on the network applying the different capacity sets is reported in Table 6. The number of unscheduled trains is divided into the different origin destination pairs for each capacity set and scenario in Tables 8, 9 and 10 (note that flow is reported for one direction but is the same for the other direction). Tables 12 and 11 show the total number of trains traversing a given link in each direction during a week for the generated schedule on respectively the 2010, Baseline 2030 and Green 2030 scenarios.

In the analysis of the network Excel sheets [1] were produced for each scenario and capacity set and graphically show the usage of each link for every hour of the week. The sheets are too large to include in the report so an example of the contents of the sheets is shown in Figure 4. In Figure 4 an extract containing the hours of a Wednesday is taken from the sheet for scenario 2010

[1] Excel sheets can be received from authors upon request.

	2030 Baseline						2030 Green					
		unscheduled						unscheduled				
pair	all	**cap1**	**cap2**	**cap3**	**cap6**	**HH**	all	**cap1**	**cap2**	**cap3**	**cap6**	**HH**
Malmo, Karlshamn	0	0	0	0	0	0	9	8	8	0	0	8
Malmo, Hallsberg	3	0	0	0	0	0	3	0	0	0	0	0
Malmo, Halmstad	6	0	0	0	0	0	6	0	0	0	0	0
Malmo, Stockholm	5	0	0	0	0	0	5	0	0	0	0	0
Malmo, Sundsvall	181	0	0	0	0	0	181	0	0	0	0	0
Malmo, Helsingki	1	0	0	0	0	0	1	0	0	0	0	0
Malmo, Tampere	1	0	0	0	0	0	1	0	0	0	0	0
Malmo, Oslo	9	0	0	0	0	0	9	0	0	0	0	0
Malmo, Trondheim	8	0	0	0	0	0	8	0	0	0	0	0
Malmo, Kleipeda	1	0	0	0	0	0	1	1	1	0	0	1
Malmo, Dresden	2	0	0	0	0	0	2	0	0	0	0	0
Malmo, Hannover	1	0	0	0	0	0	1	0	0	0	0	0
Malmo, Duisburg	2	0	0	0	0	0	2	0	0	0	0	0
Malmo, Frankfurt	1	0	0	0	0	0	1	0	0	0	0	0
Malmo, Munchen	3	0	0	0	0	0	3	0	0	0	0	0
Malmo, Rotterdam	2	0	0	0	0	0	2	0	0	0	0	0
Malmo, Paris	1	0	0	0	0	0	1	0	0	0	0	0
Malmo, Lyon	1	0	0	0	0	0	1	0	0	0	0	0
Malmo, Innsbruck	3	0	0	0	0	0	2	0	0	0	0	0
Malmo, Prag	4	0	0	0	0	0	3	0	0	0	0	0
Malmo, Athen	1	0	0	0	0	0	1	0	0	0	0	0
Malmo, Budapest	1	0	0	0	0	0	1	0	0	0	0	0
Malmo, Almhult	3	0	0	0	0	0	3	0	0	0	0	0
Malmo, Hamburg	7	0	0	0	0	0	7	0	0	0	0	0
Karlshamn, Hallsberg	0	0	0	0	0	0	5	2	1	0	0	1
Karlshamn, Halmstad	0	0	0	0	0	0	15	13	13	0	0	13
Karlshamn, Stockholm	0	0	0	0	0	0	25	12	10	0	2	12
Karlshamn, Sundsvall	216	74	74	0	0	74	216	86	91	0	1	90
Karlshamn, Oslo	2	2	2	0	0	2	2	2	2	0	0	2
Karlshamn, Trondheim	1	1	1	0	0	1	1	1	1	0	0	1
Karlshamn, Hoje Taastrup	0	0	0	0	0	0	22	20	20	10	7	20
Karlshamn, Almhult	0	0	0	0	0	0	6	4	2	0	0	1
Hallsberg, Rostock	28	0	0	0	0	0	14	0	0	0	0	0
Hallsberg, Bremen	11	0	0	1	0	0	11	0	0	2	0	0
Hallsberg, Dresden	2	0	0	0	0	0	2	0	0	1	0	0
Hallsberg, Hannover	1	0	0	0	0	0	1	0	0	0	0	0
Hallsberg, Duisburg	2	0	0	1	0	0	2	0	0	0	0	0
Hallsberg, Frankfurt	1	0	0	0	0	0	1	0	0	0	0	0
Hallsberg, Munchen	3	0	0	1	0	0	3	0	0	1	0	0
Hallsberg, Paris	1	0	0	0	0	0	1	0	0	1	0	0
Hallsberg, Innsbruck	2	0	0	1	0	0	2	0	0	0	0	0
Hallsberg, Prag	2	0	0	1	0	0	1	0	0	0	0	0
Hallsberg, Athen	1	0	0	0	0	0	1	0	0	0	0	0
Hallsberg, Budapest	1	0	0	0	0	0	1	0	0	0	0	0
Hallsberg, Hamburg	56	12	0	17	0	0	56	10	0	10	0	0
Halmstad, Bremen	2	2	0	2	0	0	2	2	0	2	0	0
Halmstad, Dresden	4	2	0	1	0	0	6	2	0	2	0	0
Halmstad, Hannover	2	2	0	2	0	0	2	2	0	2	0	0
Halmstad, Duisburg	3	2	0	2	0	0	3	2	0	2	0	0
Halmstad, Frankfurt	2	1	0	1	0	0	2	1	0	1	0	0
Halmstad, Munchen	7	5	0	4	0	0	7	5	0	5	0	0
Halmstad, Gdansk	1	0	0	0	0	0	1	0	0	0	0	0
Halmstad, Rotterdam	1	1	0	1	0	0	1	1	0	1	0	0
Halmstad, Paris	2	1	0	1	0	0	2	1	0	1	0	0
Halmstad, Lyon	1	1	0	1	0	0	1	1	0	1	0	0
Halmstad, Innsbruck	6	2	0	2	0	0	6	2	0	2	0	0
Halmstad, Prag	10	3	0	3	0	0	9	1	0	1	0	0
Halmstad, Athen	2	0	0	0	0	0	2	0	0	0	0	0
Halmstad, Istanbul	1	0	0	0	0	0	1	0	0	0	0	0
Halmstad, Budapest	3	1	0	1	0	0	2	0	0	0	0	0
Halmstad, Helsingborg	1	0	0	0	0	0	1	0	0	0	0	0
Halmstad, Hamburg	7	5	0	5	0	0	7	5	0	5	0	0

Table 8: First part of list of unscheduled trains between two locations. Since the number of trains going in one direction always is the same as the number in the other direction we only show one direction in the table.

	2030 Baseline						2030 Green					
		unscheduled						unscheduled				
pair	all	**cap1**	**cap2**	**cap3**	**cap6**	**HH**	all	**cap1**	**cap2**	**cap3**	**cap6**	**HH**
Stockholm, Rostock	10	0	0	0	0	0	5	0	0	0	0	0
Stockholm, Bremen	11	1	0	3	0	0	11	0	0	2	0	0
Stockholm, Dresden	6	0	0	0	0	0	6	0	0	0	0	0
Stockholm, Hannover	3	0	0	0	0	0	3	0	0	0	0	0
Stockholm, Duisburg	6	0	0	1	0	0	6	0	0	1	0	0
Stockholm, Frankfurt	5	2	0	1	0	0	5	0	0	1	0	0
Stockholm, Munchen	8	3	0	3	0	0	8	0	0	0	0	0
Stockholm, Gdansk	1	0	0	0	0	0	1	0	0	0	0	0
Stockholm, Rotterdam	1	0	0	1	0	0	1	0	0	0	0	0
Stockholm, Paris	3	0	0	0	0	0	3	0	0	0	0	0
Stockholm, Lyon	2	0	0	1	0	0	2	0	0	0	0	0
Stockholm, Innsbruck	5	0	0	1	0	0	4	0	0	0	0	0
Stockholm, Prag	4	0	0	0	0	0	3	0	0	0	0	0
Stockholm, Athen	2	0	0	0	0	0	2	0	0	0	0	0
Stockholm, Istanbul	1	0	0	0	0	0	1	0	0	0	0	0
Stockholm, Budapest	2	0	0	0	0	0	2	0	0	0	0	0
Stockholm, Helsingborg	1	0	0	0	0	0	1	0	0	0	0	0
Stockholm, Hamburg	51	4	0	8	0	0	51	7	0	11	0	0
Sundsvall, Bremen	4	1	0	1	0	0	4	0	0	1	0	0
Sundsvall, Dresden	8	1	0	1	0	0	8	1	0	1	0	0
Sundsvall, Hannover	5	1	0	2	0	0	5	1	0	1	0	0
Sundsvall, Duisburg	8	3	0	2	0	0	8	1	0	1	0	0
Sundsvall, Frankfurt	7	2	0	2	0	0	7	2	0	2	0	0
Sundsvall, Munchen	15	4	0	4	0	0	15	2	0	2	0	0
Sundsvall, Gdansk	2	0	0	0	0	0	2	0	0	0	0	0
Sundsvall, Warsawa	2	0	0	0	0	0	2	0	0	0	0	0
Sundsvall, Rotterdam	2	0	0	0	0	0	2	0	0	0	0	0
Sundsvall, Paris	4	1	0	1	0	0	4	1	0	0	0	0
Sundsvall, Lyon	3	0	0	0	0	0	3	0	0	0	0	0
Sundsvall, Innsbruck	6	0	0	0	0	0	6	0	0	0	0	0
Sundsvall, Prag	4	1	0	0	0	0	3	0	0	0	0	0
Sundsvall, Athen	3	1	1	1	1	1	3	1	1	1	1	1
Sundsvall, Volgograd	1	0	0	0	0	0	0	0	0	0	0	0
Sundsvall, Budapest	2	0	0	0	0	0	2	0	0	0	0	0
Sundsvall, Helsingborg	30	0	0	0	0	0	30	0	0	0	0	0
Sundsvall, Trelleborg	24	0	0	0	0	0	14	0	0	0	0	0
Sundsvall, Hamburg	65	7	0	12	0	0	65	8	0	6	0	0
Helsinki, Rotterdam	1	0	0	0	0	0	1	0	0	0	0	0
Helsinki, Hamburg	5	1	0	0	0	0	5	0	0	0	0	0
Tampere, Bremen	2	0	0	0	0	0	2	0	0	0	0	0
Tampere, Dresden	2	0	0	0	0	0	2	0	0	0	0	0
Tampere, Hamburg	18	1	0	3	0	0	18	1	0	2	0	0
Oslo, Rostosck	1	0	0	0	0	0	1	0	0	0	0	0
Oslo, Bremen	3	2	0	2	0	0	3	2	0	2	0	0
Oslo, Dresden	10	4	0	2	0	0	10	4	0	4	0	0
Oslo, Hannover	3	2	0	1	0	0	3	2	0	2	0	0
Oslo, Duisburg	5	4	0	3	0	0	5	4	0	4	0	0
Oslo, Frankfurt	5	4	0	3	0	0	5	3	0	4	0	0
Oslo, Munchen	10	8	0	5	0	0	9	6	0	7	0	0
Oslo, Gdansk	1	0	0	0	0	0	1	0	0	0	0	0
Oslo, Warsawa	1	0	0	0	0	0	1	0	0	0	0	0
Oslo, Rotterdam	5	4	0	0	0	0	5	4	0	4	0	0
Oslo, Helsingborg	2	0	0	0	0	0	2	0	0	0	0	0
Oslo, Trelleborg	1	0	0	0	0	0	1	0	0	0	0	0
Oslo, Hamburg	19	12	0	9	0	0	19	11	0	11	0	0

Table 9: Second part of list of unscheduled trains between two locations. Since the number of trains going in one direction always is the same as the number in the other direction we only show one direction in the table.

using **cap1**. Figure 4 contains a row for each capacity on a link and a column for each hour of the day. Figures 5 and 6 show for respectively the Baseline and the Green Scenario, the demand on selected links over the hours of a Wednesday not considering capacity on the edges. Note that if several times at the same price exists with no restriction on capacity the trains may without reason lump together in one time interval. Finally, in Table 7 the number of delayed trains and

pair	2030 Baseline all	2030 Baseline unscheduled cap1	cap2	cap3	cap6	HH	2030 Green all	2030 Green unscheduled cap1	cap2	cap3	cap6	HH
Trondheim, Bremen	3	2	0	2	0	0	3	2	0	1	0	0
Trondheim, Dresden	2	1	0	0	0	0	2	1	0	1	0	0
Trondheim, Hannover	1	1	0	1	0	0	1	1	0	1	0	0
Trondheim, Duisburg	2	2	0	2	0	0	2	2	0	2	0	0
Trondheim, Frankfurt	2	1	0	1	0	0	2	1	0	1	0	0
Trondheim, Munchen	4	2	0	2	0	0	4	2	0	2	0	0
Trondheim, Gdansk	1	0	0	0	0	0	1	0	0	0	0	0
Trondheim, Warsawa	1	0	0	0	0	0	1	0	0	0	0	0
Trondheim, Rotterdam	2	1	0	1	0	0	2	1	0	1	0	0
Trondheim, Helsingborg	1	0	0	0	0	0	1	0	0	0	0	0
Trondheim, Hamburg	11	7	0	5	0	0	11	7	0	7	0	0
Kleipeda, Hoje Taastrup	1	1	1	0	0	1	1	1	1	0	0	1
Kleipeda, Taulov	5	3	3	0	0	3	5	3	3	3	3	3
Kleipeda, Aalborg	3	2	2	0	0	2	3	2	2	2	2	2
Hoje Taastrup, Rotterdam	4	0	0	0	0	0	4	0	0	0	0	0
Taulov, Rotterdam	2	0	0	0	0	0	2	0	0	0	0	0
Aalborg, Rotterdam	1	0	0	0	0	0	1	0	0	0	0	0
Bremen, Almhult	1	0	0	0	0	0	1	0	0	0	0	0
Dresden, Almhult	2	1	1	0	0	0	2	0	0	0	0	0
Hannover, Almhult	2	0	0	0	0	0	2	0	0	0	0	0
Duisburg, Almhult	1	0	0	0	0	0	1	1	0	0	0	0
Frankfurt, Almhult	1	0	0	0	0	0	1	0	0	0	0	0
Munchen, Almhult	5	0	0	1	0	0	5	1	0	0	0	0
Rotterdam, Almhult	2	0	0	0	0	0	2	0	0	0	0	0
Rotterdam, Moscow	3	0	0	0	0	0	3	0	0	1	0	0
Paris, Almhult	1	1	0	0	0	0	1	0	0	0	0	0
Innsbruck, Almhult	2	0	0	0	0	0	2	0	0	0	0	0
Prag, Almhult	2	0	0	0	0	0	2	0	0	0	0	0
Athen, Almhult	1	0	0	0	0	0	1	0	0	0	0	0
Budapest, Almhult	0	0	0	0	0	0	1	0	0	0	0	0
Helsingborg, Hamburg	1	0	0	0	0	0	1	0	0	0	0	0
Almhult, Hamburg	18	3	0	2	0	0	18	2	0	3	0	0

Table 10: Third part of list of unscheduled trains between two locations. Since the number of trains going in one direction always is the same as the number in the other direction we only show one direction in the table.

the total number of minutes these trains are delayed is reported.

In Table 6 the number of routed trains are reported. From the results we can see that an increase on the **Karlshamn Hässelholm** connection increases the capacity on the network (see **cap3** and **cap5**). However the model used may not correctly reflect the capacity to **Karlshamn** as we believe that the cargo from **Sundsvall** may take an alternative route to **Karlshamn** not included in the network. It is clear that in 2030 the freight to and from **Hamburg** will use the **Femern** connection. This can be seen in Tables 12 and 11. From Table 6 it is clear that increasing the capacity on the **Øresunds** bridge from 2 to 3 trains per hour will provide capacity for many of the unscheduled trains (see **cap2**). However, when increasing this capacity to 4 trains per hour no difference is recorded in the number of scheduled trains. This is probably because the capacity on the other links at **Vigerslev** sum to 3 trains per hour where the link to **Høje Tåstrup** has capacity of 1 train per hour and the link to **Ringsted** from **Vigerslev** has capacity of 2 trains per hour. When increasing both the capacity of the **Øresunds** bridge from 2 to 3 trains per hour and the **Karlshamn Hässelholm** connection from 1 to 2 trains per hour all trains are scheduled (except for one train between Sundsvall and Athens). For the usage of the link between **Malmö** and **Vigerslev** availability spots are present in the Excel sheets[1] described earlier for **cap2** and **cap6**, whereas for **cap1** there is no unused capacity on the link. In Table 6 it can also be seen that a connection between **Helsingborg** and **Ringsted** via **Helsingør** will give the same benefits as the extra capacity on the **Øresunds** bridge (**cap2**). However, Table 7 shows that the delays maybe less using the **Helsingborg Ringsted** connection.

Figure 4: The usage of the links for a Monday 2010 divided into hours. A cell is colored red if the capacity corresponding to the column hour is used. The number of cells colored from the link definition and down corresponds to the number of trains on the link in the given hour. Excel sheets containing all scenarios for all days of the week are available upon request from authors.

In Tables reftab:linkuseBase and 11 it can be seen that a when removing the capacity restriction then a large number of trains are scheduled on the **Älmhult Hässelholm** connection between 14-15 and again between 17-18.

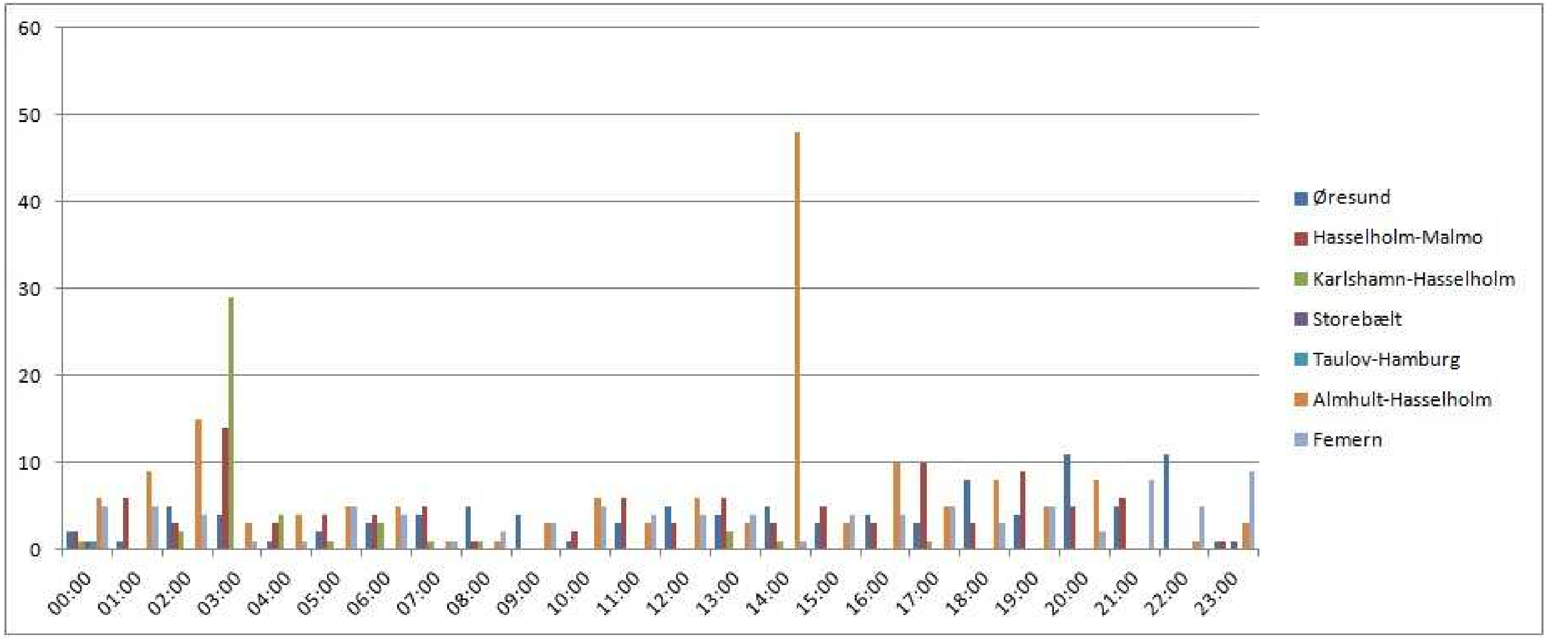

Figure 5: The number of trains per hour on selected links for the 2030 Baseline scenario on a typical workday Wednesday without capacity

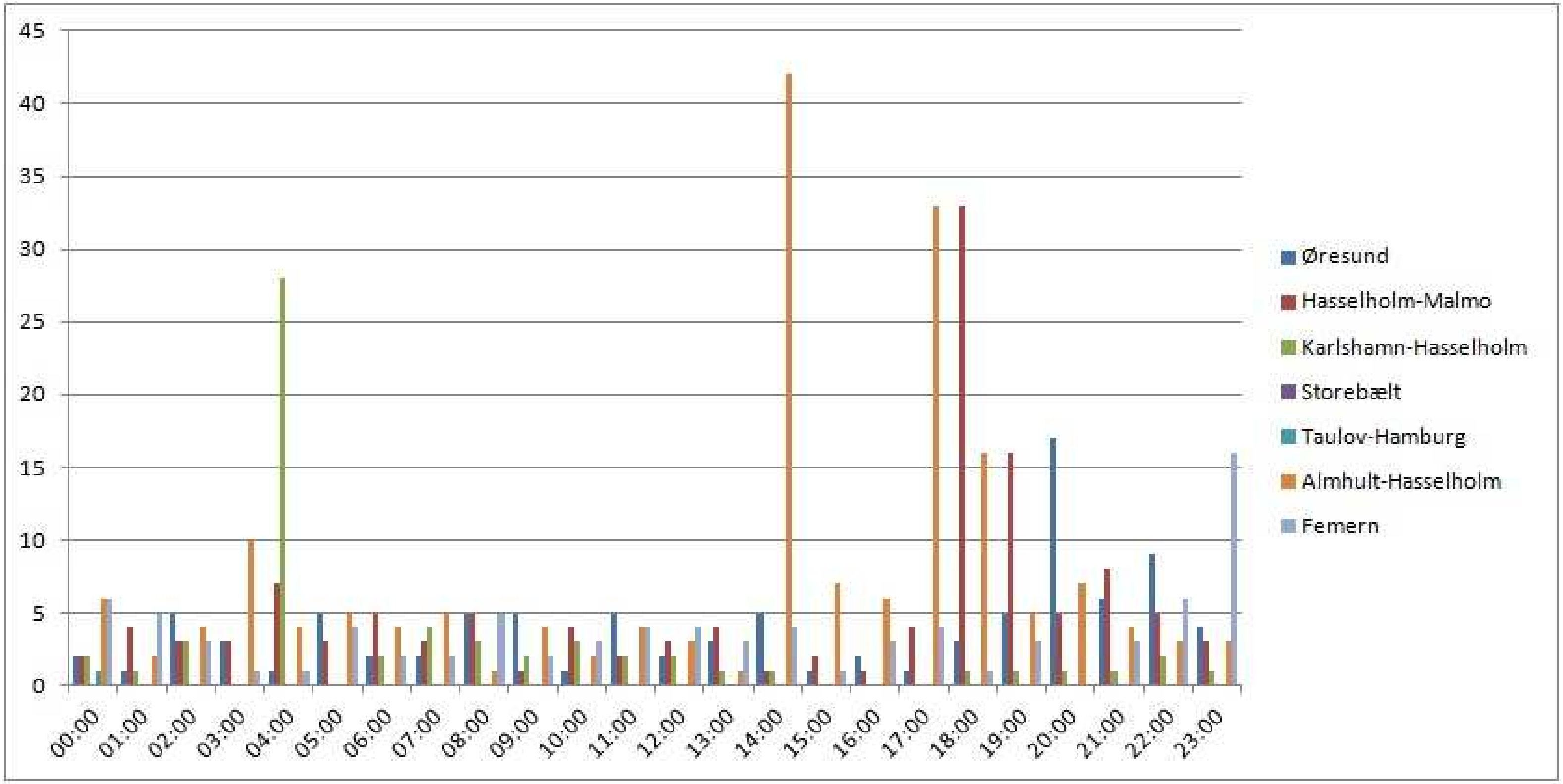

Figure 6: The number of trains per hour on selected links for the 2030 Green scenario on a typical workday Wednesday without capacity

Connections	2030									
	Green					Green SK				
	cap1	**cap2**	**cap3**	**cap6**	**HH**	**cap1**	**cap2**	**cap3**	**cap6**	**HH**
Malmø->Halmstad	103	167	107	167	63	97	167	97	167	65
Malmø<-Halmstad	103	167	106	167	65	97	167	97	167	68
Malmø->Helsingborg	2	2	2	2	1	2	2	2	2	1
Malmø<-Helsingborg	2	2	2	2	1	2	2	2	2	0
Malmø->Trelleborg	157	157	157	157	157	157	157	157	157	157
Malmø<-Trelleborg	157	157	157	157	157	157	157	157	157	157
Malmø->Vigerslev	336	454	336	467	335	336	480	336	480	335
Malmø<-Vigerslev	336	454	336	467	330	336	480	336	480	331
Malmø->Hasselholm	581	635	584	655	616	594	668	594	668	622
Malmø<-Hasselholm	581	635	585	655	619	594	668	594	668	624
Karlshamn->Hasselholm	156	156	296	296	156	95	95	95	95	95
Karlshamn<-Hasselholm	156	156	296	296	156	95	95	95	95	95
Halmstad->Helsingborg	5	5	5	5	108	5	5	5	5	105
Halmstad<-Helsingborg	5	5	5	5	109	5	5	5	5	107
Halmstad->Hasselholm	3	4	19	19	3	18	19	18	19	18
Halmstad<-Hasselholm	3	4	18	19	4	18	19	18	19	19
Høje Taastrup->Vigerslev	139	134	16	141	83	31	151	31	151	101
Høje Taastrup<-Vigerslev	133	129	18	134	115	33	148	33	148	117
Høje Taastrup->Ringsted	135	131	9	123	117	14	129	14	129	98
Høje Taastrup<-Ringsted	141	136	7	130	85	12	132	12	132	82
Taulov->Esbjerg	0	0	0	0	0	0	0	0	0	0
Taulov<-Esbjerg	0	0	0	0	0	0	0	0	0	0
Taulov->Ringsted	6	136	7	130	127	12	132	12	132	131
Taulov<-Ringsted	8	128	5	123	123	10	129	10	129	128
Taulov->Padborg	8	128	5	123	123	5	124	5	124	123
Taulov<-Padborg	6	136	7	130	127	7	127	7	127	126
Helsingborg->Hasselholm	31	31	31	31	50	31	31	31	31	77
Helsingborg<-Hasselholm	31	31	31	31	46	31	31	31	31	74
Almhult->Hasselholm	749	802	841	907	802	620	693	620	693	693
Almhult<-Hasselholm	749	802	841	907	802	620	693	620	693	693
Hamburg->Padborg	6	136	7	130	127	7	127	7	127	126
Hamburg<-Padborg	8	128	5	123	123	5	124	5	124	123
Hamburg->Putgarten	332	320	320	326	329	305	329	305	329	330
Hamburg<-Putgarten	330	328	322	333	333	307	332	307	332	333
Vigerslev->Ringsted	203	325	318	333	220	303	332	303	332	218
Vigerslev<-Ringsted	197	320	320	326	247	305	329	305	329	230
Ringsted->Putgarten	330	328	322	333	333	307	332	307	332	333
Ringsted<-Putgarten	332	320	320	326	329	305	329	305	329	330
Helsingborg->Ringsted					119					145
Helsingborg<-Ringsted					124					149

Table 11: Number of trains per link per week for each capacity set reported for the Green 2030 scenario and the Green 2030 scenario with Sundsval-Karlshamn demand removed assuming direct link between Älmhult and Karlshamn.

In Table 7, the number of delayed trains and the total number of minutes of delay are reported. It can be seen from the results on the 2030 Baseline scenario that a decrease in the number of delayed trains does not always result in a decrease in the total minutes of delays. Note that unscheduled trains are disregarded in these numbers. When compared to the number of unscheduled trains reported in Table 6 fewer cancelations do not always result in fewer delays. This is only natural as scheduling more trains may result in more total delay minutes since more trains can be delayed. An example of this can be seen for **cap2** and **cap6** where **cap2** has more cancelations than **cap6** in Table 6, however in Table 7 **cap6** has more delayed trains than **cap2** for both Green and Baseline scenario. When the capacity is large enough the delay should also be reduced as can be seen in Table 7 for **HH** and **HH2**.

For each test case the program used 10-15 minutes to find the optimal solution. This shows that the program can easily be applied to larger networks. This time was mostly spent setting up the model while only a few seconds were used on solving the model. By using better data structures the 10 minutes can easily be reduced significantly.

Connections	2010		2030									
		SK	Baseline					Baseline SK				
	cap1	**cap1**	**cap1**	**cap2**	**cap3**	**cap6**	**HH**	**cap1**	**cap2**	**cap3**	**cap6**	**HH**
Malmø->Halmstad	70	70	98	170	117	170	59	97	170	97	170	59
Malmø<-Halmstad	70	70	98	170	117	171	58	97	170	97	170	58
Malmø->Helsingborg	0	0	2	2	2	2	1	2	2	2	2	1
Malmø<-Helsingborg	0	0	2	2	2	2	0	2	2	2	2	0
Malmø->Trelleborg	88	88	165	165	165	165	165	165	165	165	165	165
Malmø<-Trelleborg	88	88	165	165	165	165	165	165	165	165	165	165
Malmø->Vigerslev	150	150	336	471	336	477	336	336	477	336	477	336
Malmø<-Vigerslev	150	150	336	471	336	477	334	336	477	336	477	334
Malmø->Hasselholm	295	295	590	653	571	659	628	591	659	591	659	628
Malmø<-Hasselholm	295	295	590	653	571	658	632	591	659	591	659	632
Karlshamn->Hasselholm	71	10	147	147	230	230	147	14	14	14	14	14
Karlshamn<-Hasselholm	71	10	147	147	230	230	147	14	14	14	14	14
Halmstad->Helsingborg	2	2	5	5	5	5	118	5	5	5	5	118
Halmstad<-Helsingborg	2	2	5	5	5	5	116	5	5	5	5	116
Halmstad->Hasselholm	2	2	2	3	3	3	2	3	4	3	4	3
Halmstad<-Hasselholm	2	2	2	3	3	4	3	3	4	3	4	4
Høje Taastrup->Vigerslev	150	150	129	144	9	145	94	9	147	9	147	91
Høje Taastrup<-Vigerslev	150	150	129	143	11	144	124	11	145	11	145	125
Høje Taastrup->Ringsted	150	150	133	147	14	147	128	14	148	14	148	128
Høje Taastrup<-Ringsted	150	150	133	148	12	148	98	12	150	12	150	94
Taulov->Esbjerg	0	0	0	0	0	0	0	0	0	0	0	0
Taulov<-Esbjerg	0	0	0	0	0	0	0	0	0	0	0	0
Taulov->Ringsted	150	150	6	148	12	148	140	12	150	12	150	145
Taulov<-Ringsted	150	150	8	144	10	147	139	10	147	10	147	144
Taulov->Padborg	147	147	8	144	5	142	139	5	142	5	142	139
Taulov<-Padborg	147	147	6	148	7	143	140	7	145	7	145	140
Helsingborg->Hasselholm	19	19	31	31	31	31	56	31	31	31	31	62
Helsingborg<-Hasselholm	19	19	31	31	31	31	51	31	31	31	31	57
Almhult->Hasselholm	367	306	758	820	809	896	820	613	680	613	680	680
Almhult<-Hasselholm	367	306	758	820	809	896	820	613	680	613	680	680
Hamburg->Padborg	147	147	6	148	7	143	140	7	145	7	145	140
Hamburg<-Padborg	147	147	8	144	5	142	139	5	142	5	142	139
Hamburg->Putgarten			334	327	327	332	335	327	330	327	330	335
Hamburg<-Putgarten			332	331	329	333	336	329	333	329	333	336
Vigerslev->Ringsted			207	328	325	333	212	325	332	325	332	211
Vigerslev<-Ringsted			207	327	327	332	240	327	330	327	330	243
Ringsted->Putgarten			332	331	329	333	336	329	333	329	333	336
Ringsted<-Putgarten			334	327	327	332	335	327	330	327	330	335
Helsingborg->Ringsted							135					141
Helsingborg<-Ringsted							137					143

Table 12: Number of trains per link per week for each capacity set reported for scenario 2010, Baseline 2030 and Baseline 2030 with Sundsval-Karlshamn demand removed assuming direct link between Älmhult and Karlshamn.

7 Conclusion

A track allocation model has been used to analyze the capacity of the rail network. With the knowledge of the train operators and railway planner this model should be able to aid in the decision process of railway expansions and planning.

Assuming that the forecast for the freight transport through the Danish and Southern Swedish region holds and that the other assumptions such as the weekly distribution of trains Table 1 and departure and arrival times are representative, the tests show that increasing the capacity between **Malmø** and **Vigerslev** from 2 to 3 trains per hour will make it possible to transport all the freight in the forecast by train. However, even by increasing the capacity between **Malmø** and **Vigerslev** to 3 trains per hour there are still many delays in the network and the usage is for some links is close to 100% over the entire week. This could indicate that the amount of freight estimated to be transported by rail is much higher than expected. An alternative to increasing the capacity on the link between **Malmø** and **Vigerslev** (**Øresund**) is to build a new link between **Helsingborg** and **Ringsted** with capacity for 2 trains per hour. The test show that including the **Helsingborg Ringsted** link results in less delays than increasing the **Malmø Vigerslev** (**Øresund**) connection. However, there are still many delays when using the **Helsingborg** and **Ringsted** connection.

Another issue maybe even more pressing issue is the freight between **Sundsvall** and **Karlshamn** where a direct link between **Älmhult** and **Karlshamn** is needed to commodate the freight volume. The rail network between **Älmhult** and **Sundsvall** is not part of the network investigated and investigations on the capacity of that network maybe necessary.

Acknowledgments

The authors wish to thank Mikkel Krogsgaard Niss, Eva Lindborg and Jens Brix for valuable discussions and input to the project.

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A Appendix: IP Model

N The set of nodes

E The set of connections in the time expanded graph

O The set of demands

Sr^k the time expanded set of sources of demand $k \in \mathbf{O}$.

Sk^k the time expanded set of sinks of demand $k \in \mathbf{O}$.

O_{od} The set of demands with the same origin station o and destination station d.

We use the following parameters

q_{ij} the capacity per hour on a link $e \in \mathbf{E}$.

a_p^k The start time for the soft time window for departure of demand k

b_d^k The end time for the soft time window for arrival of demand k

pd^+ penalty for departure before a_p^k

pa^+ penalty for arrival after b_d^k

c_{ij}^k the cost of demand $k \in \mathbf{O}$ traveling on connection ij where the penalty for late arrival is also introduced for each demand on the connections from the departing station and to the arrival station.

P^k Penalty for not routing demand $k \in \mathbf{O}$

A.1 Appendix: Edge Model

Using the definition described in Section A the edge variable model can be formulated by using the variable $x^k_{i_t j_{t'}}$ which is 1 if demand k is transported on a direct connection between i_t and $j_{t'}$ and 0 otherwise. Here t is the time at station i and t' is the time at j. he variable h^k is 1 if demand k is routed and 0 other wise. Let t_{ij} be the travel time on connection ij and t_i be the time of node i in the time expanded graph.

$$\textbf{Min:} \sum_{k \in \mathbf{O}} \left(P^k h^k + \sum_{i_t \in \mathbf{N}} \sum_{j_{t'} \in \mathbf{N}} c^k_{i_t j_{t'}} x^k_{i_t j_{t'}} \right) \tag{1}$$

s.t.

$$\text{(Flow)} \quad \sum_{j \in \mathbf{N}} x^k_{ji} = \sum_{j \in \mathbf{N}} x^k_{ij} \qquad \forall k \in \mathbf{O}, \forall i \in \mathbf{N} \setminus \{Sr^k \cup Sk^k\} \tag{2}$$

$$\text{(StartEnd)} \quad \sum_{j \in \mathbf{N}} \sum_{i \in Sr^k} x^k_{ij} - \sum_{j \in \mathbf{N}} \sum_{i \in Sk^k} x^k_{ji} = 0 \qquad \forall k \in \mathbf{O} \tag{3}$$

$$\text{(End)} \quad \sum_{j \in \mathbf{N}} \sum_{i \in Sk^k} x^k_{ij} \leq 1 \qquad \forall k \in \mathbf{O} \tag{4}$$

$$\text{(Start)} \quad \sum_{j \in \mathbf{N}} \sum_{i \in Sr^k} x^k_{ji} \leq 1 \qquad \forall k \in \mathbf{O} \tag{5}$$

$$\text{(Delay)} \quad \sum_{j \in \mathbf{N}} \sum_{i \in Sk^k} t_i x^k_{ji} \leq 24 + b^k_d \qquad \forall k \in \mathbf{O} \tag{6}$$

$$\text{(Capacity)} \quad \sum_{k \in \mathbf{O}} x^k_{ij} \leq q_{ij} \qquad \forall i, j \in \mathbf{N} \tag{7}$$

$$\text{(Routed)} \quad \sum_{j \in \mathbf{N}} \sum_{i \in Sr^k} x^k_{ij} + h^k \geq 1 \qquad \forall k \in \mathbf{O} \tag{8}$$

$$\text{(Return)} \quad \sum_{k \in O_{od}} h^k - \sum_{k \in O_{do}} h^k = 0 \qquad \forall O_{od} \in \mathbf{O} \tag{9}$$

$$x^k_{ij} \in \{0,1\} \qquad \forall i, j \in \mathbf{N}, \forall k \in \mathbf{O} \tag{10}$$

$$h^k \in \{0,1\} \qquad \forall k \in \mathbf{O} \tag{11}$$

Constraints (2) ensure that a train entering a node will also leave the node unless the node is the origin or destination of the train. Constraints (3) ensure that a train which departs also arrives. Constraints (4) and (5) ensure that a train journey leaves its start location and enters its end location at most once. Constraints (6) will prevent trains from arriving more than 24 hours late at the end location. The capacity constraints (7) ensure that the hourly capacity of the track is not exceeded. Constraints (8) introduce a penalty if a train is not scheduled. Finally, constraints (9) ensure that if a train between o and d is unscheduled then a train in the opposite direction is also unscheduled. This is to ensure that all trains return. It should be noted that there are no variables x^k_{ij} where i and j are time expanded vertices of the same station. This model has $O(|K||E|)$ variables. In our case where $|E|$ contains several thousand edges due to the time expanded graph an increase in the number of commodities will increase the number of variables significantly. In the three test instances delivered there are between 900 and 2500 trains to be routed in both directions. Therefore there are more than 1 million variables in the instances. This was not solveable and a different approach was used to solve the problem. Moreover this model may construct routes which are undesireable for the operators. Such routes could be routes which travel for parts in the opposite direction of the destination to ensure arrival at links when capacity is available.

A.2 Appendix: Path Model

To solve the problem of many variables and to ensure that the routes constructed are acceptable for the operators, we have chosen to decompose the model. In the decomposition each train has a set of possible paths to chose from. The acceptable paths for the trains through the network is provided by the operators and for these paths time-dependent paths are generated in the subproblem. The goal is to maximize the number of trains scheduled and to minimize the total delay.

A.2.1 Master

The master problem is the problem which selects a set of paths which will not exceed the capacity on the links in the time expanded graph and which minimizes the cost for the cancelation penalty, the travel cost and the delay cost.

To select the paths we use the variable λ^k_{Pt} which indicates if path Pt is selected for demand k. The parameter α^{Pt}_{ij} is 1 if the connection between i and j in the time expanded graph is part of the path Pt. The variable h^k is 1 if demand k is routed and 0 other wise.

$$\textbf{Min: } \sum_{k \in \mathbf{O}} \left(P^k h^k + \sum_{Pt \in P(k)} \lambda^k_{Pt} c^k_{Pt} \right) \tag{12}$$

$s.t.$

$$\text{(Capacity)} \quad \sum_{k \in \mathbf{O}} \alpha_{ij} \lambda^k_{Pt} \leq q_{ij} \qquad \forall i,j \in \mathbf{N} \tag{13}$$

$$\text{(Routed)} \quad \sum_{Pt \in P(k)} \lambda^k_{Pt} + h^k \geq 1 \qquad \forall k \in \mathbf{O} \tag{14}$$

$$\text{(Returned)} \quad \sum_{k \in O_{od}} h^k - \sum_{k \in O_{do}} h^k = 0 \qquad \forall O_{od} \in \mathbf{O} \tag{15}$$

$$\lambda^k_{Pt} \in \{0,1\} \qquad \forall i,j \in \mathbf{N}, \forall k \in \mathbf{O} \tag{16}$$

$$h^k \in \{0,1\} \qquad \forall k \in \mathbf{O} \tag{17}$$

In the objective function (12) the cost c^k_{Pt} is the cost of the path Pt with respect to demand k. This also corresponds to the sum $\sum_{i,j \in \mathbf{N}} c^k_{ij} \alpha^{Pt}_{ij}$ for a path $Pt \in P(k)$. The objective function (1) will clearly minimize the delay penalty on the departure through the cost c^k_{Pt}. By making the penalty P_k for not scheduling a train very large we can ensure that trains are only unscheduled if no other option is possible. Note that this ensures that the number of unscheduled trains is minimized however the trains unscheduled are not selected using some criteria. Using this objective trains which introduce more cost will be unscheduled. This could be trains which travel far and therefore have a larger travel cost and/or trains which in a solution would have a larger delay penalty. In this **Master problem** we have capacity constraints (13) to ensure that the capacity is not exceeded. Constraints (14) correspond to the constraints (8) where it is ensured that if no path is used for a commodity then a penalty is paid. Finally the constraints (15) ensure that when a train is unscheduled, a train in the opposite direction is also unscheduled.

A.2.2 Subproblem

For each S-E pair a set of paths is defined in advance by a user with knowledge of which transportation paths are acceptable. This can in later versions be changed so that the acceptability of a path is calculated from the increase in cost using some threshold value. For each of the given paths, the program generates a path for each valid time period of start and end. In our case we look at hourly departures and a path will be created for each of those time intervals as long as they are valid according to the hard time window of the demand. The cost of the path is calculated with respect to the desired time window of the demand. In this way between 70 000 and 500 000 paths are generated. This is also the number of variables in the master problem.